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ORIGINAL ARTICLE

Characteristics of wind-blown sand in the region of the Crescent Moon Spring of Dunhuang, China

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Abstract Based on the detailed wind data, this paper aims to investigate wind regime, drift potential and the movement of mega-dunes at the Crescent Moon Spring, an important scenic spot in western China and to clarify the dominant factors that control sand transport in this region. The results of this paper revealed that the dominant wind directions at the spring were NW and SW. The spring region belonged to a low-energy wind environment. The wind regime and sand drift potential were hugely influenced by local topography, and the regional atmospheric circulation intensified the complexity of their variations. Besides, the movement of the southern and northern mega-dune towards the spring greatly endangered the preservation of this scenic spot. These results provide insights into the characteristics of wind-blown sand at the Crescent Moon Spring that will guide efforts to control sand damages.

Keywords Crescent Moon Spring · Sand-laden wind · Drift potential · Wind rose

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Introduction

Dunhuang (92° 15′ to 95° 30′ E, 39° 40′ to 41° 35′ N) is an ancient way station along the Silk Road in western China. It lies at the western end of the Hexi Corridor in Gansu Province and covers an area of 3.12×10^4 km^2. It is surrounded by the Kumtagh Desert to the west and the Altyn Mountains to the south. Dunhuang has attracted many tourists from around the world due to the Buddhist shrine at the Mogao Grottoes, the Crescent Moon Spring and the large area of Yardangs nearby (Qu et al. 2001; Stone 2008; Liu et al. 2011).

Dunhuang has a typical hyper-arid continental climate (Zhang et al. 2004). The annual mean wind velocity exceeds 3.0 m/s, and strong winds (with an instantaneous wind velocity >17 m/s) occur more than 20 days per year. The annual rainfall is only about 40 mm and mainly falls during the summer. The annual potential evaporation is 2,488 mm (Wang et al. 2005). The Crescent Moon Spring, looking like a bright new moon, lies in the wild desert, 5 km south of Dunhuang City (Ding and Gong 2004). It is surrounded by mega-dunes on all sides (Fig. 1). A 105-m tall pyramidal mega-dune lies on the north side of the Spring. On the south side, there is a 95-m tall linear sand dune. To the west of the spring is a pyramid dune and it has two peaks with heights of 150 and 170 m. The northern arc of the Crescent Moon Spring is 240 m long and its maximum north–south width is 39 m. The water surface covers 8.8×10^4 m^2 and the water depth reaches a maximum of 3.0 m (Yin and Wei 2010). The mega-dune sand around the Crescent Moon Spring is mainly composed of coarse, medium, fine and very fine sands (Table 1). Fine sand accounts for 47.24–68.49 %, medium sand accounts for 20.93–34.42 % and very fine sand accounts for 1.43–4.74 % of the total weight of the mixed dune sand, varying with the sampling position on a mega-dune and the location of the dune. The median diameter generally ranges from 0.19 to 0.89 mm. The standard deviation is between 0.09 and 1.01 with a mean value of 0.40.

The Crescent Moon Spring has been protected by its surrounding mega-dunes for thousands of years, and there are records describing its existence as far back as the Eastern Han Dynasty (25–220 AD). Sand-driving winds occur frequently every year, and deposit considerable amounts of sand at the periphery of the spring. However, it is not yet understood why this spring has not been buried by shifting sands (Wen 1990; Dong and Bian 2004; Sang 2005).

Because of its historical importance and popularity as a tourist destination, managers are attempting to find ways to preserve the Crescent Moon Spring. To achieve this target, it is necessary to better understand the characteristics of windblown sand in the region. In order to provide this knowledge, the field observations were conducted to characterize the flow of the sand-laden wind, the flow field, drift potential and changes in the surrounding mega-dunes. This paper aims to clarify the characteristics of wind-blown sand at the Crescent Moon Spring and to provide the scientific basis for the protection of this scenic spot.

Data sources and methods

The wind data used in this paper was obtained from seven meteorological observation sites located throughout the region surrounding the Crescent Moon Spring (Fig. 2). Since the No. 4 observation site lies about 1.8 km northeast of the No. 3 observation site, it is not shown in Fig. 2. At each observation site, wind data were measured by self-recording anemometers at intervals of 10 min and a height of 2 m above the ground. The wind speed was measured by a cup anemometer and wind direction by a wind vane in sixteen compass azimuths whose periodic signals were recorded on a data logger. Resolution of the sensor for wind speed is 0.1 m/s and 3° for wind direction. The distribution of sand-moving winds around the Crescent Moon Spring was described based on the synchronous data from the 7 observation stations in 2009. The changes in the region's topography were determined by comparing the relief maps at the scale of 1:5,000 in 1985 with that in 2009.

Wind regimes

The dominant winds surrounding the Crescent Moon Spring flow from the northwest and southeast. Wind speed is strongly affected by the presence of the mega-dunes. The monthly variations of wind speed at the different observation sites are listed in Table 2. It indicates that the wind speed is the lowest at the Crescent Moon Spring (No. 1 site), with an annual average value of 1.75 m/s. At the mega-dune to the south of the Crescent Moon Spring, the annual mean wind speed is 2.78 m/s (No. 5 site). Strong winds are the most common during spring and the average wind speed exceeds 3.0 m/s.

Threshold of entrainment

One of the most important concepts in aeolian geomorphology is the critical velocity required to move sand

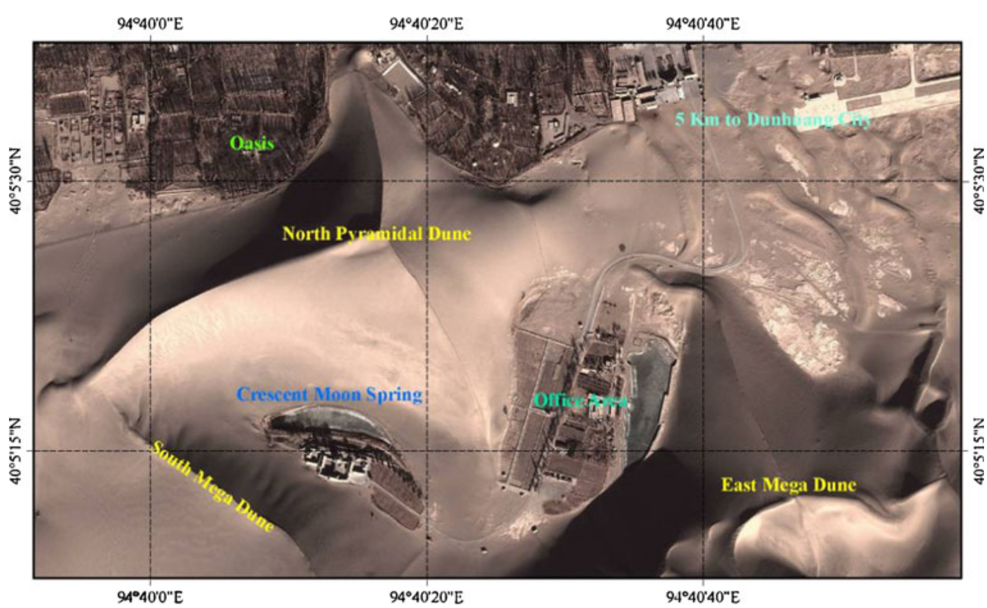

Fig. 1 The Crescent Moon Spring which lies in the desert about 5 km south of Dunhuang City in western China

Table 1 Grain size distribution of the sand surface at multiple locations around the Crescent Moon Spring (%)

Location	Coarse sand (1.00–0.40 mm)	Medium sand (0.40–0.25 mm)	Fine sand (0.25–0.125 mm)	Very fine sand (0.063–0.125 mm)	Silt (0.004–0.063 mm)
Pyramidal dune n = 31	16.88	34.42	47.24	1.43	0.06
Linear dune n = 9	6.29	20.93	68.49	3.96	0.33
East sand dune n = 9	0.84	28.20	66.22	4.74	0.00

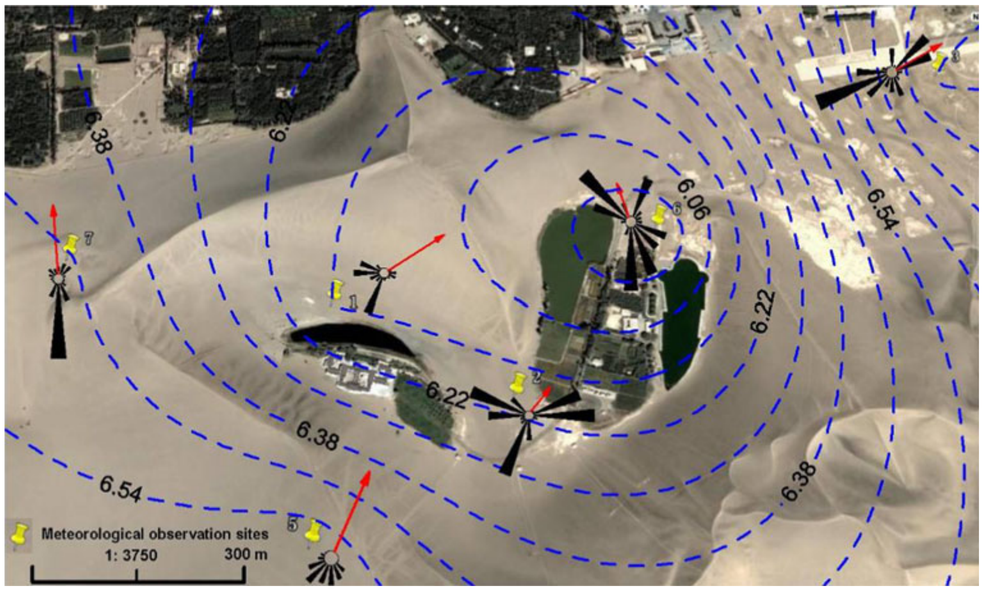

Fig. 2 The location of the observation sites, isolines for the threshold wind speed (m/s) and sand-driving wind roses at the observation sites

Table 2 Monthly variations of wind speed at the different sites in the area surrounding the Crescent Moon Spring (unit: m/s)

Sites	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1	1.27	1.80	2.20	2.62	1.18	1.76	1.61	1.35	2.22	1.60	1.58	1.86
2	2.20	2.08	2.38	2.24	2.54	2.04	1.97	1.60	1.75	1.69	1.73	1.67
3	2.32	2.51	2.96	3.04	3.29	2.56	2.61	2.08	2.30	2.31	2.02	2.49
4	2.11	1.79	2.16	2.49	2.58	2.26	2.10	1.66	1.80	1.46	1.76	1.71
5	2.80	2.72	2.99	2.66	3.17	2.79	2.88	2.76	2.61	3.13	2.21	2.68
6	1.69	1.97	2.39	2.63	2.28	2.44	2.34	1.99	1.99	2.11	1.73	1.89
7	2.08	2.57	3.03	3.23	3.07	2.72	2.52	2.29	2.31	2.77	2.16	2.12

grains (Bagnold 1941). This is known as the threshold velocity for sand movement. It is very important to understand the intensity of wind-blown sand that results from a region's wind environment, and this, in turn, allows the analysis of the relationship between dune types and the wind regime (Wu 1987; Zou et al. 1999). In our study area, the threshold wind velocity for sand entrainment is about 5.0 m/s at a height of 2 m based on the field wind tunnel experiments.

To describe the spatial distribution of wind velocities stronger than this threshold, the data of wind velocities when sand transport occurred in the observation sites were interpolated to develop the isoline profiles for the annual sand-driving wind intensity at each position around the spring (Fig. 2). The results show that the frequency of sand-driving winds depended heavily on the terrain. For example, the No. 3 observation site lies to the northeast of the Crescent Moon Spring and in a valley that concentrates the wind. As a result, the wind was stronger here than that in other parts of the study area. When the wind reached the No. 6 observation site, the wind speed decreased slightly to 6.06 m/s. The maximum annual wind speed occurred at the No. 5 observation site with the value of 6.54 m/s.

Sand-driving wind roses and local circulation

It is also shown from Fig. 2 that the prevailing wind direction varies obviously with the terrain. The dominant directions of sand-driving winds at the Crescent Moon Spring are southwest and west, accounting for 30 and 20.1 % of the total frequency of sand-driving winds, respectively. The resultant drift direction (RDD) is 58°, which indicates that a SW sand-driving wind prevails at the Crescent Moon Spring and that sand motion is primarily towards the northeast. Sand-driving winds from the north or the east are rare, which is confirmed by the sand-driving wind roses at the No. 5 and No. 7 observation sites. Especially at the No. 5 site, the dominant directions of the sand-driving winds are south and southwest, accounting for 75.2 % of the total, and the RDD is 25°.

A wind from the south-southwest passes over the mega-dunes to the south of the Crescent Moon Spring. Under the influence of the dune's shape, the sand-driving wind rose at the No. 2 site is characterized by three groups of dominant winds: east-northeast, south-southwest and northwest. Due to the presence of trees and a village to the south of the No. 6 observation site, the sand-driving wind rose has a complicated distribution, with dominant winds from the southwest, northwest and northeast.

Mountain-valley winds

Due to the overall influence of the terrain, the mountain-valley wind is obvious in the study area. During the day, the sun heats up the valley air between the mega-dunes rapidly. This causes it to rise, causing a warm and upslope wind. At night, the process is reversed. The mega-dune air cools rapidly at night and "falls" downslope, causing a wind going in the other direction. In addition, the presence of the spring in the valley intensifies the development of the mountain-valley wind because of the differences of thermodynamic properties between sand and water. Firstly, the heat capacity of water is higher than that of sand. Secondly, the surface reflectance ratios of water and sand are different. This leads to the air temperature above and near the water is cooler than that above the sand during the day while warmer at night. These differences of air temperature create changes in the pressure field, and thus promote the development of the mountain-valley wind. Figure 3 shows the frequency of wind during the day and night at the No. 1 observation site. The wind direction mainly distributes from 281.25° to 78.75° during the day, that is, wind flows down from the northern pyramidal mega-dune towards the Crescent Moon Spring. During the night, the wind flows from the opposite direction (between 101.25° and 258.75°), passing over the southern mega-dune. Thus, the wind flows mostly between the southwest and the southeast.

Sand ripples are created by the combination of a sand source, the wind direction, and the wind speed (Livingstone and Warren 1996). Some ripples have sharp brinks, whereas others are smooth. The ripple moves forward with the wind by erosion on the windward slope and accumulation in the lee (Howard 1977). Most ripples are aligned roughly at a right angle to the direction of the wind that formed them. Therefore, the strike of sand ripples reflects the wind direction (Neuman et al. 1997). The length and height of a sand ripple reveal the magnitude of the wind that causes it to form. To describe the local circulation patterns around the Crescent Moon Spring, the characteristics of sand ripples at 151 different positions were described. Based on this data, a map of the local circulation patterns was created (Fig. 4).

When the easterly wind prevails, wind blows from the No. 3 observation site, but it is deflected towards the north by the blocking effect of the mega-dune to east of the spring. The airflow then separates and flows in two directions near the No. 2 observation site. One flow passes along the northern side of the Crescent Moon Spring and moves west, and the other flows south and is deflected to the west by the blocking effect of the southern mega-dune. The west wind at the No. 1 site combines with the downward western flow from the southern mega-dune and accelerates through the gap between the dunes to the south of the spring and south of the No. 2 site.

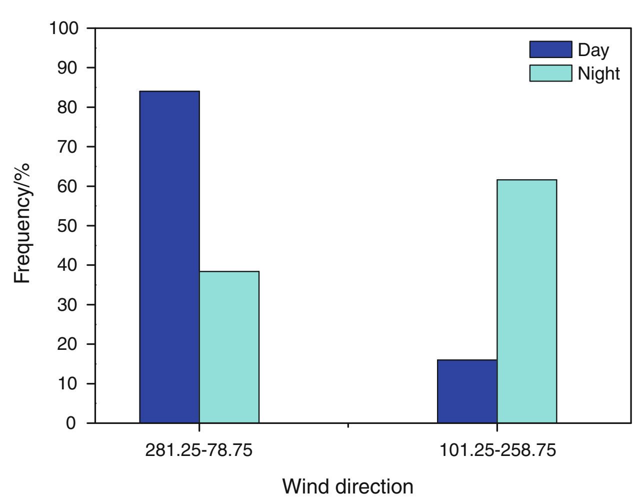

Fig. 3 Frequency of Mountain-valley winds during the day and night in the Crescent Moon Spring

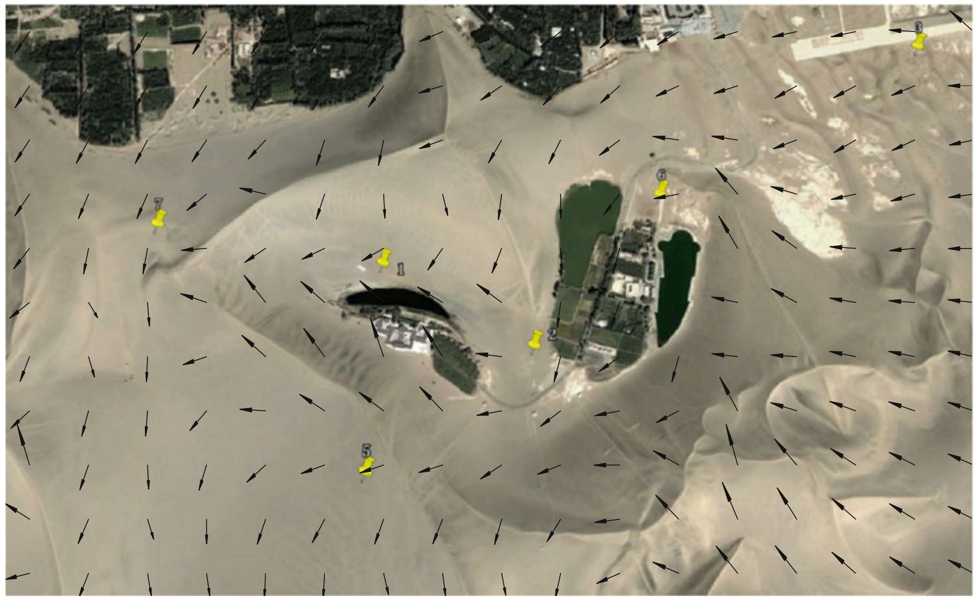

Fig. 4 Flow field around the Crescent Moon Spring based on data from 151 sand ripples on the dunes surrounding the Crescent Moon Spring

Fig. 5 Drift potential (DP) roses for the area around the Crescent Moon Spring

Drift potential

Drift potential (DP) is the most frequently used method for indicating the energy of the surface winds (McKee 1979; Bullard 1997). The calculation of drift potential in this paper refers to (Fryberger and Dean 1979) as follows.

$$DP = V^2(V - V_t)t$$

where DP is the drift potential, which is numerically expressed in vector units (VU); V is the wind speed above the threshold velocity; V_t is the threshold velocity for sand movement; and t is the duration of sand-driving wind, expressed as a percentage of the total time.

The direction and magnitude of the net vector that represents the DP values from the 16 standard compass directions are the resultant drift direction (RDD) and the resultant drift potential (RDP), respectively. An index of the directional variability of the wind can be calculated by RDP/DP. The greater the directional variability of the effective winds varies, the lower the RDP/DP.

The average DP around the Crescent Moon Spring is 88.07 VU, which indicates a low-energy wind environment. The lowest DP is 10.29 VU at the No. 1 site and the highest DP is 147.05 VU at the No. 5 site. Due to the effects of the terrain, RDP and RDD varied greatly (Fig. 5).

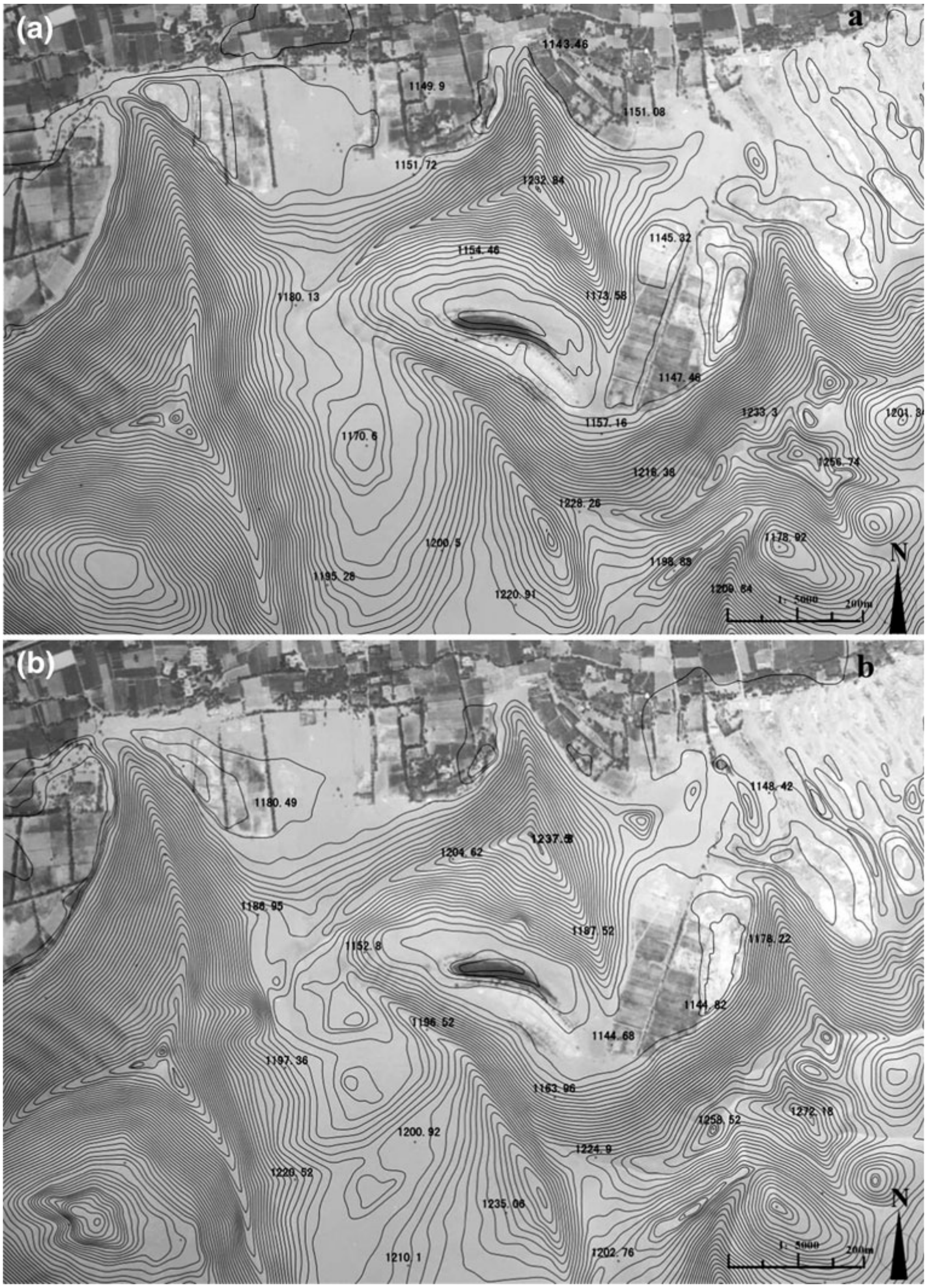

Fig. 6 Topographical contour maps for the area around the Crescent Moon Spring in 1985 (**a**) and 2009 (**b**)

Movement of the mega-dunes

Apart from sand availability, a region's wind regime is an important factor that determines the dune type (Wasson and Hyde 1983). Studies of the geometry of sand dunes mainly aim to characterize the cyclic changes in a dune's features over time (Lancaster 1987; Pye and Tsoar 1990). Due to the effects of local circulation patterns, the northern pyramidal mega-dune is increasing in size and its southeastern crest line is moving south towards the Crescent Moon Spring. The presence of this dune affects the intensity of vortex above its lee slope and creates a new vortex on the windward slope that changes the balance between erosion and accumulation near the Crescent Moon Spring. To detect the differences in the morphology of the mega-dunes bordering the Crescent Moon Spring, two topographical contour maps in 1985 and 2009 were compared (Fig. 6).

Figure 6 clearly shows that the configuration of the sand dunes changed greatly between 1985 and 2009. The height of the northern mega-dune increased towards the Crescent Moon Spring by 20–28 m within 130 m from the crest. The height of the southern slope of the southern mega-dune also increased towards the Crescent Moon Spring by 5–15 m. The ridgelines beside the Crescent Moon Spring changed slightly during this period, moving by 5–10 m towards the centre of the Crescent Moon Spring.

Conclusions

Wind regime and drift potential at the Crescent Moon Spring are mainly controlled by local topography, and the regional atmospheric circulation aggravates the complexity of their variations. The dominant wind directions at the spring are NW and SW. The average DP around the spring is 88.07 VU and the resultant drift direction (RDD) is 58°, indicating that the spring region belongs to a low-energy wind environment and sand motion is primarily towards the northeast. Both the northern and southern mega-dunes move towards the Crescent Moon Spring, and their respective heights have increased by 20–28 and 5–15 m in 24 years, greatly endangering the preservation of this scenic spot.

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