Morphological variation of star dune and implications for dune management: a case study at the Crescent Moon Spring scenic spot of Dunhuang, China (Postprint)

Authors: ZHANG Weimin, TAN Lihai

Date: 2019-06-20T00:00:00+00:00

Abstract

Aerial photographs and 3-D laser scans of a 90-m high star dune at the Crescent Moon Spring scenic spot in Dunhuang, China, were used to investigate changes in dune morphology on timescales from months to decades. Results revealed that relative-equilibrium airflow strength in three wind directions—northeast, west, and south—was an important condition for the stability of star dunes with limited migration. Transverse and longitudinal airflows exerted a crucial impact on variation processes of star dune morphology. Controlled by transverse airflows, the easterly winds, the east side was dominated by wind erosion; and strong deposition occurred on the south-south-east arm with a maximum deposition rate of 0.44 m/a in the 46-a monitoring period, causing the east side to become steep and high. Controlled by longitudinal airflows, the westerly winds, the west-north-west side was mainly eroded and the north arm migrated from west to east with a rate of 0.30 m/a, causing the dune slope to become gentle and elongate. The local air circulation (southerly winds) exerted a significant impact on the development process of the star dune. Due to the influence of human activities, the south side presented surface processes from a concave profile to a convex profile in 46 a, which is a potential threat to the Crescent Moon Spring. The results indicate that rehabilitating the airflow field at most is a crucial strategy to the protection of Crescent Moon Spring from burial. Opening up the passage of easterly, westerly and southerly winds through intermediately cutting the protection forest, demolishing the enclosed wall and changing the pavilion into a porous pattern have been suggested to protect the Crescent Moon Spring from burial.

Full Text

Preamble

Morphological variation of star dune and implications for dune management: a case study at the Crescent Moon Spring scenic spot of Dunhuang, China

ZHANG Weimin*, TAN Lihai, AN Zhishan, ZHANG Kecun, GAO Yang, NIU Qinghe

Dunhuang Gobi Desert Research Station, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China

Abstract: Aerial photographs and 3-D laser scans of a 90-m high star dune at the Crescent Moon Spring scenic spot in Dunhuang, China, are used to investigate changes in dune morphology on timescales from months to decades. The results reveal that relative-equilibrium airflow strength from three wind directions—northeast, west, and south—constitutes an important condition for the stability of star dunes with limited migration. Transverse and longitudinal airflows exert a crucial impact on variation processes of star dune morphology. Controlled by transverse airflows (the easterly winds), the east side experienced wind erosion while strong deposition occurred on the south-southeast arm with a maximum deposition rate of 0.44 m/a during the 46-year monitoring period, causing the east side to become steep and high. Controlled by longitudinal airflows (the westerly winds), the west-northwest side was mainly eroded and the north arm migrated from west to east at a rate of 0.30 m/a, causing the dune slope to become gentle and elongate. The local air circulation (southerly winds) exerted a significant impact on the development process of the star dune. Due to human activities, the south side exhibited surface processes transforming from a concave to a convex profile over 46 years, which poses a potential threat to the Crescent Moon Spring. The results indicate that rehabilitating the airflow field is a crucial strategy for protecting Crescent Moon Spring from burial. Opening up the passage of easterly, westerly, and southerly winds through intermediate cutting of the protection forest, demolishing the enclosed wall, and changing the pavilion into a porous pattern have been suggested to protect the Crescent Moon Spring from burial.

Keywords: star dune; morphology variation; erosion and deposition; time scale; Crescent Moon Spring

Citation: ZHANG Weimin, TAN Lihai, AN Zhishan, ZHANG Kecun, GAO Yang, NIU Qinghe. 2019. Morphological variation of star dune and implications for dune management: a case study at the Crescent Moon Spring scenic spot of Dunhuang, China. Journal of Arid Land, 11(3): 357–370. https://doi.org/10.1007/s40333-019-0099-1

1 Introduction

Star dunes are the largest aeolian landforms in many sand seas and may reach heights of more than 300 m [?, ?, ?, ?]. They contain a greater volume of sand than any other dune type [?, ?] and seem to occur in areas that represent depositional centers [?, ?, ?]. Star dunes, with their tall bodies, special morphology, balanced development, and relatively limited migration, are usually distributed in specific geographical areas that have multi-directional wind regimes [?]. They grow vertically as they accumulate sand brought in from multiple directions [?]. Their near-surface airflow fields and sedimentary structures are also very complex [?, ?, ?, ?, ?, ?]. The surface processes and dynamics of star dunes have been relatively little observed and documented, and patterns of erosion and deposition under different wind velocities and directions are less well known. By studying the airflow fields of a star dune' s surfaces and internal structure in Dumont dune field, California, Nielson and Kocurek (1987) believed that the strength, direction, and duration of seasonal primary winds, the size of the dune and its arms, and secondary airflow all played critical roles in the maintenance and growth of star dunes. Lancaster (1989, 1996) systematically studied the near-surface airflow fields and patterns of deposition and erosion of a star dune in Gran Desierto, Mexico. After field observation of the migration characteristics of a star dune under multidirectional winds on the top of the sandstone massif of Mogao Grottoes near Dunhuang, China, Qu et al. (1992) and Zhang et al. (2000) considered that local wind circulation played an important role in the evolution of star dunes. Generally, star dunes are relatively stable with less movement, which distinguishes them from transverse and longitudinal dunes [?, ?, ?, ?, ?]. The oscillation of their arms is in accordance with seasonal variation of wind directions, exhibiting movement features of transverse or linear dunes [?].

Aeolian processes over the star dune bed surface consist of three basic types: erosion, transport, and deposition [?], of which erosion and deposition processes over the dune sides are significant for revealing dune dynamic processes. However, aeolian erosion and deposition over dune sides cannot be quantified at present. The large volume and complex morphology of star dunes lead to difficulties in field observations of their dynamic processes. To date, star dunes remain one of the least investigated dune types because of the complexity of morphology combined with spatial and temporal variability [?, ?, ?, ?, ?, ?]. Thus, it is difficult to accurately measure the erosion and deposition patterns of star dunes using traditional monitoring methods such as erosion pins. Furthermore, dune migration characteristics are strongly influenced by features of near-surface airflow, such as transverse and longitudinal airflows [?]. The concave or convex profile of dune sides, one of the important factors influencing the dynamic process of mega dunes, exerts a significant effect on the airflow field and in turn causes variation of the sand flux profile [?, ?]. However, it is still unclear what the dominating factor is for the transition between erosion and deposition. Long-term and contiguous wind regime data are also scarce in desert environments, leading to difficulties in comparison between wind regime and dune dynamics. Thus, relatively little is known about the mutual feedback between star dune dynamics at different monitoring time scales and the corresponding wind regime [?, ?, ?, ?, ?].

Star dunes are one of the main dune types in the Mingsha Mountain-Crescent Moon Spring area, Dunhuang, China. The airflow field over Mingsha Mountain has been disturbed by buildings and protection forests constructed around the scenic spot in recent decades, aiming to improve tourism environments and facilities. The variation of airflow field causes the star dune at the north side of the spring and the mega dune at the south side to move toward each other, thus threatening the survival of the spring and endangering sustainable development of local tourism [?, ?]. The proper coordination among natural heritage protection, human activity impact, and dune management has become a new research problem in the study area. Though much observation of wind-blown sand over the star dune has been performed in recent years, it is still unable to explain what causes the star dune and the mega dune to move toward the spring and the swell on the south side of the star dune. To date, these circumstances can only be described qualitatively due to the lack of quantitatively evaluating morphological change in the field, and the management of mega dunes has not yet been reported in the literature. This study focuses on aeolian erosion and deposition processes over the star dune at the north side of the Crescent Moon Spring at time scales from months to decades using digital elevation model (DEM) data from aerial photographs and 3-D laser scans, aiming to reveal star dune dynamic processes under human impacts and thus provide scientific evidence for proper coordination among natural heritage protection, human activity impact, and dune management.

2 Study Area

The Crescent Moon Spring is located north of Mingsha Mountain and approximately 5 km south of Dunhuang city, a famous historical and cultural city in Gansu Province, China. The Mingsha Mountain-Crescent Moon Spring is famous for its unique natural landscape of "spring mirroring sand hills" and is considered an outstanding tourism resource that plays an important role in the local economy. Mingsha Mountain, extending 10–15 km from north to south and approximately 30 km from east to west, is located on the eastern edge of the Kumtag Desert and is an aeolian depositional landform composed of pyramidal mega dunes, complex linear dunes, and complex mega dunes, all superimposed on low bedrock hills. Mingsha Mountain is 300 m high, with an altitude of 1250–1600 m. Over the period 1990–2000, the recorded mean annual precipitation at the meteorological station (40°08 N, 94°47 E) in Dunhuang City was approximately 39.7 mm, with 64% falling from June to August. The mean annual potential evaporation is about 2465 mm, which is 62 times the precipitation. Winds in the study area are from east, west, and south. The easterly winds dominate in spring and summer, while westerly winds prevail in winter, and southerly winds occur at midnight throughout the year, particularly from October to February of the following year.

The monitored star dune (40.09°N, 93.67°E), with a relative height of 90 m, is located at the north edge of the Mingsha Mountain dune field and north of Crescent Moon Spring (Fig. 1 [Figure 1: see original paper]). This star dune has three arms radiating from the central peak and extending to the north (N, 5°), south-southeast (SSE, 140°), and west-southwest (WSW, 250°). The two adjacent arms constitute the east (E), south (S), and west-northwest (WNW) dune sides. The E side, with a slope length of 386 m, is a typical avalanche face at angles of 25°–32°, and a gently sloping plinth is present on this side. The S and north (N) sides have respective slope angles of 15°–30° and 20°–30° and respective slope lengths of 266 and 209 m (Fig. 1).

3 Materials and Methods

The airflow fields over dune sides of the investigated star dune were measured by a HOBO station with four wind cups at 0.2, 0.5, 1.0, and 2.0 m and one wind vane at 2.0 m above the dune surface (Fig. 1). Wind speeds were recorded at 1-min intervals. Five 3-D ultrasonic anemometers (Young Model 81000, R. M. Young, USA) were combined to measure the 3-D wind speed at a frequency of 1 Hz at a height of 3 m (Fig. 1). The measurement period was from January to December 2015.

Aerial photographs from 1963, 1985, 2004, and 2009 were processed by a digital photogrammetric workstation (JX-4C, Beijing Geo-Vision Tech. Co. Ltd., China), which had strong human-computer interaction and product quality control and was mainly used to produce digital orthophoto maps, digital line graphs, and DEMs at various scales [**?**, **?**]. These photographs were used to perform interior orientation, relative orientation, absolute orientation, epipolar image resampling, image correlation, and feature matching. In this study, a DEM with a cell size of 3 m × 3 m was created. We acquired 28 ground-control points on relatively flat terrain around the star dune (buildings, curves, and road intersections visible on the photographs), which were used to validate the digital elevation data. The horizontal and vertical accuracy of the GPS (Trimble 5800) points after post-processing was <10 cm. We estimated the horizontal accuracy of the DEM to be less than 20 cm and the vertical accuracy to be 30–40 cm.

The DEM data were then processed using arithmetic operations in ArcGIS 9.3 (ESRI, Redlands, USA). Erosion and deposition of the dune surface could be reflected from changes in elevation indicated by the D-values between former elevation data (1963, for example) and latter data (1985, for example). Aeolian erosion and deposition characteristics of dune sides were visualized and analyzed using Surfer 8.0 software (Golden Software, Golden, USA).

Four monitoring periods were selected to show variation processes of star dune morphology controlled by different near-surface airflow fields at different time scales: 1963–2009, 1963–1985, 1985–2004, and 2004–2009. The dynamic process of the star dune in 1963–2009 was under the influence of the airflow field without human activity impact and represented the original state. In 1985–2004 and 2004–2009, the processes were under the effect of human activities, such as pavilions inside the scenic spot and protection forests around it [**?**, **?**].

The dynamic process of the star dune at the time scale of months was monitored by a 3-D laser scanner (Leica Scan Station C10, Leica Geosystems AG, Switzerland). The surveys were conducted from July to September 2011, July 2014 to February 2015, and February to April 2015, when morphological variations of the star dune were under the effects of southerly, easterly, and westerly winds, respectively.

Pre-existing stable structures (typically man-made) found within scan range were used as benchmarks for co-registration of surveys from different dates [**?**]. A local coordinate system was established to guarantee that multi-phase survey data were located in an identical coordinate system, and four sphere targets were set between two stations to control the corresponding accuracy to less than 6 mm. The density of the scanned dataset was 10 cm × 10 cm. Processing of the point-cloud data was performed within the Cyclone software package (http://hds.leica-geosystems.com). Then, a DEM with a cell size of 3 m × 3 m was created. Further data processing was consistent with that of aerial photographs mentioned above. The coordinate system of topographic maps applied a geodetic coordinate system, while the 3-D laser scanner used its own coordinate system, and both of them were matched. Thus, changes in elevation using the dataset from aerial photographs could not be compared with those from scanning.

The drift potential (DP), expressed in vector units (VU), was widely used to describe sand activities in relation to the power of winds [**?**].

$$DP = \sum (V - V_t)^2 \cdot t$$

where V is the wind speed above the threshold velocity (m/s); Vt is the threshold velocity (m/s), and t is the frequency (%) of sand-driving wind, expressed as a percentage of the total time. The resultant drift potential (RDP) refers to the net drift potential of different wind directions, and the resultant drift direction (RDD) determines this direction.

4.1 Near-surface Airflow Fields over the Star Dune under Three Wind Directions

The regional aeolian environment in the study area was described by Pang et al. (2014) and Zhang et al. (2016). The star dune in this area was formed by winds from three directions. Using the 2015 wind data at the dune top, the annual DP calculated at the dune crest was 232.9 VU (Fig. 2 [Figure 2: see original paper]). A three-directional wind regime was present: the primary peak in the southern direction (SSE, S, SSW, and SW), the secondary peak in the western direction (WSW, W, WNW, and NW), and the third peak in the eastern direction (NNE, NE, ENE, and E). The drift potentials (DPs) in the three directions mentioned above were 90.8, 86.8, and 36.1 VU, respectively. Considering that the DP of the eastern direction in the upper one-third section of the E side reaches 107.2 VU, the star dune develops in a relative-equilibrium aeolian environment with three wind directions (Fig. 2). According to Fryberger' s classification of aeolian environment, this wind regime belongs to the intermediate-energy environment with a directional variability (RDP/DP) of 0.45.

Near-surface airflow field is the key to indicating erosion and deposition processes and, in turn, the dynamic mechanism of star dunes. Figure 3 [Figure 3: see original paper] shows that the investigated star dune north of Mingsha Mountain was formed by winds from three directions. The DPs in 2015 in different wind directions were calculated to show the near-surface airflow field over the investigated star dune. Wind speeds 5 m/s (the threshold wind speed at the height of 2 m) and directions of 20° to 90° at the lower section of the E side were selected, and thus the corresponding time was determined. Wind speeds (5 m/s) and directions in 2015 at different locations were also selected. The DP of easterly winds accounted for 46% of the total DP, indicating that easterly winds were relatively strong among the three wind directions. The amplification effect of easterly winds was remarkable as they flowed over the E side. For example, the annual DP at the toe of the E side in 2015 was 3.4 VU with a main speed range of 5–9 m/s, whereas the DPs in the upper one-third section of the E side and the top of the dune increased to 107.2 and 38.1 VU, respectively, with a main speed >9 m/s. Crescent Moon Spring was surrounded by mega dunes in the south, west, and north with a gap in the east, and easterly winds deflected the lower section of the SSE arm while airflow amplified at the toe of the S side. Consequently, the annual DP at the toe of the S side was 20 VU with a SE direction.

In periods of westerly winds, wind speeds 5 m/s and directions from 200° to 270° at the lower section of the WNW side were selected using the same method as under easterly winds. The annual DP of westerly winds at the dune top was 58.6 VU, accounting for 25% of the total DP (Fig. 4 [Figure 4: see original paper]). The DP increased from 11.5 VU at the toe of the WNW side to 27.0 VU in the upper one-third section and 58.6 VU at the dune top, representing respective increases of 2.3 and 5.0 times. During westerly winds, the DP in the upper one-third section reached 37.3 VU and the main wind direction deflected from W to SW. The DP on the E side ranged from 1.3–1.8 VU, which was basically unaffected by westerly winds. Thus, as a longitudinal airflow, westerly winds mainly affected the development of the WNW side [**?**].

Given that southerly winds were affected by the pavilions south of Crescent Moon Spring (Fig. 1), wind speeds 5 m/s and directions of 110°–180° at the lower section of the E side were selected using the same method mentioned above. The results showed that the DP of southerly winds was 43.4 VU with a main speed range of 9-11 m/s, accounting for 18% of the total DP at the dune top (Fig. 5 [Figure 5: see original paper]). Under the influence of the pavilions, the DP at the toe of the S side was 0.6 VU with a speed range of 5-9 m/s in a SE direction. The DP at the dune top increased to 43.4 VU with a main speed >9 m/s. Southerly winds that were unaffected by the pavilions flowed over the SSE arm, causing the DP at the toe of the E side to increase to 36.6 VU; wind speeds were concentrated at 9-11 m/s because of the funneling effect caused by the gap in the east of Crescent Moon Spring.

4.2 Morphological Variation of Star Dune in Time Scales from Years to Decades

The maximum erosion depth (rates) and deposition height (rates) were calculated to show the variation process of star dune morphology, which was significant for probing into star dune dynamics. Figure 6a [Figure 6: see original paper] shows the variation process of star dune morphology at a time scale of 46 years. The results showed that erosion and deposition processes occurred on the three sides of the star dune and oscillation presented on the three arms. Generally, the variation process of star dune morphology followed the basic rule that aeolian erosion occurred on the windward slope and deposition on the lee side, whereas complex erosion and deposition processes presented on the sides of the star dune such as the S side because of deflecting airflows.

In particular, the E side of the star dune was mainly affected by easterly winds. During the 46-year period, the E side was dominated by surface erosion with a noticeable feature that strong sand deposition occurred on the SSE arm. The maximum erosion depth on the E side was 16.1 m during 1963-2009 with a maximum erosion rate of -0.35 m/a (Table 1), which mainly occurred on the lower part of the E side. Meanwhile, the maximum deposition on the SSE arm of the E side was 20.2 m with a maximum deposition rate of 0.44 m/a (Fig. 6a; Table 1). The variation process of morphology over the E side in the three monitoring periods showed a similar pattern to that during 1963-2009 [**?**]. However, the respective maximum erosion rates on the E side were -0.86, -0.49, and -0.93 m/a during the three monitoring periods 1963-1985, 1985-2004, and 2004-2009 (Table 1); and the maximum deposition rates were 0.82, 0.28, and 2.26 m/a, respectively. Thus, the stronger the easterly winds were, the more remarkable the upward growth of the star dune was. Besides, the average erosion or deposition rates of the E side were -0.08, -0.07, and 0.33 m/a in the three periods of 1963-1985, 1985-2004, and 2004-2009, respectively.

Table 1 Erosion and deposition statistical data of dune sides and migration rates of dune arms during different monitoring periods

Monitoring period	Erosion and deposition rates (m/a)	Arm migration rates (m/a)
	E side	WNW side

Monitoring period	Erosion and deposition rates (m/a)	Arm migration rates (m/a)
1963-1985	-0.86/0.82	-0.50/0.16
1985-2004	-0.49/0.28	-0.50/0.16
2004-2009	-0.93/2.26	-0.50/0.16

Note: Emax, maximum erosion rate; Dmax, maximum deposition rate; Mean, average erosion or deposition rate; W→E, migration of N (north) arm from W (west) to E (east); N→S, migration of WSW (west-south-west) arm from N to W at the upper part of the WSW arm; S→N, migration of WSW arm from S (south) to W at the lower part of WSW arm; SW→NE, migration of SE (southeast) arm from SW (southwest) to NE (northeast). Positive value means deposition, negative value means erosion, and -means no migration.

The erosion at the WNW side, with an average erosion rate of -0.19 m/a, a maximum erosion rate of -0.50 m/a, and a maximum erosion depth of 23.2 m during 1963-2009, was under the effect of westerly winds. Deposition mainly occurred on the dune top with a maximum deposition rate of 0.16 m/a. In addition, westerly winds played an important role in the migration of dune arms. The crest line of the SSE arm end migrated by 30.2 m from SW to NE with an average rate of 0.66 m/a, and the N arm migrated by 13.8 m from W to E with an average migration rate of 0.30 m/a during the monitoring period (Table 1). The variation pattern of morphology on the WNW side in the three monitoring periods (1963-1985, 1985-2004, 2004-2009) showed little difference from that during 1963-2009 (Fig. 6). The average migration rates of the SSE arm from SW to NE in the three periods were 1.35, 0.51, and 0.32 m/a, respectively, and the average migration rates of the N arm from W to E were 0.35, 0.45, and 0.78 m/a, respectively (Table 1).

Over the 46-year period, erosion and deposition processes on the S side varied over a wide range. The results revealed that aeolian erosion and deposition occurred on the S side, where erosion mainly occurred around the WSW arm with a maximum erosion depth of 25.3 m, whereas deposition mainly distributed on the section around the SSE arm with a maximum deposition height of 19.7 m. The annual maximum erosion rate and deposition rate were -0.55 and 0.43 m/a, respectively. Moreover, the eastern two-thirds part of the WSW arm migrated with a maximum of 17.0 m from N to S, whereas the western one-third part of the WSW arm migrated with a maximum of 9.5 m from S to N during the monitoring period. The corresponding migration rates were 0.37 and 0.21 m/a (Table 1).

Star dunes are usually distributed in areas with strong local air circulation [?, ?, ?, ?, ?, ?]. The results of variation processes of star dune morphology further illustrated the strength of southerly winds in the study area. The entire south-oriented side was mainly dominated by erosion from 1963 to 1985 [?]. The maximum erosion depth reached 24.3 m with a maximum erosion rate of

-1.10 m/a (Table 1). However, some pavilions that had been rebuilt since the 1990s hindered the channel of southerly winds, lessened the strength of southerly winds, and damaged the near-surface airflow field, thus resulting in a change from wind erosion to sand deposition on the S side. The maximum sand deposition thickness from 1985 to 2004 was 26.9 m, and sand was deposited at a maximum rate of 1.42 m/a; deposition mainly occurred on the upper two-thirds section of the S side [**?**]. As sand deposition on the S side reached a certain degree, convex streamline curvature and significant wind speed acceleration occurred at the windward slope, causing a transition from aeolian deposition to erosion [**?**]. In 2004-2009, aeolian erosion dominated on the S side again, and the maximum erosion depth was 17.4 m with a maximum erosion rate of -3.49 m/a (Fig. 6b; Table 1). These results indicated that southerly winds exerted a significant impact on the development process of the star dune. As wind erosion achieved a certain level, concave streamline curvature resulted in streamwise deceleration and sand deposition occurred. Consequently, the development of the star dune sides follows cyclic processes from concave to convex slope profiles.

4.3 Morphological Variation of the Star Dune in the Time Scale of Months

The airflow patterns on the dune and the resulting patterns of erosion and deposition are dominated by interactions between the preexisting dune form and airflow as winds change direction seasonally [**?**]. During each wind season, the dune form adjusts to the new airflow field around it, which reflects the erosion and deposition patterns [**?**]. The morphological variation of the star dune at the time scale of months reflects the effect of the recent wind regime, and the changes in dune morphology under three wind directions embody the different roles of the three groups of winds in shaping the dune surface.

In the period from July 2014 to February 2015, the total DP at the dune top was 93.1 VU and the RDP was 22.9 VU with a resultant wind direction of 56.1° (Fig. 7 [Figure 7: see original paper]). In this period, the DP of westerly winds (W, WNW, and NW), southerly winds (S, SSW, and SW), and easterly winds (NNE, NE, and ENE) were 15.5, 36.5, and 45.1 VU, respectively. It is apparent that easterly winds were stronger than westerly and southerly winds. The amplification effect of easterly winds was remarkable. For example, the DP at the toe of the E side was 1.23 VU with a main velocity range of 5-7 m/s, while that in the middle of the E side was 45.1 VU with a velocity 11 m/s, which was 36 times that at the toe. The DP at the toe of the WNW side was 1.63 VU with a velocity range of 5-9 m/s, and that of the upper one-third section of the E side was 14.84 VU with a velocity range of 5-9 m/s, which was 9 times that at the toe. The DP at the toe of the S side was 11.7 VU with a velocity range of 9-11 m/s, and that of the upper one-third section of the E side was 71.3 VU with a velocity 9 m/s, which was 6 times that at the toe.

The monitoring results of variation processes of star dune morphology revealed that aeolian erosion dominated on the E side with erosion depths of 0.2-0.6

m, and deposition only occurred at the end of the SSE arm and lower E side, with deposition heights of 0.2–1.0 m (Fig. 7). The WSW arm was dominated by erosion with a depth of 0.2 m, while the WNW side was dominated by deposition with a height of 0.2 m. Significant deposition occurred on the S side with a height of 0.6–2.6 m. Aeolian sediment flux flowing over the S arm resulted in sand deposition on the S side, which was mainly dominated by SSE and SE winds with a speed range of 9–11 m/s.

From February to April 2015, the DP of westerly winds (W, WNW, and NW) was 27.4 VU, accounting for 43.2% of the total DP (63.4 VU; Fig. 8 [Figure 8: see original paper]). The DP of easterly winds (NNE, NE, and ENE) was 29.7 VU, and the DP of southerly winds (S, SSW, and SW) was 19.0 VU, indicating that westerly winds prevailed. The DP at the toe of the WNW side was 5.3 VU with a main velocity range of 5–9 m/s, and that of the upper one-third section of the WNW side was 15.6 VU with a velocity range of 5–9 m/s. The DP at the toe of the S side was 9.1 VU with a velocity range of 7–11 m/s, and that of the upper one-third section of the S side was 27.6 VU with a velocity range of 9–11 m/s.

Wind erosion occurred on the WNW side with a depth of 0.3 m, and relatively strong deposition mainly occurred over the upper half of the E side with a height range of 0.3–0.6 m, which was mostly contributed by westerly winds (Fig. 8). Weak deposition occurred on the bottom of the S side with a height of 0.3 m.

From July to September 2011, the total DP at the dune top was 4.2 VU and the RDP was 2.4 VU with a resultant wind direction of 58.6°. The DPs of southerly, westerly, and easterly winds were 2.2, 1.0, and 0.9 VU (Fig. 9 [Figure 9: see original paper]), respectively. During southerly winds, a noticeable feature of the variation process of star dune morphology was that strong erosion occurred over the upper half of the S side with a maximum depth of 3.0 m, and the depth of the lower half part of the S side ranged from 0.0 to 1.0 m (Fig. 9). Another noticeable feature was that the crest line of the WSW arm migrated by 3.0–4.1 m from S to N. These results indicated that southerly winds were strong and played an important role in the development of the S side, and that southerly winds could entrain the deposited sand from easterly winds. Deposition occurred on the WNW side and the upper half of the E side with respective deposition heights of 1.0–3.5 m and 0.5–1.5 m. Moreover, deposition occurred at the end of the SSE arm because of deflecting easterly winds.

5.1 Development of the Star Dune Controlled by Airflows in Three Wind Directions

Near-surface airflow in different directions is a dominant factor for different dune surface processes [**?**, **?**, **?**]. The development of the star dune is the result of mutual effects of transverse airflow, longitudinal airflow, and local air circulation. The incident angle between the easterly winds and the SSE arm is greater than 30°, and the airflow is called transverse airflow [**?**, **?**, **?**]. Transverse airflow causes the dune side to become higher and steeper. The easterly wind is one of the dominant factors for the upward growth of the monitored star dune. The airflow flowing along the E side has high vertical and horizontal wind speeds, and the wind speed reaches the maximum near the crest line. The airflow diverges over the crest line, and a reverse and helical vortex occurs [?, ?, ?, ?, ?]. At the star dune crest, the convergence of the windward sand stream on the stoss slope and reverse sand stream on the lee slope leads to sand accumulation, causing vertical ridge growth over a small area. This mechanism explains the formation of distinct peaks along the crest line of the dune. With gradual vertical development of the ridge, avalanching of sands at the crest occurs down the lee side, causing the crest to advance. Thus, the windward easterly winds with high vertical velocity result in the development of a reverse and helical vortex, which is the mechanism of upward growth of star dunes [?]. The movement of star dunes is a transverse migration, and dune sides become increasingly steep and high.

When the incident angle between westerly winds and the WSW arm is smaller than 30°, the airflow is called longitudinal airflow [?, ?, ?, ?]. The longitudinal airflow plays a significant role in the development of the WNW side and WSW arm. The longitudinal airflow causes strong wind erosion on the WNW side. Meanwhile, the airflow flowing over the WSW arm causes aeolian erosion, and the sand eroded from the windward flank does not deposit on the lee flank but continues to move along the dune lee flank with the deflected wind. Deposition occurs when the incident angle of the wind becomes less acute and its magnitude over the lee side decreases. Given that the reverse vortex near the crest line of the WSW arm is relatively weak, the ridge moves forward longitudinally as the longitudinal airflow flows over the WSW arm. Consequently, the dune side becomes increasingly gentle and long. This confirms that sand transport or deposition on the lee side is mainly determined by the incident angle [?].

Star dunes mostly develop in piedmont areas, and the piedmont causes an increase in the complexity of regional wind flow and the generation of secondary flows through differential surface heating [?]. The local air circulation usually has high frequency and long duration [?, ?, ?, ?]. Generally, local air circulation is considered to be weak in wind power. However, during southerly winds, wind speed at the top of the star dune can reach 9.2 m/s, and wind speed can reach 6.9 m/s at the height of 2 m above the surface south of the star dune toe. Thus, the local air circulation (southerly winds) and the regional wind regime (northeast and west winds) constitute three wind directions in the study area, contributing to the maintenance and development of star dunes. The dunes in the study area evolve into linear dunes when southerly winds weaken or disappear [?]. In addition, the S side of the star dune can also be influenced by westerly and easterly winds as they deflect over the crest lines of the star dune. The S side suffers from the most complex airflow effect and is also the side with the greatest variation in erosion and deposition rates in the monitoring periods.

5.2 Star Dune Management

Mingsha Mountain-Crescent Moon Spring has existed since the Han Dynasty according to historical records. The harmonious coexistence of Crescent Moon Spring and Mingsha Mountain was due to the unique regional atmospheric circulation [?, ?]. The secret that Crescent Moon Spring cannot be buried by shifting sand has always been an unresolved issue. Our study shows that, as the airflow field over the star dune is affected by human activities, the equilibrium between surface erosion and deposition is damaged, causing anomalous deposition on the S side of the star dune, which is a potential threat to the spring. Two main reasons for this situation are as follows: (1) the decline of easterly winds due to large-scale construction of protection forests around Mingsha Mountain since the 1980s, causing more sand to deposit on the S side and mega dunes on the north and south sides of the spring to migrate closely toward each other [?]; and (2) the pavilions south of the spring obstruct the passage of southerly winds, causing the decrease of wind speed at the lower section of the S side of the star dune and eliminating the ability of airflow to entrain deposited sand brought by easterly winds.

The construction of aeolian engineering should be supported by the theory of aeolian geomorphology; otherwise, it can even bring counterproductive results. Consequently, clarification of star dune dynamics is a precondition. Rehabilitating the airflow field is a crucial strategy for protecting Crescent Moon Spring from sand burial. Artificial interference should be reduced by demolishing the enclosed wall influencing airflows and changing the pavilion south of the spring inside the scenic spot into a porous pattern, increasing the ability of southerly winds to entrain deposited sand on the S side. Besides, opening up the passage of easterly winds through intermediate cutting of the protection forest and demolishing some buildings in the upwind direction of the spring can greatly amplify the strength of easterly winds and thus entrain deposited sand on the S side, eliminating the potential hazard of spring burial caused by closer migration of these mega dunes. Recently, the management strategy of opening up the passage of easterly winds has acquired a certain effect. For example, the DP of easterly winds on the star dune top in 2015 was two times that in 2014 after intermediate cutting of forest trees by the local government in the upwind direction of easterly winds. Further study on the effect of increased wind strength of easterly winds on aeolian erosion and deposition on the S side needs to be conducted.

6 Conclusions

The relative-equilibrium near-surface airflow field under three wind directions is the key factor affecting the migration of the star dune. The patterns of surface erosion and deposition reflect the variation of the relative-equilibrium near-surface airflow field. Easterly winds, which are transverse airflows, erode sand on the E side, causing the E side to become steep and high. Westerly winds, which are longitudinal airflows, cause erosion on the WNW side, resulting in windward migration of the N and SSE arms. The local air circulation (southerly winds) contributes to the maintenance and development of star dunes.

The transition between erosion and deposition occurs on the S side in the monitoring period of 46 years. The cyclic process from a concave slope profile to a convex one is the dynamic process of the S side. The concave or convex slope shape alters the feature of near-surface airflow, causing the transition between aeolian erosion and deposition. The S side was mainly dominated by erosion from 1963 to 1985 with a maximum erosion rate of -1.10 m/a. However, some pavilions that had been rebuilt since the 1990s decreased the strength of southerly winds, and the S side was mainly dominated by deposition from 1985 to 2004 with a maximum deposition rate of 1.42 m/a. When sand deposition on the S side reached a certain degree, erosion dominated on the S side again with a maximum erosion rate of -3.49 m/a from 2004 to 2009.

Human activities damage the airflow field state, contributing to the swell on the S side and the closer migration between northern and southern mega dunes. Clarifying the near-surface airflow field and the morphological variation of the star dune and providing scientific evidence for resuming the airflow field are key strategies for protecting Crescent Moon Spring. Opening up the passage of northeasterly and westerly winds through intermediate cutting of the protection forest, demolishing the enclosed wall, and changing the pavilion south of the spring into a porous pattern have been suggested to protect Crescent Moon Spring from burial.

Acknowledgements This work was funded by the National Natural Science Foundation of China (41271023). We thank the Crescent Moon Spring Management Agency for their help in the field work.

References

Breed C S, Grow T. 1979. Morphology and distribution of dunes in sand seas observed by remote sensing. A study of global sand seas, USGS Professional Paper, 1052: 253-303.

Burkinshaw J R, Rust I C. 1993. Aeolian dynamics on the windward slope of a reversing transverse dune, Alexandria coastal dunefield, South Africa. In: Pye K, Lancaster N. Aeolian Sediments Ancient and Modern. [1993-05-27]. https://onlinelibrary.wiley.com/doi/10.1002/9781444303971.ch2.

Cooke R U, Warren A, Goudie A S. 1993. Geomorphology in Deserts. London: UCL press, 390-391.

Dong J H, Bian Z F. 2004. Proposal for the protection of natural heritage of Singing Sand Mountain and Crescent Moon Spring in Dunhuang City, China. Journal of Natural Resources, 19(5): 561-566.

Dong Z, Zhang Z, Qian G, et al. 2013. Geomorphology of star dunes in the southern Kumtagh Desert, China: control factors and formation. Environmental Earth Sciences, 69(1): 267-277.

Fryberger S G. 1979. Dune forms and wind regime. In: McKee E D. A Study of Global Sand Seas. USGS Professional Paper, 1052: 137-169.

Hu S, Wu Z. 1997. The study on the model for pyramid dune formation in the Mingsha mountain, Dunhuang City. Geographical Research, 16(1): 60-67.

Katz O, Mushkin A. 2013. Characteristics of sea-cliff erosion induced by a strong winter storm in the eastern Mediterranean. Quaternary Research, 80(1): 20-32.

Lancaster N. 1983. Controls of dune morphology in the Namib sand sea. Developments in Sedimentology, 38: 261-289.

Lancaster N. 1989a. The dynamics of star dunes: an example from the Gran Desierto, Mexico. Sedimentology, 36(2): 273-289.

Lancaster N. 1989b. Star dunes. Progress in Physical Geography, 13(1): 67-91.

Lancaster N. 1996. The role of field experiments in studies of dune dynamics and morphology. Annals of Arid Zone, 35(3): 161-172.

Mulligan K R. 1988. Velocity profiles measured on the windward slope of a transverse dune. Earth Surface Processes and Landforms, 13(7): 573-582.

Nielson J, Kocurek G. 1987. Surface processes, deposits, and development of star dunes: Dumont dune field, California. Geological Society of America Bulletin, 99(2): 177-186.

Pang Y, Qu J, Zhang K, et al. 2014. Quantitative analysis on the dynamic characteristics of megadunes around the Crescent Moon Spring, China. Journal of Arid Land, 6(3): 255-263.

Qu J, Ling Y, Zhang W, et al. 1992. Preliminary observation and study on the formation mechanism of pyramid dune. Journal of Desert Research, 12(4): 20-28.

Qu J, Gong G, Wen Z, et al. 1997. Sand drift encroachment in the Dunhuang Mogao Grottoes District and its control. Science in China Series D: Earth Sciences, 40(2): 197-206.

Tan L, Zhang W, Bian K, et al. 2016. Numerical simulation of three-dimensional wind flow patterns over a star dune. Journal of Wind Engineering and Industrial Aerodynamics, 159: 1-8.

Tsoar H. 1983. Dynamic processes acting on a longitudinal (seif) sand dune. Sedimentology, 30(4): 567-578.

Tsoar H, Blumberg D G, Stoler Y. 2004. Elongation and migration of sand dunes. Geomorphology, 57(3-4): 293-302.

Walker I J, Hesp P A, Davidson-Arnott R G, et al. 2009. Responses of three-dimensional flow to variations in the angle of incident wind and profile form of dunes: Greenwich Dunes, Prince Edward Island, Canada. Geomorphology, 105(1-2): 127—138.

Wang T, Zhang W, Dong Z, et al. 2005. The dynamic characteristics and migration of a pyramid dune. Sedimentology, 52(3): 429-440.

Wasson R J, Hyde R. 1983. Factors determining desert dune type. Nature, 304: 337-339.

Wiggs G F, Livingstone I, Warren A. 1996. The role of streamline curvature in sand dune dynamics: evidence from field and wind tunnel measurements. Geomorphology, 17(1—3): 29-46.

Wilson I G. 1973. Ergs. Sedimentary Geology, 10(2): 77-106.

Yang X, Scuderi L, Liu T, et al. 2011. Formation of the highest sand dunes on Earth. Geomorphology, 135(1-2): 108-116.

Zhang K, Niu Q, An Z, et al. 2015. Aeolian dynamics environments near earth surface in desert-oasis transitional zone of Dunhuang area. Bulletin of Soil and Water Conservation, 35(4): 8-11.

Zhang W, Qu J, Dong Z, et al. 2000. The airflow field and dynamic processes of pyramid dunes. Journal of Arid Environments, 45(4): 357-368.

Zhang W, Qu J, Tan L, et al. 2016. Environmental dynamics of a star dune. Geomorphology, 273: 28-38.

Zhu Z D, Chen Z P, Wu Z, et al. 1981. Study on Aeolian Sand Landforms of Taklimakan Desert. Beijing: Science Press, 27-55.

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