Abstract

Flow dynamics and sand deposition processes over nebkhas were investigated using computational fluid dynamics simulations, wind tunnel experiments, and field measurements. The computational fluid dynamics simulations showed that nebkha width affects both the elongation and broadening of the wind shadows. The length of the wind shadows decreased as the wind shear velocity increased, following a power function, irrespective of the width and height of the nebkha. There are some uncertainties about the effect of the aspect ratio of the nebkha on the formation of wind shadows as a result of the omission of the transport of sand in the simulations. It is suggested that the length of wind shadows is dependent on the absolute values of nebkha width and height rather than the nebkha aspect ratio. Although the numerical results were consistent with the results of the wind tunnel experiments, the wind tunnel experiments showed that the height of the nebkha had a negative effect on the elongation of the shadow dunes. The sedimentary structures revealed by ground-penetrating radar surveys of the dunes in the Taitema Dry Lake, in the eastern Taklimakan Desert, China, showed that the formation of shadow dunes can be divided into three phases. Shadow dunes are initially controlled by horizontal separation flow and then elongate following the same growth mechanisms as linear dunes, eventually breaking up into isolated barchans or short, temporary linear dunes. However, the formation of shadow dunes does not necessarily call for the three phases depending on the local wind regime and sediment supply.

1. Introduction

Shadow dunes are aerodynamic bedforms with a quasi-pyramidal profile created by horizontal flow separation on the lee of barriers (e.g., hill, mound, plant, and nebkhas; Bagnold, 1941; Gunatilaka & Mwango, 1989). They are formed from the sand depositing downwind of obstacles. Shadow dunes have partial characteristics of linear dunes and can extend in the resultant transport direction a few kilometers or hundreds of meters depending on the local wind regime and sand availability conditions (Courrech du Pont et al., 2014; Lucas et al., 2015). Secondary airflow is considered as one of the major controls on the formation of shadow dunes (Andrew & Gary, 1996; Lynch et al., 2008; Walker, 1999; Walker & Nickling, 2002), which is generated by flow-topography interactions (e.g., flow separation and reattachment, reversal cells, and shear layers). Parameters such as the fluid velocity, direction, pressure, and shear stress in secondary airflow are altered by the topography of obstacles (Walker & Nickling, 2002; Wang & Huang, 2017). Secondary airflow differs in energy and direction due to variations in the geometry and alignment of obstacles and the wind regime (e.g., wind velocity, wind direction, and angle of incidence; Escurriaiza & Sotiropoulos, 2011; McKenna-Neuman and Bédard, 2015; Meire et al., 2014; McKenna-Neuman et al., 2015; Vinuesa et al., 2015; Bruno et al., 2018; Kindere & Ganapathisubramani, 2018; Sun & Huang, 2018; He et al., 2018). Although the relationships between the geometric parameters of the obstacles, the wind velocity, and the length of flow reattachment and recovery have been reported previously (Clemmensen, 1986; Gillies et al., 2014; Gunatilaka & Mwango, 1987; Hesp, 1981; Hesp & Smyth, 2017), questions remain about the sensitivity of these secondary airflow structures to changes in wind velocity, the geometry of the obstacles, and the subsequent shadow dune formation.

Previous studies found that the length of shadow dunes increases with the basal width of plants forming an obstacle to airflow, but no apparent relationship with the height of the plants was observed (Hesp, 1981; Hesp & Smyth, 2017). However, research on transverse dunes showed that the separation zone and the flow recovery distance were sensitive to changes in the height of dunes (Parsons et al., 2004). Most of the
characteristic lengths over aeolian dunes, such as the length of the reversed flow and flow reattachment, are defined by the height of the obstacles (Walker & Nickling, 2002). The conclusions derived from previous research (Hesp, 1981) may be applicable to porous obstacles. However, if the obstacle is a bluff body, such as a mound, hill, or rock, then the length of reattachment and recovery might be closely associated with the height of the obstacles (Allen, 1978; Houser & Mathew, 2011; Walker & Nickling, 2002).

Few studies have reported the relationship between the height of an obstacle and the formation of shadow dunes (Hesp, 1981). Parameters such as the aspect ratio and the angle of the stoss slope are often used to assess the effects of topography on sand or snow deposition processes (Hesp & Smyth, 2017; Iversen et al., 1990; Luo et al., 2012, 2014; Parsons et al., 2004). However, it is assumed that when the aspect ratio or the stoss slope is fixed, then the flow patterns around the topographic obstacles change with the variation of the width and height of the obstacles.

Nebkhas are also called coppice dunes or hummocky dunes (Gile, 1966; Pye & Tsoar, 2009), which are the typical topographical obstacles developed by the trapping of sediments within plants (Cooke et al., 1993). There are a large number of shadow dunes that have formed on the leeside of nebkhas in the Taitema Dry Lake, in the eastern Taklimakan Desert, China. These nebkhas develop when sand is trapped by the growth of Tamarix shrubs, forming topographic obstacles that are roughly hemispherical cones or domes in shape (Figure 1). The major sand source for the development of these shadow dunes on the leeside of the nebkhas is from the upwind region and the windward slope of the nebkhas. Most of the nebkhas in this area have been denuded as a result of the degradation of the shrubs growing on them. The shadow dunes vary in both length and height as the geometry and spatial alignment of the nebkhas change (Figures 1b–1e). Based on the clear description of flow dynamics around nebkhas reported by Hesp and Smyth (2017), we studied the effects of wind velocity and nebkha geometry parameters (e.g., width, height, and aspect ratio) on the morphology of shadow dunes. The computational simulation was used to study the effects of incident wind velocity,
nebkha geometry (e.g., nebkha height, width, and aspect ratio) on the wind shadow formation. Furthermore, a wind tunnel experiment was undertaken to study the erosion and deposition patterns of sand around model nebkhas. In addition, a topographic survey and ground-penetrating radar (GPR) profiles were collected across the crest of a large shadow dune in the Taitema Dry Lake area to provide information on the internal sedimentary structure of a shadow dune. The objectives of this research were to study the effects of wind velocity and the geometry parameters of nebkhas (e.g., width, height, and aspect ratio of nebkhas) on the formation of shadow dunes and to analyze the associated growth mechanisms.

2. Methods

2.1. Computational Fluid Dynamics Simulations

2.1.1. Description of Computational Fluid Dynamics Simulation Code

To simulate the effects of wind speed, nebkha geometry (nebkha height, width, and aspect ratio) on flow dynamics around the nebkhas, the ANSYS Fluent code (Version 17.0) was used. The finite volume method was used to solve the Reynolds-averaged Navier-Stokes equations. The incident flow was considered as an incompressible Newtonian fluid because the flow velocities used in our simulations were much smaller than the velocity of sound. The renormalization group theory $k$–$\varepsilon$ method was used to model the turbulence. This method yields the most accurate results for the strongly separated flow downwind of aeolian landforms (Araújo et al., 2013; Smyth, 2016; Walker & Nickling, 2002).

The default pressure-velocity coupling scheme of the Fluent software was chosen to solve the Navier-Stokes equations (Patankar & Spalding, 1972). We considered that convergence was achieved when the residuals for the velocities $U(x)$, $U(y)$, and $U(z)$ were <0.00001 and the residuals for both $k$ (turbulence kinetic energy) and $\varepsilon$ (turbulence dissipation rate) were <0.0001. The ANSYS ICEM tool was used to build the morphology and numerical grid. The structured hexahedron grid method was used over the entire computational domain.

2.1.2. Boundary Conditions

The height of the computational domain is generally much lower than the atmospheric boundary layer height. Profiles such as the vertical distribution of the wind velocity $U(y)$, the turbulent kinetic energy $k(y)$, and the energy dissipation $\varepsilon(y)$ at the inlet are therefore simplified using equations (1), (2), and (3) assuming a constant shear stress (Table 1) with height (Richards & Hoxey, 1993):

$$
U(y) = \frac{u^*}{k} \ln \left( \frac{y + y_0}{y_0} \right),
$$

$$
k(y) = \frac{u^*}{\sqrt{C_{\mu}}},
$$

$$
\varepsilon(y) = \frac{u^*}{k(y + y_0)},
$$

where $U(y)$ is the wind velocity at a height of $y$ (m), $\kappa = 0.40$ is the von Karman constant (Richards & Norris, 2011), $u^*$ is the wind shear velocity assuming a constant shear velocity with height, $y$ is the height above the surface, $y_0$ is the surface roughness length (0.1 mm), and $C_{\mu} = 0.085$ is a constant in renormalization group $k – \varepsilon$ (Richards & Norris, 2011). In addition, to generate a pressure gradient in the flow direction, fully developed conditions, that is, zero gradient along the streamwise direction, were assumed, and the relative static pressure ($P = 0$) was set equal to zero at the outlet (Araújo et al., 2013; De Lima et al., 2015; Faria et al., 2011; Tian et al., 2013).

A structured hexahedral mesh was used over the entire computational domain. The global cell height was determined to be 0.2 m, although the heights of the cells adjacent to the walls were refined to meet the requirement of the computational fluid dynamics (CFD) simulation based on the recommendations of Blocken et al. (2007).

Table 1: Shear Velocities and the Corresponding Wind Velocities at 1-m Height

| Shear velocity (m/s) | Wind velocity at 1-m height (m/s) |
|----------------------|----------------------------------|
| 0.30                 | 6.91                             |
| 0.35                 | 8.06                             |
| 0.40                 | 9.21                             |
| 0.45                 | 10.36                            |
| 0.50                 | 11.51                            |
| 0.55                 | 12.66                            |
| 0.60                 | 13.82                            |
| 0.80                 | 18.42                            |
| 1.00                 | 23.03                            |
where $y_p$ is the distance from the center of the cell adjacent to the wall, $K_s$ is the roughness of sand grains, and $C_s = 0.50$ is the roughness constant. According to these parameters, $K_s = 0.00196$.

We used the heights of the cell adjacent to the bottom surface of the computational domain and the dune surface as 0.6 and 0.3 cm, respectively. Based on these settings, the dimensionless wall unit, $y^+$, was between 30 and 250, and the nondimensional roughness height was $K_s^+ = K_s u_L/ν ≈ 9.793 y_p/C_s$, which is in the transitional regime (Blocken et al., 2007). The no-slip boundary condition was applied to the dune and the wall surface of the computational domain (Figure 2).

To study the effects of wind velocity on the flow dynamics over nebkhas, simulations were performed using a series of wind shear velocities (increasing in increments of 0.05 m/s from 0.3 to 1.0 m/s; Table 1). Three kinds of nebkhas were chosen to examine the influence of the geometric parameters on the flow dynamics: (1) nebkhas with the same aspect ratio (1:3) but different heights (0.3, 0.4 and 0.5 m) and basal diameters (0.9, 1.2 and 1.5 m); (2) nebkhas at a fixed height (0.5 m) with basal diameters 0.60, 0.90, 1.10, 1.20, 1.30, 1.40, and 1.5 m; and (3) nebkhas with a fixed basal diameter (1.0 m) but with the height increasing in 0.05 m increments from 0.25 to 0.70 m. Based on the work of Hesp and Smyth (2017), we calculated the equivalent wind velocities corresponding to the chosen shear velocities at 1 m above the surface (Table 1). The Reynolds numbers corresponding to any equivalent velocity and the characteristic length, width, or height of the nebkhas ranged from $1.2 \times 10^5$ to $2.4 \times 10^6$, demonstrating that in all cases the flow is fully turbulent.

### 2.2. Wind Tunnel Experiment

To verify the results from the numerical simulation, the effects of wind velocity and the geometry of nebkhas on flow dynamics and the deposition of sand were simulated in a wind tunnel. The tunnel is a blow-type, noncirculating wind tunnel, built by Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. The cross section of the wind tunnel is 1.3 m × 1 m, and the test length is 4 m (Figure 3a). The wind profiles of the mean streamwise velocity at 10 heights under three incident wind velocities of 7, 12, and 16 m/s were measured with Pitot tubes in the empty test section in the wind tunnel. Then we took the height with the wind velocity that accounts for 99% of the incident wind velocity as the height of the boundary layer. Therefore, under the described measurements, the boundary layer thickness is 15 cm in the test section. The free streamwise wind velocity at the test section can be adjusted continuously from 1 to 20 m/s.

In order to understand the effects of wind velocity and nebkha geometry on shadow dune formation, we used different nebkha models in the wind tunnel experiments (Table 2). For example, to simulate the effects of the basal width of nebkhas on the fluid dynamics and sand accumulation over them, three nebkha models with different diameters (0.15, 0.20, and 0.25 m) but the same height ($H = 0.05$ m) were used. To analyze the effects of the height of the nebkhas on flow dynamics and shadow dune formation, three nebkhas of different heights (0.03, 0.05, and 0.07 m) but the same diameter (0.20 m) were used. In view of the geometry of the nebkha models (hemisphere or dome in shape) and their height (0.5–4.8 m) and width (1.4–18 m) ranges in Taitema Dry Lake and the parameters of nebkha models used in wind tunnel (Figure 3b and Table 2), the geometric scaling of the nebkhas in wind tunnel was between 1:6 and 1:70.

Nebkhas in Taitema Dry Lake were semispherical. Some of them were covered by the living plant, but some were denuded due to the long-term drought. Therefore, it is thus impossible to make a single nebkha model that is geometrically similar to all kinds of nebkhas in the field. Furthermore, plant density on nebkhas can affect the flow dynamics and sand transporting patterns (Castro, 1971; Dong et al., 2008). To avoid the effects of density differences on our results, a unique plant density (i.e., 19%) was artificially chosen in wind tunnel experiment. The plant on nebkha models was made of 1-mm-thick artificial grass with 0.05 m high. The artificial grasses were evenly planted in the holes with the diameter of 5 mm on the nebkha models. The density of the artificial grass was defined on the basis of the ratio between the total hole area and the total area of the nebkha base. The density was adjusted by changing the number of the holes on nebkha models.

All the nebkha models were positioned 2.4 m (this distance is 16 times the boundary layer thickness, meeting the general requirement of the mean nondimensional velocity profile; White, 1996) downstream of the leading edge of the working section in the wind tunnel. The ratio of the largest nebkha width (0.25 m) to the
Figure 3. Schematic view of the wind tunnel experiment with the nebkha models. (a) Wind tunnel elements and location of the nebkha model. The hot wire sensor and Pitot tube were used to measure the wind pressure. All the measured data were logged into the computer. The wind speed was derived from these wind pressure values. The brown hemisphere represents the nebkha model. The area marked with light olive color is the sand bed (1 m in width, 1.3 m in length, and 4 cm in thickness), which demonstrates the method of feeding the sand particles into the wind tunnel. (b) The lateral view of the nebkha models. $H$ refers to the nebkha height, and $D$ the basal diameter. Green artificial plant-like material placed on the surface of nebkha models with a density of 19%.

Figure 2. Setup of the computational fluid dynamics simulations. (a) Global arrangement of the grid. (b) Grid details near the obstacle model. (c) Computational domain. (d) The morphology of nebkha models with hemisphere dome-like bluff shape. These nebkha models have the same diameter (1.0 m), but different heights (from left to right, the heights are 0.4, 0.5, 0.6, and 0.7 m, respectively).
width of working section of wind tunnel was 0.192 (25:130), which ensures that the side wall effects of wind tunnel on the flow patterns around the nebkha models would be insignificant. Different undisturbed velocities ($U_r = 8, 10, \text{ and } 12 \text{ m/s}$) were set at the wind tunnel inlet. The corresponding velocity profiles in the working section of the tunnel are shown in Figure 4. In view of the constraints of wind tunnel experimentation, it is difficult to allow all the similarity requirements to be met simultaneously. Therefore, some compromises must be adopted (Musick et al., 1996). The geometric scale of the models in our study suggests that it is almost impossible to satisfy the strict Reynolds number scaling for dynamic. However, we tried to meet the generally recommendation of "Reynolds number independence" from White (1996). Based on the nebkha model geometry parameters and three free-stream wind velocities, we calculated the Reynolds number using the equation $Re = \frac{\rho uL}{\eta}$, where $\rho$ is the density of air (1.255 kg/m$^3$), $u$ is the streamline velocity at a height of 0.5 m, $L$ is the diameter of the nebkha at a fixed height or the height of the nebkha at a fixed diameter, and $\eta$ is the viscosity of air (0.000018 Pa s). The Reynolds numbers for the three undisturbed velocities ranges from $8.92 \times 10^4$ to $2.03 \times 10^5$, which are large enough to meet the requirements of the Reynolds number independence regime recommended by White (1996).

The ratio of the height of the nebkha to the thickness of the boundary layer is an important issue in the wind tunnel experiment. It is reasonable to keep the nebkha height in the lower 20% of the wind tunnel boundary layer (White, 1996). For our present study, the maximum height of the nebkha (12 cm) is 80% of the thickness of the boundary layer in the wind tunnel (15 cm), which does not satisfy the requirement of wind tunnel experiment recommended by White (1996). This means that the results of our study could not be extrapolated to the full-scale condition. However, according to White (1996), if the Reynolds number exceeds a minimum critical value of $10^4$, the required ratio >20% of the height of the nebkha to the thickness of the boundary layer in the wind tunnel and full-scale condition can be relaxed. In our wind tunnel experiments, Reynolds numbers for the three undisturbed velocities ranged from $8.92 \times 10^4$ to $2.03 \times 10^5$, which are large enough to meet the requirements of the Reynolds number independence regime recommended by White (1996). Therefore, our wind tunnel experiments can be used to validate the CFD simulations and also are useful to understand the formation mechanisms of the shadow dunes.

The flow dynamics over the model nebkhas were measured using Pitot tubes (Figure 3a). Each of the Pitot tubes was connected with a setra pressure transmitter. The model of the setra pressure transmitter is No. 268, serial number is c2028467, the sampling accuracy is ±0.25%FS, and the frequency of the sampling is 1 Hz. All the data were logged by a data collection card (Model: AC6624, 16-bit high-precision A/D data collection card). The wind velocity in the vertical profile (at heights of 1, 2, 3, 5, 7, 10, 15, 30, and 50 cm) at each point was measured under a steady-state flow. Figure 5 shows the distribution of the measurement points in the wind tunnel.

**Table 2**

| Experiment No. | Height (m) | Diameter (m) | Aspect ratio | $U_r$ (m/s) | Reynolds number |
|---------------|------------|--------------|-------------|-------------|----------------|
| 1             | 0.08       | 0.20         | 0.15        | 8           | 118,961        |
| 2             | 0.10       | 0.20         | 0.25        | 10          | 135,975        |
| 3             | 0.12       | 0.20         | 0.35        | 12          | 162,653        |
| 4             | 0.10       | 0.15         | 0.33        | 8           | 89,221         |
| 5             | 0.10       | 0.25         | 0.20        | 12          | 148,701        |

*Figure 4.* Incident velocity profiles obtained in the working section of the tunnel with three undisturbed wind velocities at the inlet of the wind tunnel. The height was presented in logarithmic scale.

*Figure 5.* The distribution of the measurement points in the wind tunnel.
During the experiments to examine sand deposition patterns around the nebkhas, a sand bed was set in front of the leading edge of the working section. To get a stable deposition pattern around nebkhas, a series of preliminary experiments were carried out. From these tests we observed that a sand bed with a dimension of 100-cm width, 130-cm length, and 4-cm thickness was large enough to get a stable deposition pattern for all given conditions (Figure 3a). The steady state was considered to be reached when the boundary of the sand shadow no longer changed even though the sand feeding process continued. The thickness of sand around the nebkha was recorded at grid points with a spatial resolution of 2 × 2 cm. Two infrared distance meters (model DT500, resolution ±1.5 mm) were used to measure the thickness of sand deposition at each point. Based on the symmetry of the flow and the deposition of sand around the nebkha, the measurements were only performed on one side of the nebkha, and the results are presented by mirroring the measurements on the symmetrical side.

In order to get the sand flux structure, the sand flux at different heights (1, 3, 6, 10, 12, 14, 16, 18, and 20 cm) above the floor of the wind tunnel has been measured using a step-like sand collector, which was set at the end of the working section of the wind tunnel. The step-like sand collector is 40 cm high, 16 cm wide, 1.4 cm thick with 20 vertical openings (the area of each opening is 1 × 1 cm²), whose collection efficiency is up to 50%. The wind-blown sand enters the sand collector through these openings. Sand particles in each tube were weighed using an electronic (with precision of 0.001 g). The percentage of sand mass in each opening to the total sand mass in all of the openings was calculated. In view of the short time to reach the equilibrium transport rate, the experiment duration was set as 2 min.

### 2.3. Definition of Wind Shadow Length

Wind shadow means an area sheltered by some topographical obstacles when they encounter the wind flow. Flow dynamics and sand transporting processes in this region are controlled by secondary airflow, such as the reverse vortex and separation flows (Walker & Nickling, 2002). To quantify the length of the wind shadow, the method of Hesp (1981) was used. Hesp (1981) assumed that the length of wind shadow refers to the horizontal distance from the top of the obstacle to the point at which the wind velocity is equal to the sand transporting velocity (4 m/s) 0.01 m above the surface (see also Bagnold, 1941; Hesp & Smyth, 2017). Furthermore, previous researchers reported that for the dry sand of medium grain size, the minimum threshold wind velocity is about 4 m/s (Hsu, 1973). The mean grain diameter of test sand was in this study is 300 μm. Therefore, the threshold wind shear velocity at 0.01 m above the surface could be calculated as below:

$$ u_\tau = A \sqrt{\frac{\rho_s - \rho}{\rho} g d}, \quad (5) $$

where $u_\tau$ is the threshold wind shear velocity, meters per second; $A = 0.11$ is a constant; $\rho_s = 2,650$ kg/m³ is the sand grain volume density; $\rho$ is the density of the air, 1.225 kg/m³; $g$ is the gravitational acceleration.
constant, 9.8 m/s²; and \( d = 300 \mu m \) the mean sand grain diameter; the threshold wind velocity for sand transporting at 0.01 m above the surface could be calculated from

\[
u_{0t} = 5.75 \times u^* \times \log \left( \frac{z}{z_0} \right),
\]

(6)

where \( z = 0.01 \) m is the height above the surface and \( z_0 = 0.000032 \) m is the aerodynamic roughness length.

The threshold sand transporting wind velocity at 0.01 m above the surface is 3.87 m/s. To compare our result with previous observations, we also set the threshold wind velocity as 4 m/s in the CFD simulations. In view of the lack of morphodynamic feedbacks between sand deposition and wind flow patterns in the CFD simulation (no sand was considered in numerical simulations) and wind tunnel flow field measurement, we used the term of wind shadow length for the results of the CFD simulations and flow data from the wind tunnel. We measured the wind shadow length without saltation after the equilibrium state was reached. When the flow field data in the CFD and wind tunnel simulations were analyzed, we mapped the boundary of the region downwind of the simulated nebkha at which wind speed increased above the estimated threshold wind speed (4 m/s), where we expect that the sand transported around the nebkha would no longer be stably deposited into the shadow dune.

### 2.4. Field Measurement of Dune Morphology and Sedimentary Structure

To analyze the relationship between the nebkha width and shadow dune length, both of these two parameters were measured on the Google Earth images with 0.23-m resolution on 12 November 2014 shown in Figure 1a. In view of the asymmetry of the nebkhas, we measured the nebkha width perpendicular to the prevailing wind direction. To compare the measurements to the modeled estimates and avoid the effects of nebkha spatial arrangement on the length of shadow dunes, only single nebkhas and their corresponding shadow dunes were measured. A total of 185 nebkhas and the corresponding shadow dunes were measured (Figure 6). All the measurements were carried out under the same coordinate system and reference.

The length of shadow dunes in this study does not consider the effects of the growth of the shadow dunes on the flow dynamics. We speculated that horizontal separation flow might not be the driving force for the extension of these shadow dunes at Taitema Dry Lake. To determine the elongation processes of shadow dunes, the internal sedimentary structure of one shadow dune in Taitema Dry Lake was measured using GPR (Figures 7). The selected dune is a relatively long shadow dune with a large nebkha, which may have formed over a longer period of time than the other dunes, and contains distinct and complete sedimentary structures as revealed by the GPR surveys.

To get topography-corrected sedimentary structures, the topography of this shadow dune was measured in January 2019 using the Global Positioning System (GPS) real-time kinematic technology, which is a new GPS measurement method with high spatial resolution (the spatial resolution can reach centimeter level). Seventeen transects normal to the dune crest were measured. During the measurements, each transect was measured twice, first from NW to SE and then from SE to NW. Each transect consists of hundreds of data points. All of the transect points were processed into a profile by calculating the distance between adjacent points. Furthermore, following the same transects from the GPS measurement, 17 GPR profiles were collected across the dune using a pulse EKKO PRO with 500-MHz antennas, a step size of 0.02 m, and antenna separation 0.1 m (short lines in the white background of Figure 7a). Each of the GPR profile images have been adjusted using the corresponding topographic data.

To study the spatial and temporal dynamics of the selected shadow dunes, four satellite images from Google Earth at 15 August 2005 (with 0.23-m resolution), 19 March 2009 (with 0.23-m resolution), 30 December 2012 (with 0.23-m resolution), and 10 October 2013 (with 0.23-m resolution) were collected. Before we extracted the outline of the dunes at different times, the satellite image in 2013 was used as the basis to
conduct the image registration. Thirty control points (fixed nebkhas) were selected to coreference the images in 2005, 2009, and 2012 for image registration implementation with the relative error less than 1 pixel. When the relative errors are greater than 1 pixel, we deleted the control points. Actually, in image registration process, the error of artificial interpretation is always less than 1 pixel (see the geometric correction process and RMS error analysis in the supporting information). The results of image registration were shown in Figure 7b.

3. Results
3.1. CFD Simulation Results
3.1.1. Effects of Incident Wind Shear Velocity on the Length of Wind Shadow
Figure 8 shows the streamline wind velocity over the nebkha with $D = 1.5$ m and $H = 0.5$ m for three wind shear velocities ($u_* = 0.3$ m/s, $u_* = 0.5$ m/s, and $u_* = 1.0$ m/s) on a plan view 0.10 m above the surface (Figures 8a, 8c, and 8e) and on a vertical transect through the central axis of the computational domain.
Figure 8. Distribution of streamwise wind velocity at 0.10 m above the surface (a, c, and e) and along the axis line of nebkhas from the upwind to downwind directions (b, d, and f) under three incident shear velocities ($u^* = 0.3, 0.5$ and 1.0 m/s). The diameter and height of the nebkhas are 1.50 and 0.50 m, respectively. The black solid lines are the 4 m/s contour lines. The white solid lines in (a), (c), and (e) are the 0 m/s contour lines used to quantity the length of the reattachment. The blue dashed lines in (b), (d), and (f) mark the position of the reattachment point, and the black dashed lines show a height of $H = 0.10$ m. The airflow is from left to right.

(Figures 8b, 8d, and 8f). This figure demonstrates that the length of the wind shadow decreases as the shear velocity increases. However, the rate of decrease of the wind shadow length ($L_l - L_h$/$L_l$, where $L_l$ is the length of the wind shadow at low velocities and $L_h$ is the length of wind shadow at high velocities) becomes increasingly small as the shear velocity increases. For example, the rate of decrease from 0.3 to 0.5 m/s is 0.59 but is only 0.24 from 0.5 to 1.0 m/s. The relationships between the wind velocity and the length of the wind shadow are considered in detail in section 3.2.4. It is apparent that lower wind shear velocities contribute more to the elongation of wind shadow. Figures 8a, 8c, and 8e show that the length of the reattachment (represented by the length of the zero contour line) has reached a steady state and is independent of the wind velocity. It can therefore be inferred that the location of flow recovery moves forward as the wind velocity increases.

3.1.2. Effects of Nebkha Diameter on the Wind Shadow

Figure 9 shows the streamline wind velocity over nebkhas with different diameters ($D = 0.50, 0.90,$ and 1.50 m) but a fixed height ($H = 0.50$ m), 0.10 m above the surface (Figures 9a, 9c, and 9e) and on a vertical transect through the central axis of the computational domain (Figures 9b, 9d, and 9f) for $u^* = 0.40$ m/s. The length of the wind shadow appears to be a linear function of the diameter of the nebkha, a wider nebkha leading to longer wind shadow. This is consistent with previous observations (Bagnold, 1941; Hesp, 1981; Hesp & Smyth, 2017). Figure 9 also shows that large diameter nebkhas contribute to the downward movement of the locations of reattachment and recovery.

3.1.3. Effects of Nebkha Height on the Wind Shadow

Figure 10 shows the streamline wind velocity over nebkhas with different heights ($H = 0.45, 0.70,$ and 1.00 m) but a fixed diameter ($D = 1.00$ m) at 0.10 m above the surface (Figures 10a, 10c, and 10e) and on a vertical transect through the central axis of the computational domain (Figures 10b, 10d, and 10f) for $u^* = 0.40$ m/s. The data represented in this figure suggest that the length of the wind shadow increases slightly with the height of the nebkhas. For example, when $u^* = 0.40$ m/s, the lengths of the wind shadows are 2.21 m ($H = 0.45$ m), 2.57 m ($H = 0.70$ m), and 2.90 m ($H = 1.00$ m), indicating that the length of the wind shadow is more dependent on the width of nebkhas than the height of nebkhas. Figure 10 shows that the lengths of the reattachment and the wind shadow increase with the height of the nebkhas.
3.1.4. Effects of Nebkha Aspect Ratio on Wind Shadow

Figure 11 shows that when nebkhas have the same aspect ratio, but different heights and widths, the lengths of the wind shadow are also different. The tips of the wind shadow and the reattachment zones move downwind as the nebkha height and width increase. For example, the lengths of the wind shadow are 1.71, 2.38, and 2.78 m for the same aspect ratio 1/3 (Table 3). The length of reattachment also shows an increasing trend from 0.8 m ($H_1 = 0.30$ m, $D_1 = 0.90$ m), 1.11 m ($H_2 = 0.40$ m, $D_2 = 1.20$ m), to 1.34 m ($H_3 = 0.50$ m, $D_3 = 1.50$ m) for forms with the same aspect ratio (Table 3). Therefore, although nebkhas have the same aspect ratio, the secondary airflow parameters, such as the length of reattachment and the length of flow recovery, over these nebkhas are different due to the differences among the absolute values of the nebkha widths and heights. The characteristics of the wind shadow and secondary airflow are more dependent on the absolute width and height of the nebkhas than the aspect ratio. Therefore, we might be unable to draw accurate conclusions based on the nebkha aspect ratio or the nebkha slope.

Although the CFD results show the effects of wind shear velocity and obstacle geometry (nebkha width, height, and aspect ratio) on the wind shadow formation, additional data from wind tunnel or field observations are required to further validate these results.

3.2. Wind Tunnel Experimental Results

3.2.1. Flow Dynamics and Sand Deposition Over Nebkhas Under Different Wind Velocities

Figure 12 shows the flow dynamics (Figures 12a, 12c, and 12e) and sand deposition patterns (Figures 12b, 12d, and 12f) on the leeside of nebkhas ($H = 0.50$ m) but different diameters ($D = 0.50$, 0.90, and 1.50 m). The incident shear velocity is 0.40 m/s. The black solid lines are the 4 m/s contour lines. The white solid lines in (a), (c), and (e) are the 0 m/s contour lines. The black dashed lines show a height of $H = 0.10$ m. The airflow is from left to right.

Figure 9. Streamwise wind velocity at 0.10 m above the surface (a, c, and e) and along the axis line of the nebkhas from the upwind to downwind direction (b, d, and f) for nebkhas with the same height ($H = 0.50$ m) but different diameters ($D = 0.50$, 0.90, and 1.50 m). The incident shear velocity is 0.40 m/s. The black solid lines are the 4 m/s contour lines. The white solid lines in (a), (c), and (e) are the 0 m/s contour lines. The black dashed lines show a height of $H = 0.10$ m. The airflow is from left to right.
3.2.2. Flow Dynamics and Deposition of Sand Over Nebkhas With Different Diameters

Figure 13 shows the flow dynamics and sand deposition around the nebkhas with a fixed height (H = 10 cm) but different diameters (D = 15, 20, and 25 cm) at a wind velocity of 10 m/s in the wind tunnel. Figures 13a, 13c, and 13e show that the length of the wind shadow increases linearly with the width of the nebkha, which indicates that a wider nebkha can result in a larger area enclosed by the 4 m/s contour line and longer wind shadow. We therefore conclude from both the CFD and wind tunnel simulations that the length of wind shadow increases linearly with the width of nebkhas. To verify this conclusion, we measured the thickness of sand deposition on the leeside of nebkhas in the wind tunnel (shown as the normalized depth $H/H_a$ in Figures 13b, 13d, and 13f). The lengths of the shadow dunes on the leeside of nebkhas with different diameters (D = 15, 20, and 25 cm) are 65, 80, and 86 cm, respectively, suggesting that the length of the sand tail increases with the diameter of the nebkhas. These results are also confirmed by CFD simulations (Figure 9) and previous observations (Hesp & Smyth, 2017).

3.2.3. Flow Dynamics and Sand Deposition Over Nebkhas With Different Heights

Figure 14 shows the flow dynamics and sand deposition around nebkhas of the same diameter (D = 20 cm) and different heights (H = 8, 10, and 12 cm) at an incident velocity of 10 m/s. Figures 14a, 14c, and 14e show that the length of the wind shadow increases linearly with the height of the nebkha, which indicates that a higher nebkha can result in a larger area enclosed by the 4 m/s contour line and longer wind shadow. We therefore conclude from both the CFD and wind tunnel simulations that the length of wind shadow increases linearly with the height of nebkhas. To verify this conclusion, we measured the thickness of sand deposition on the leeside of nebkhas in the wind tunnel (showed as the normalized depth $H/H_a$ in Figures 13b, 13d, and 13f). The lengths of the shadow dunes on the leeside of nebkhas with different heights (D = 15, 20, and 25 cm) are 65, 80, and 86 cm, respectively, suggesting that the length of the sand tail increases with the height of the nebkhas. These results are also confirmed by CFD simulations (Figure 9) and previous observations (Hesp & Smyth, 2017).
transport of sand at 0.1 m above the surface is inappropriate when the height of the nebkha changes. Figures 14b, 14d, and 14f show that the height of the nebkha has a negative effect on the elongation of shadow dunes, which may result from the distribution of wind-blown sand in the vertical profile.

Usually, there is a horizontal symmetrical reverse vortex at the leeside of a bluff-body obstacle (Figures 15a and 15b; Hesp, 1981; Gunatilaka & Mwango, 1989; Tavakol et al., 2010; Rashidi et al., 2016). Wind flow in this area travels toward the leeward slope of the obstacle. When the flow velocity is higher than the threshold sand transporting velocity, most of the sediments in this area will be transported toward the leeward slope of obstacles (Araújo et al., 2013). We call this region the reverse flow region (red box in Figures 15a and 15b). Figures 15c and 15d present the streamwise flows and the corresponding sand deposition patterns under different incident wind velocities ($U = 8$, 10, and 12 m/s) along the centerline of the wind shadow. It shows that an area of strong erosion was clearly visible in the reverse flow region (the erosion area was marked by green, orange, and blue dashed horizontal color bars in Figure 15d). The depth of erosion depends on the incident wind velocity. Based on the depositional patterns around the models in the wind tunnel, sand particles at zones of horizontal separation flows were transported into the wake region at the beginning of the development of the shadow dunes. Some of these particles were deposited at the margins of the wake region, whereas others were deposited downwind at the point where the horizontal separation flows merged (section A in Figure 15a). If the sand was supplied continuously, the sand accumulating at the two margins of shadow dunes would avalanche into the reverse flow region. This process continues until a sand ridges form.

### 3.2.4. Relationships Between Wind Velocity, the Geometric Parameters of Nebkhas, and the Lengths of Wind Shadows

Figure 16 shows the relationships between the length of the wind shadow, wind velocity, and the width and height of nebkhas. The length of the shadow dunes decreases in the form of a power function of the wind shear velocity independent of the width and height of the nebkhas. This decrease is sharp when the $u_\ast / u_{\ast r} < 1.5$ ($u_\ast = 0.4$ m/s when $u_\ast / u_{\ast r} = 1.5$ in Figures 16a and 16b) and only slight when $1.5 < u_\ast / u_{\ast r} < \frac{u_{\ast}}{u_\ast}$.

### Table 3

| Model No. | Diameter (m) | Height (m) | Aspect ratio | Reattachment length (m) | Wind shadow length (m) |
|-----------|--------------|------------|--------------|-------------------------|-----------------------|
| 1         | 0.90         | 0.30       | 1:3          | 0.80                    | 1.71                  |
| 2         | 1.20         | 0.40       | 1:3          | 1.11                    | 2.38                  |
| 3         | 1.50         | 0.50       | 1:3          | 1.34                    | 2.78                  |

**Figure 12.** (a, c, and e) Streamwise wind velocity at 1 cm above the wind tunnel surface when the incident airflows (8, 10, and 12 m/s) was devoid of particles. The black lines show the 4 m/s contour lines. (b, d, and f) Patterns of deposition surrounding a nebkha of 10-cm height and 20-cm diameter under three incident airflows (8, 10, and 12 m/s) fed with saltating particles. The sand tail thickness in (b), (d), and (f) were normalized using the average thickness ($H_{\text{avg}}$) of the shadow dunes. The white dashed lines show the length of the shadow dunes accumulated on the leeside of the nebkhas. The airflow is from left to right.
2.22 ($u^* = 0.6 \text{ m/s}$ when $u^* / u_{*} = 2.22$); there is almost no variation when $u^* / u_{*} > 2.22$. Figure 16c shows that the length of the wind shadow always has a positive linear relationship with the diameter of nebkhas independent of the wind velocity. To some extent, the relationships of wind shadow length with incident wind velocity and nebkha width can be verified with the wind tunnel results. However, it is interesting that the nebkha height plays a negative role on the shadow dune formation in wind tunnel experiment.

Figure 13. (a, c, and e) Streamwise wind velocity at 1 cm above the surface when the incident airflow (10 m/s) was devoid of particles. (b, d, and f) Patterns of deposition surrounding the nebkhas of the same height ($H = 10$ cm) but different diameters ($D = 15, 20, \text{ and } 25$ cm) when the incident flow (10 m/s) was fed by saltating particles. $Ha$ is the average height of the shadow dune. The black dashed lines show the length of the shadow dunes, which is defined using the 4 m/s contour. The white dashed lines show the length of the shadow dunes accumulated on the leeside of the nebkhas. The airflow is from left to right.

Figure 14. (a, c, and e) Streamwise wind velocity at 1 cm above the surface when the incident airflow (10 m/s) was devoid of particles. (b, d, and f) Patterns of deposition surrounding nebkhas of the same diameter ($D = 20$ cm) but different heights ($H = 8, 10, \text{ and } 12$ cm) when the incident airflow (10 m/s) was fed with saltating particles. $Ha$ is the average height of the shadow dune. The black dashed lines show the contour lines of 4 m/s. The airflow is from left to right.
**Figure 15.** Streamline distribution, sand deposition pattern, and flow dynamics along the centerline of the wind tunnel. (a) Plan view of streamline distribution around the nebkha model. (b) Lateral view of streamline distribution over the nebkha. The red box marks the area of reverse flow. Section A marks the merging point of two symmetrical horizontal reverse vortexes. (c) Flow dynamics along the centerline of the wind tunnel at 1 cm above the wind tunnel floor for different incident wind velocities (8, 10, and 12 m/s). The black dashed line marks a wind speed of 4 m/s. The dashed vertical lines mark the locations of the ends of the shadow dunes. (d) The dimensionless deposition height of shadow dunes along the centerline of wind tunnel for different incident wind velocities. The green, orange, and blue thick lines mark the area that was eroded by the reverse flow. The dimensionless deposition height ($H/H_a$) is the ratio of measured deposition height $H$ to the mean height $H_a$ of the shadow dunes. Here, the nebkha model is 8 cm in height and 20 cm in diameter. The wind blows from left to right.
This result is definitely different from the CFD simulations. This difference might be caused by length scale effects between the height of the nebkhas and the height of the saltation cloud in the wind tunnel. It is also recognized that saltation length scales are different between wind tunnels and those in the natural boundary layer (Li & McKenna Neuman, 2012; Martin & Kok, 2017; Sherman & Farrell, 2008), which could further impact this observed relationship. For a given wind velocity and sand grain size, the saltation height is almost invariable (Ho et al., 2014; Martin & Kok, 2017). When the obstacles are higher than the average saltation height, most of the sand particles would be stagnated in the obstacles or transported away at the margins of the obstacles. This process might result in the starvation of sand particles leaping over the obstacle height for shadow dune formation.

Almost all of the CFD simulation results have been verified by the wind tunnel experiments except for the effects of nebka height on shadow dune formation. However, all the results from CFD and wind tunnel were based on the strict assumptions (Smyth, 2016; White, 1996). We could not completely understand the elongation mechanism of the shadow dunes. Therefore, the field observations, such as the internal sedimentary structure of shadow dunes, are helpful revealing the growth mechanisms.
3.3. Sedimentary Structure of the Shadow Dunes

Shadow dunes in Taitema Dry Lake, in the eastern Taklimakan Desert, vary in length from a few meters to hundreds of meters. In view of short formation age and the lack of apparent sedimentary structure of the short shadow dunes, the target shadow dune for measuring must be quite long to insure an adequate evolution period. The shadow dune selected is 600 m in length and 7.5 m in height (at the proximal end), with a sharp and extremely straight dune ridge (Figure 17a) under a high elongation rate (i.e., 14 m/year from 2005 to 2018 in Figure 17b). Three transects normal to the dune ridge were measured with GPR at the beginning, middle, and tip of the shadow dune (Figure 7a). Figure 17 shows that the sedimentary structures from TR1 to TR3 could be divided into two types. The first type is TR1 (Figure 17a), in which northwestward and southeastward dipping sets of cross-stratification were formed during vertical accretion by the horizontal separation flow. The cross-stratification is similar to the triangular-shaped cross-strata described in Gunatilaka and Mwango (1989). The cross-strata pattern suggests unequal wind strengths lead to a continuous avalanche from the slope of the left shadow dune, which results in the dominant dip orientation of the southeastward dipping cross-strata (Figure 17a). Furthermore, the morphological asymmetry of the nebkha may be another reason for this unevenness of the wind flow. As the shadow dune elongates, the sedimentary structure of the cross-stratification is increasingly similar to that of linear dunes (Bristow et al., 2000, 2007). Bristow et al. (2000) presented that the extension of the linear dunes can result in vertically stacked sets of cross-stratification dipping to the stoss and lee slope, separated by an erosion bounding surface. In our study, bimodal dips were also found in TR2 and TR3 profiles (Figures 17e and 17f). These bimodal dips were formed during the extension of the shadow dune and led to vertically stacked sets of cross-strata to the southeast and northwest directions (normal to the resultant transport direction), separated by the bounding surface. Reflections dipping toward NW and SE formed during wind reversals at the dune crest. Generally, the vertically stacked sets of cross-strata are the typical sedimentary structure of linear dunes. Therefore, the elongation of shadow dunes can be similar to how linear dunes (Bristow et al., 2000; Bristow et al., 2007; Lucas et al., 2015; Zhou et al., 2012).

4. Discussion

4.1. Dependence of Wind Shadow on the Wind Velocity and Nebkha Diameter

Both the numerical simulations (Figure 9) and the wind tunnel experiments (Figure 13) show that the length of the wind shadow increases with the diameter of the nebkha. These results are consistent with previous observations (Gillies et al., 2014; Hesp, 1981; Hesp & Smyth, 2017; Leenders et al., 2011; Mayaud et al., 2017). Although the obstacles in Hesp (1981) were clusters of grass and the shadow dunes were pyramidal in shape, the length of the shadow dunes also increased with the width of the plants, suggesting that wider obstacles produce longer shadow dunes, irrespective of the type of obstacle. The measurements from Google Earth images plotted in Figure 6 verify the relationship between the width of the nebkhas and the length of the shadow dunes. However, the length of the shadow dunes may not always increase linearly with the width of an obstacle due to wind speed effects. It has been reported previously that the width of obstacles has a greater effect on the length of shadow dunes than the wind velocity (Hesp, 1981). However, Hesp and Smyth (2017) reported that the length of wind shadows increased continuously with the width of nebkhas at low incident wind velocities, but only increased slightly at high velocities. They reported a critical wind shear velocity of the order of 0.4 m/s. They found that shadow dune length increases as nebkha width increases when the wind shear velocity is lower than 0.4 m/s and is barely affected when the wind shear velocity is higher than 0.4 m/s. The results of both our numerical simulations and wind tunnel experiments showed the same pattern. Figures 16a and 16b show that the length of the wind shadow decreases as a power function with wind velocity irrespective of the width and height of the nebkhas. However, the rate of decrease is large when the incident wind shear velocity is <0.4 m/s, slight when the wind shear velocity is between 0.4 and 0.6 m/s, and near-zero when the wind shear velocity is >0.6 m/s ($u^*/u_* = 0.22$ in Figure 16a). However, these previous studies did not report the relationship between wind shear velocity and wind shadow length.

4.2. Effects of the Height of Nebkhas on the Formation of Shadow Dunes

Obstacle height plays a key role on the secondary airflow (e.g., flow separation, the reattachment length, and recovery distance) and wind shadow length. From the pattern of flow fields both in the CFD simulations and
wind tunnel experiments (when the length of the shadow dune was defined by a threshold wind velocity of 4 m/s), it can be inferred that higher nebkhas formed longer wind shadows. However, shorter shadow dunes were formed in the wind tunnel experiments (Figures 14b, 14d, and 14f). Our results suggest that the locations of flow reattachment and recovery moved downwind as the height of the nebkhas increased (Figures 10 and 14), which should contribute to the elongation of shadow dunes. However, by comparing the sand deposition patterns on the leeside of the nebkhas for different nebkha heights in the wind tunnel experiments, we found that the length of shadow dunes decreased with the height of nebkhas (Figures 14b, 14d, and 14f), indicating that the height of the nebkha has a negative effect on the formation of shadow dunes. Due to different flexibility of the obstacles and different transport processes around porous and nonporous obstacles, our present result is not consistent with the study reported by Hesp (1981), who found no clear relationship between the length of shadow dunes and plant height. We were also unable to derive a relationship between plant height and the length of the shadow dunes. In addition, the flow separation processes and the associated sand transport were modified when the airflow passed through the plant, which also modified the sand transport processes (Gunatilaka & Mwango, 1989). The form of this bleed flow modified by the porosity of the obstacles can alter the location and pattern of the separation bubble (Bauer et al., 2013; Castro, 1971; Dong et al., 2008; Mayaud et al., 2016; Mayaud et al., 2017) and influence the morphology of the shadow dunes (Gunatilaka & Mwango, 1989).

For porous obstacles, the flow dynamics around the obstacles is controlled by the plant morphology, density, and porosity (Castro, 1971; Dong et al., 2008). Sand flow around the porous obstacles could penetrate though the plant gap. While for the nonporous obstacles, there was no bleed flow, and consequently, the horizontal and vertical separation flow around obstacles were the major forces for sand transport. Generally, nebkha is a semiporous obstacle, there are two kinds of flow dynamics around them. First, flow dynamics around the plant is similar to the porous obstacles. Although plant on nebkha could contribute to the wind shadow area, they were too high to trap the saltation particles and to supply sediments for the development of shadow dunes. Second, flow dynamics around the dune mass are similar to flow dynamics around the nonporous.
For nebkhas in Taitema Dry Lake, plants on them have been massively degraded, most of the shadow dunes formed on the leeside of these degraded nebkhas. Therefore, nebkhas in Taitema Dry Lake can be seen as the nonporous obstacles. Their heights are relatively fixed comparing with the obstacle in Hesp (1981).

The vertical structure of the sand flux in the wind tunnel shows that most of the saltating particles (95%) were distributed within 3 cm of the wind tunnel surface (Figure 18). Even under field conditions (above the sandy surface), most of the saltating particles (90%) are distributed within 20 cm of the surface (Ding, 2010). When the wind containing drifting sand encounters a plant, some of the sediment will be transported downwind by the accelerated flow at the margins of the plant. Some sediment will be trapped by the plant, thus contributing to the formation of shadow dunes as a result of the bleed flow. Sand moving over the nebha surface is transported downwind by the horizontal separation of flow and deposited in the separation bubble due to symmetrical contra-rotating vortices (Gunatilaka & Mwango, 1987; Gunatilaka & Mwango, 1989; Hesp, 1981), contributing to the formation shadow dunes as well.

4.3. Relationships Between Nebkha Aspect Ratio and the Formation of Wind Shadows

It should be noted that topographic parameters like the obstacle aspect ratio, slope presented some uncertainties in assessment of the effects of obstacle topography on sand deposition processes. The aspect ratio is often used to evaluate the effects of the height and width of obstacles on flow dynamics and sediment deposition (Hesp & Smyth, 2017; Iversen et al., 1990; Luo et al., 2012; Parsons et al., 2004; Wang, 2016). For example, Iversen et al. (1990) found that the amount of erosion on the leeside of a cylinder increased as $H/D$ decreased, where $H$ is the height of a cylinder and $D$ is the diameter. The inverse trend was observed for erosion on the windward side of the cylinder. Our results suggest that the erosion capacity around a cylinder with the same aspect ratio ($H/D$) varies as the height and diameter of the cylinder change. A fixed value of $H/D$ has many different combinations of $H$ and $D$, but Iversen et al. (1990) only illustrated the erosion capacity at particular heights and diameters of the cylinder. Furthermore, it is well known that the separation zone length at leeside of a dune plays a key role for the sand deposition and dune space (Walker & Nickling, 2002). Parsons et al. (2004) showed that the separation zone length increases with aspect ratio of transverse dune. However, as presented in this study, the aspect ratio of transverse dune also presents some uncertainty. Even if the aspect ratio is fixed, the separation zone length varies with dune height and stoss length. Wang (2016) studied the deposition of snow over complex terrain and found that the deposition of snow behind obstacles was significantly different when the aspect ratio was $>0.4$. When the aspect ratio was 0.4, $H$ and $D$ varied in a large parameter space (e.g., $H/D = 0.1/0.25$, $1/2.5$, and $10/25$), leading to notable differences of the depositional process. Consequently, in view of the uncertainties, topographic parameters (e.g., aspect ratio and topographic slope) should be carefully used to study the shadow dune formation.

4.4. Elongation of Shadow Dunes

Based on the sedimentary structures of the shadow dune in our study, three stages for the shadow dune formation were identified. The initial stage of shadow dunes is mainly controlled by horizontal separation flow (e.g., Figure 1b; the general morphology of shadow dune in this stage). The incident wind velocity and geometry of obstacles play a key role in their development (Hesp, 1981; Hesp & Smyth, 2017). Generally, the morphology of shadow dunes, which develop on the leeside of a single nebha is stable through time due to the limited effective sheltering area of the nebha and the dynamic equilibrium between sand deposition and flow dynamics.

However, the length of shadow dunes is not always fixed. For example, the flow field resulting from the mutual interference of two adjacent nebkhas causes the shadow dunes on the leeside of these nebkhas to grow longer than for a single nebha. This is a common phenomenon in the Taitema Dry Lake, in the

![Figure 18. Vertical structure of the sand flux near the bed (note that the y axis is in log scale). The blue dashed line represents the vertical structure in an empty wind tunnel at velocity of 8 m/s. The red dashed line represents the vertical structure over a sandy surface with mean grain diameter 250 μm, and wind velocity 8.7 m/s at 2 m above the surface (Ding, 2010). The percentage of sand flux refers to the percentage of the total vertically integrated flux that is accounted for at a particular height.](image-url)
eastern Taklimakan Desert, China. For example, the bead-like shadow dunes or the shadow dunes developed on the leeside of side-by-side neighboring nebkhas at our field site elongate continuously (Figures 1c–1e). Their elongation rate likely depends on nebkha morphology, wind direction, and sand availability. We therefore recognize the elongation stage of the shadow dunes as the second stage. We supposed that there were two major forces contributing to the elongation of shadow dunes under unimodal wind regime and sand starvation condition: first, the merging of two neighboring shadow dunes in streamwise (i.e., the final form is bead-like shadow dune) or spanwise enlarged the sand dune body—this progress provides the topographical condition for the elongation of shadow dunes—and, second, the secondary airflow-deflected flow around the dune ridge. This deflected flow around the dune ridge might be the driving force for the transportation of sand and the elongation of shadow dunes (Bristow et al., 2000; Gunatilaka & Mwango, 1989).

The GPR profiles show that sedimentary structures of shadow dunes are similar to linear dunes. It should be noted that linear dunes usually form under bimodal wind regimes (Courrech du Pont et al., 2014; Pye & Tsoar, 2009); however, shadow dunes in Taitema Dry Lake formed under unimodal wind regime (Figure 1a). The cross-strata at the crestline might be resulted from the repeated changes in the prevailing wind direction (north-east, north-north-east, and east-north-east) at our study site (Figures 17e and 17f). However, these types of shadow dunes do not elongate indefinitely and eventually break up into barchans or isolated linear dunes (Gao et al., 2015; Lucas et al., 2015). This segmentation process is recognized as the third stage for development of shadow dunes (morphology of the shadow dune in Figure 1e). The specific time of segmentation depends on the wind regime, the availability of sand, and the distance from the tip of the shadow dune to the nebkha.

As confirmed by field observations, the shadow dune length increases linearly with the size of the obstacles (nebkhas), suggesting that sediment availability behind the vegetated mounds in the downwind direction plays a fundamental role for dune elongation. The shadow dunes can reach a steady state when the local supply-limited and transport-limited conditions are in a dynamic equilibrium state. The grain size that is assumed for the sake of estimating the sand shadow depositional patterns has an important effect on the threshold wind velocity choice. We suggest that shadow dunes occur, elongate, and segment where certain wind regimes and sediment availability conditions are met. Although the effects of spanwise flow on the shadow dune formation are not discussed in our study, they are crucial for the development of flow dynamics, especially for wind shadow patterns on the leeside of adjacent obstacles. Zu and Lam (2018) reported that due to the effects of across-wind forces (e.g., the spanwise wind flow), the flow interference between two neighboring buildings create different patterns. In the four types of interference regions (i.e., wake interference region i, wake interference region ii, proximity interference region, and weak-interference region), the fluctuating across-wind force on the downstream building is significantly magnified, slightly magnified, largely reduced, and nearly unchanged, respectively (Zu & Lam, 2018). Furthermore, in water and aeolian systems, the spanwise flow plays a vital role in sand deposition (Burkow & Griebel, 2016; Furieri et al., 2014; Meire et al., 2014; Sutton & McKenna-Neuman, 2008a; Sutton & McKenna-Neuman, 2008b). Meire et al. (2014) found that there was a secondary sedimentary region at the leeside of two neighboring vegetation patches, which was caused by the merging of adjacent horseshoe vortices. This secondary region plays a key role for the merging of the neighboring sand tails. This interesting phenomenon had been also found by Sutton and McKenna-Neuman (2008b) in a wind tunnel experiment. Based on these observations, it is assumed that the shadow dunes in Figure 7 were influenced by the interference of spanwise flow during their initial development. Because of the interference of the spanwise flow, the separated shadow dunes on the leeside of these nebkhas potentially merge, becoming one dune. A bigger obstacle under unimodal wind regime contributes to a better elongation of shadow dunes by the deflected flow around the dune ridges.

5. Conclusions

Numerical simulations and wind tunnel experiments were used to analyze the flow patterns over artificial nebkha models scaled according to field measurement of nebkha geometry in Taitema Dry Lake, in the eastern Taklimakan Desert, China. The relationships between the length of shadow dunes...
and wind velocity, the geometric parameters of the nebkhas (e.g., the width, height, and aspect ratio) were investigated. This study highlighted the complexity and uncertainty of the geometric parameters on the shadow dune formation. The GPR successfully imaged the internal sedimentary structures of shadow dunes. It is suggested that we might be able to roughly predict local shadow dune length in terms of the suitable wind regime, sediment supply, and topographic obstacles. Moreover, the results of our study suggest that the reverse flow region is most likely to result in strong wind erosion (Figure 15d). The main conclusions are as follows.

1. The size of the shadow dune always increases as the width of the obstacle increase, irrespective of the types of the obstacles (plants and nebkhas). However, the increasing rate of the shadow dune length with respect the incident wind shear velocity would decrease when the wind shear velocity is >0.4 m/s.

2. Due to a wind tunnel scaling issue, our wind tunnel experiments showed that the height of the nebkhas has a negative effect on the formation of shadow dunes, which is not observed in field conditions. Available field observations do not seem to support that somewhere there are nebkhas that show an inverse relationship between height and shadow length.

3. The length of shadow dunes decreases with the increasing wind shear velocity as a power function, irrespective of changes in the morphology of the obstacle. The decrease in length is roughly large when the wind shear velocity is <0.4 m/s; however, the length of shadow dunes decreases less with the wind shear velocity when it is >0.6 m/s.

4. Parameters such as the aspect ratio and topographic slope weaken the effects of the topographic height on the flow dynamics. When we quantify the erosion and deposition dynamics around an obstacle with a fixed aspect ratio, we should consider the absolute height of the obstacle, and the ratio of the height between the obstacle and saltating cloud.

5. The development of shadow dunes can be divided into three phases. Their formation experiences at least one of the three phases. They are initially controlled by the horizontal separation flow, then elongate with the similar growth mechanisms of linear dunes, and eventually break up into isolated barchans or short linear-like dunes.

This study is useful to understand the development processes of shadow dunes on the leeside of nebkhas in dry land environments. Our study has shown that linear dunes may develop under a unimodal wind regime with suitable conditions (e.g., suitable obstacle morphology and sediment supply). However, we cannot meet all of the similitude parameters simultaneously for the scaled nebkha models. Therefore, some limitations of the wind tunnel experiment and CFD simulation should be noted. In wind tunnel experiments, the limited space might generate conditions with the airflow and saltation dynamics that differ sufficiently from full-scale conditions, suggesting that sand deposition patterns around the obstacles in our study are not representative of full-scale conditions. Results of airflow around the nebkhas ignored the effects of saltation particles in wind tunnel simulations. However, it may be possible to examine the characteristics of the airflow fields under the sand-laden flow conditions saturated with saltating sand particles using laser-Doppler anemometry and particle imaging velocimetry instruments, although both techniques have to discriminate between the seed and sedimentary particles (Taniere et al., 1997; Zhang et al., 2008 and Li and McKenna Neuman, 2012). In CFD simulation, the lack of morphodynamic feedbacks between sand deposition and wind flow patterns, the lack of the plant on nebkha models, and the relatively smooth surface of the nebkha models would marginally affect the modeling results and subsequent interpretations. Therefore, accurately simulation of the dynamic interactions between the flow, sand deposition, and topographic changes should be studied fundamentally in the future. Furthermore, the mutual feedback mechanism of flow fields and the associated sediment flux surrounding the topographic obstacles has not been analyzed in this study. We have only studied the flow dynamics and sand deposition patterns on the leeside of single nebkhas and have ignored the condition of nebkhas organized into dune fields where flows and sediment transport processes interact. The flow dynamics on the leeside of two or more nebkhas are extremely complex than the case of a single nebkha due to the interference between neighboring nebkhas. In addition, the similarity of the sedimentary structures between shadow dunes and linear dunes implies that linear dunes could also form under unimodal wind regime due to the effects of topographic obstacles, suitable unimodal wind condition, and sand availability. However, the elongation mechanisms of linear dunes under unimodal wind regime require further investigation.
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