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Environmental dynamics of a star dune

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ABSTRACT

Star dunes, the largest aeolian bedforms in the sand seas of the world, are usually distributed within specific geographical areas that have multi-directional wind regimes. However, relatively few studies have focused on the environmental factors that impart such great volumes of sand to these dunes. Specifically, verification of the developmental processes of star dunes through long-term monitoring is scarce. In this study, by observing 3-D airflow fields and long-term dune dynamics, we demonstrate how topographic barriers, which generate vertical airflow and local air circulation, control the development of a star dune on Mingsha Mountain in Dunhuang, China. Results show that airflow stagnation and deflection caused by topography is one of the major mechanisms for the formation of star dunes. In our study, topographic barriers contribute to the development of intensive vertical airflow dominated by easterly winds. This intensive vertical airflow is one of the main driving mechanisms of the upward growth of mega-dunes. Vertical airflow is the strongest developed airflow reported in available data on aeolian geomorphology. In addition, star dunes are usually distributed in areas where the local air circulation is strong. The results of long-term dune dynamics verify that local air circulation, which forms three wind directions with the regional wind regime, contributes to the maintenance and development of star dunes. Our study indicates that complex mega-dunes are products of topographic barriers, which facilitate their recognition in aeolian geomorphology. We introduce a new evolution pattern of star dunes under the influence of local environment and topographic barriers.

1. Introduction

Star dunes are the largest aeolian bedforms in many sand seas and may reach heights of >300 m (Cooke and Warren, 1973; Wilson, 1973; Lancaster, 1989a). They contain a greater volume of sand than any other dune type (Wasson and Hyde, 1983; Yang et al., 2011) and seem to occur in areas that represent depositional centers (Mainguet and Callot, 1978; Lancaster, 1983; Dong et al., 2004). 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 (Fryberger, 1979). They grow vertically as they accumulate sand brought in from numerous directions (Lancaster, 1989a). Their near-surface flow fields and sedimentary structures are also complex (Nielson and Kocurek, 1987; Lancaster, 1989a, 1989b; Qu et al., 1992; Zhang et al., 2000), and their movement is different from those of transverse and longitudinal sand dunes, that is, it is stable with minimal movement (Breed and Grow, 1979; Qu et al., 1992; Zhang et al., 2000; Wang et al., 2005). Thus, star dunes have a unique position in the research field of aeolian geomorphology.

A close association between topographic barriers and the occurrence of star dunes has been observed (Zhu et al., 1981; Mainguet and Chemin, 1983; Lancaster, 1989b; Pye and Tsoar, 1990; Yan et al., 2001). The main effects of topographic barriers are probably an increase in the complexity of regional wind flow and the generation of secondary flows through differential surface heating (Lancaster, 1989b). Topographic barriers also create traps for sand transport, leading to the accumulation of thick sand deposits that are associated with the occurrence of star dunes (Lancaster, 1989b). Previous studies on the effect of topographic barriers on dune formation have primarily concentrated on simple dunes, such as echo and climbing dunes (Tsoar, 1983b). Topographic barriers can have a significant effect on the size, shape, and orientation of dunes, regardless of type or variety. The formation of star dunes also has some bearing on topographic barriers (Lancaster, 1989b; Qu et al., 1992). Recently, a numerical simulation group showed that soil topography can also affect the shape of barchan dunes (Parteli et al., 2014a). The group also indicated that obstacles can be used to induce dune formation in the combat against desertification (Parteli et al., 2014b). However, historically, the long-term dynamics of star dunes under such wind regimes has been difficult to investigate systematically in the field because of their size, and thus an extensive study on star dunes has not yet been conducted (Breed and Grow, 1979; Mader and Yardley, 1985; Nielson and Kocurek, 1987; Pye and Tsoar, 1990; Wang et al., 2005; Zhang et al., 2012). To date, relatively limited information

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has been published regarding how environmental factors (e.g., topographic barriers and local air circulation) cause star dunes to contain such large sand volumes (Lancaster, 1989b; Zhang et al., 2000; Andreotti et al., 2009; Yang et al., 2011).

Star dunes, as products of sand deposition, are usually distributed in a unique sedimentary environment. Consequently, conventional weather anemometers cannot accurately measure the influence of environmental factors, such as vertical airflow. Specifically, verification of the developmental processes of star dunes through long-term monitoring is scarce. Star dunes remain one of the least-studied dune types.

In this paper, we present field observations of vertical airflow, local air circulation, and long-term dynamics (1963–1985 and 1985–2004) of a giant star dune on Mingsha Mountain in Dunhuang, China. Special attention is paid to the effects of vertical airflow, local air circulation, and topographic barriers on the formation and development processes of the star dune.

2. Aeolian environment

The study area is located on Mingsha Mountain in the Crescent Moon Spring scenic area located approximately 5 km south of the city of Dunhuang, a famous historical and cultural city in Gansu Province, China (40.09° N, 93.67° E). This area is famous for its unique natural landscape variously described as “spring mirroring sand hills” and is considered an outstanding tourism resource in the northwest arid region of China. The specifically monitored star dune, with a relative height of 90 m, is located at the northern edge of the Mingsha Mountain dune field and north of the Crescent Moon Spring. This star dune has three arms radiating from the central peak and extending to the N (5°), SE (140°), and WSW (250°). The two adjacent arms constitute the E, S, and WNW dune sides. The E side is a typical avalanche face at angles of 25°–32°, with a slope length of 386 m, and a gently sloping plinth ahead of this side. The S and WNW sides have respective slope angles of 15°–30° and 20°–30° and respective slope lengths of 266 and 209 m (Fig. 1).

Mingsha Mountain is 10–15 km wide from north to south and approximately 30 km from east to west. It is an aeolian depositional landform composed of complex linear dunes, star dunes, and complex mega-dunes, all of which are superimposed on low bedrock hills. Mingsha Mountain is approximately 1250–1600 m a.s.l, with a relative height of about 300 m (Fig. 1).

The recorded mean yearly precipitation at the meteorological station (40°08′N, 94°47′E) in Dunhuang City is approximately 39.7 mm, mainly falling between June and August and equaling 64% of the annual amount. However, the annual potential evaporation is approximately 2465 mm, which is almost 62 times that of the precipitation.

The regional environment of Mingsha Mountain was described by Zhang et al. (2000). The star dune in this area was formed by three wind directions. The 2014 wind data at the dune top were used to calculate the drift potential according to the method reported by Fryberger (1979). The annual DP at the dune crest was 221.6 VU. A clear three-directional wind regime existed, with a primary peak in the western direction (WSW, W, WNW, NW) (75.0 VU), a secondary peak in the southern direction (SE, SSE, S, SSW) (73.1 VU), and a third peak in the eastern direction (NNE, NE, ENE, E, ESE) (20.7 VU). According to Fryberger's classification of the wind environment standard, which reflects the complexity of wind regimes, this wind regime belongs to a moderate wind-energy environment with a directional variability (resultant DP/DP) of 0.45 (Fig. 2). Westerly winds mainly prevailed in winter, easterly winds were the dominant wind directions in spring and summer, and southerly winds occurred mainly at midnight throughout the year, especially during the months of October to February. The regional wind regime was mainly characterized by easterly and westerly winds. Field observations atop the Mogao Grottoes, 1.2 km southeast from the monitored star dune, have shown that the easterly winds are stronger than the westerly winds (Zhang et al., 2000, 2014). Given that the mega-dune developed in the piedmont area, the strength of easterly winds varied in different locations of mountain front; here, easterly winds are the weakest wind direction in the study area. Southerly winds are a critical local circulation in this area (Qu et al., 1992; Zhang et al., 2000; Wang et al., 2005), and with high frequency and long duration, they constitute the three wind directions with the regional wind regime, thus contributing to the development of star dunes.

3. Methods

The wind profiles over the dune sides of the star dune were measured by HOBO anemometers with four wind cups at heights of 0.2, 0.5, 1.0, and 2.0 m and one wind vane at a height of 2 m above the dune surface. Wind speeds were collected at 1 min intervals. Five 3-D ultrasonic anemometers (Young Model 81000) were also used to measure 3-D wind velocity at a frequency of 1 Hz and a height of 3 m (Fig. 3). The 3-D wind velocity refers to the resultant u (horizontal streamwise), v (horizontal spanwise), and w (vertical) wind components, including 3-D velocity magnitude, azimuth angle, and flow elevation angle. Azimuth angle refers to the angle in the horizontal u–v plane between the incoming wind vector and the geographical north. Flow elevation angle refers to the angle between the 3-D wind vector and the horizontal u–v plane (-90–90°). The measurement period was from November 2013 to December 2014.

Aerial photographs in 1985 and 2004 were processed by a digital photogrammetric workstation (JX-4C, Beijing Geo-Vision Tech. Co. Ltd., China). A digital elevation model (DEM) with a cell size of $1\ \text{m} \times 1\ \text{m}$ was then created. The digital cartographic dataset of the elevations in 1963 and 2008 was supplied by the Center of Mapping Geography Information in Gansu Province, China. We processed the DEM data and the digital cartographic dataset of the elevations by using the arithmetic operation in ArcGIS 9.3 (ESRI, USA), as well as analyzed dune erosion and deposition by using Surfer 8.0 software (Golden Software, USA). The movement characteristics of dune crestlines were also analyzed.

4. Results

4.1. Wind flow patterns

Wind flow over the star dune could be divided into transverse and longitudinal airflows, which functioned together to form different dune arms and sides. Transverse airflow (easterly winds) converged sand streams in the windward slope and diverged near the crest, where sands accumulated and caused the vertical growth of the southeast ridge. Longitudinal airflow (westerly winds) transported sand obliquely along a stoss or lee slope and induced the migration of the north and southeast crestlines.

4.1.1. Effect of easterly winds

In periods of easterly winds, the development of strong vertical airflows was the main characteristic of the flow field of the studied star dune. In the piedmont area, a mega-dune barrier contributed to the decrease in wind speed, and airflow was impeded and climbed along the side of the mega-dune, resulting in the development of a strong vertical airflow. For example, the process of easterly winds (selected at 6:00 a.m.–6:30 a.m. on March 19, 2014) flowing over the E side with a reference average wind velocity of 11.3 m s^{-1} at 2 m above the ground surface and a wind direction of 56.9°, is shown in Fig. 4. The results showed that the strength of the vertical airflow was closely related to the locations on the E side. The 60 s running average vertical wind velocities of the lower, middle, and top locations of the E side (see Fig. 3) were 3.50, 6.23, and 3.59 m s^{-1}, respectively; the corresponding 3-D wind speeds were 8.52, 12.78, and 11.23 m s^{-1}, respectively. The maximum instantaneous vertical wind speeds reached 6.84, 9.18, and