

## Wind Regimes and Associated Sand Dune Types in the Hinterland of the Badain Jaran Desert, China (Postprint)

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**Date:** 2022-05-25T00:00:00+00:00

### Abstract

Abstract: Wind controls the formation and development of sand dunes. Therefore, understanding the wind regimes is necessary in sand dune research. In this study, we combined the wind data from 2017 to 2019 at four meteorological stations (Cherigele and Wuertabulage stations in the lake basins, and Yikeri and Sumujilin stations on the top of sand dunes) in the hinterland of the Badain Jaran Desert in China, with high resolution Google Earth images to analyze the correlation between the wind energy environments and dune morphology. The results of data analysis indicated that both the wind direction and sand drift intensity exhibited notable spatial and temporal variations. The highest level of wind activity was observed in spring. Northwesterly and northeasterly winds were the dominant in the Badain Jaran Desert. At the Cherigele, Wuertabulage, and Yikeri stations, the drift potential (DP) was below 200.00 vector units (VU). The wind energy environments in most areas could be classified as low-energy environments. The resultant drift direction differed at different stations and in different seasons, but the overall direction was mainly the southeast. The resultant drift potential (RDP)/DP ratio was greater than 0.30 in most parts of the study area, suggesting that the wind regimes mainly exhibited unimodal or bimodal characteristics. Differences between the thermodynamic properties and the unique landscape settings of lakes and sand dunes could alter the local circulation and intensify the complexity of the wind regimes. The wind regimes were weaker in the lake basins than on the top of sand dunes. Transverse dunes were the most dominant types of sand dunes in the study area, and the wind regimes at most stations were consistent with sand dune types. Wind was thus the main dynamic factor affecting the formation of sand dunes in the Badain Jaran Desert BJD. The results of this study are important for understanding the relationship between the wind regimes and aeolian landforms of the dune field in the deserts.

## Full Text

### Preamble

#### Wind Regimes and Associated Sand Dune Types in the Hinterland of the Badain Jaran Desert, China

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**Abstract:** Wind controls the formation and development of sand dunes, making understanding wind regimes essential in dune research. This study combined wind data from 2017 to 2019 at four meteorological stations (Cherigele and Wuertabulage stations in lake basins, and Yikeri and Sumujilin stations on sand dune tops) in the hinterland of China' s Badain Jaran Desert with high-resolution Google Earth images to analyze correlations between wind energy environments and dune morphology. Data analysis revealed notable spatial and temporal variations in both wind direction and sand drift intensity. The highest wind activity occurred in spring, with northwesterly and northeasterly winds dominating the Badain Jaran Desert. At Cherigele, Wuertabulage, and Yikeri stations, drift potential (DP) was below 200.00 vector units (VU), classifying most areas as low-energy environments. Resultant drift direction differed across stations and seasons, though the overall direction was mainly southeast. The resultant drift potential (RDP)/DP ratio exceeded 0.30 in most parts of the study area, suggesting wind regimes primarily exhibited unimodal or bimodal characteristics. Differences in thermodynamic properties and unique landscape settings of lakes and sand dunes could alter local circulation and intensify wind regime complexity. Wind regimes were weaker in lake basins than on dune tops. Transverse dunes were the most dominant dune types in the study area, and wind regimes at most stations were consistent with sand dune types. Thus, wind was the main dynamic factor affecting sand dune formation in the Badain Jaran Desert.

These results are important for understanding the relationship between wind regimes and aeolian landforms in desert dune fields.

**Keywords:** sand-driving wind; drift potential; wind energy environment; sand dune; local circulation; Badain Jaran Desert

**Citation:** MENG Nan, WANG Nai' ang, ZHAO Liqiang, NIU Zhenmin, SUN Jiaqi. 2022. Wind regimes and associated sand dune types in the hinterland of the Badain Jaran Desert, China. *Journal of Arid Land*, 14(5): 473-489. <https://doi.org/10.1007/s40333-022-0063-3>

## 1 Introduction

Dune geomorphology represents one of Earth's most significant geomorphological systems. Sand dunes are primary features of many deserts and sand-rich landscapes, and their morphology constitutes a vital research component in dune geomorphology (Wu, 2003). Wind regimes, sediment availability, and surface conditions (e.g., vegetation cover) are key factors controlling dune formation and development (Wasson and Hyde, 1983; Schatz et al., 2006; Reffet et al., 2010; Gao et al., 2015; Zhang et al., 2015). A range of sand dune types develops due to differences in these controlling factors (as shown in Fig. 1 [Figure 1: see original paper]). Although factors influencing dune geomorphology are complex, wind regimes—especially wind direction—are the most important factors shaping dune type, distribution, morphology, and resulting dune field patterns (McKee et al., 1979; Wasson and Hyde, 1983; Thomas et al., 1997; Parteli et al., 2009; Tsoar et al., 2016). Wind regimes are widely studied to understand sand transport intensity and trends and to classify dune geomorphology (Lancaster et al., 1994; Thomas et al., 1997; Wu, 2003; Zhang et al., 2012; Dong et al., 2013; Wang et al., 2015; Zhang et al., 2015; Gao et al., 2019). Therefore, characterizing regional wind regimes in terms of direction, strength, and variability is essential.

Dune patterns can be described using morphologic and morphodynamic classifications. Based on morphology, dunes are classified as crescent, linear, transverse, reversing, and star dunes, while morphodynamic classification depends on dune crest orientation relative to dominant or resultant sand transport direction, yielding transverse, longitudinal, or oblique dunes (Wu, 2003). Aeolian researchers have investigated relationships between regional wind regimes and dune forms (Breed et al., 1979; Fryberger et al., 1979; Wasson and Hyde, 1983; Rubin et al., 1987). Transverse, linear, and star dunes have been associated with unimodal, wide unimodal or bimodal, and obtuse bimodal or complex regimes, respectively (Fryberger et al., 1979). Barchan dunes occur where wind patterns are unidirectional, transverse dunes develop where wind is moderately variable, star dunes form where wind shows maximum variability, dune networks occur where two winds are near-vertical, and pyramid dunes form in regions with multidirectional winds (Wasson and Hyde, 1983; An et al., 2014). Sand-driving wind and drift potential (DP) are important indicators for measuring regional aeolian sand activity intensity and evolution of aeolian landforms, making them widely used in studies of regional wind activity and dune morphology (Fryberger et al., 1979; Bullard et al., 1996; Al-Awadhi et al., 2005; Zhang et al., 2013a; Hereher et al., 2014; Tian et al., 2021).

The Badain Jaran Desert (BJD) is China's second-largest desert, with two major properties deserving particular attention (Bai et al., 2011). First, its dunes are the highest on Earth and exceed all other dunes found to date on other planetary bodies. Second, several permanent lakes exist in low-lying inter-dune areas. The formation and evolution of these megadunes and why lakes are not buried by dunes have puzzled researchers, making consensus difficult to reach.

Previous studies have proposed various hypotheses to explain megadune formation and desert lake water recharge (Yan et al., 2001; Yang et al., 2003; Dong et al., 2004; Chen et al., 2006; Bai et al., 2011; Wang et al., 2016; Niu et al., 2021). Early studies indicated that underlying topography plays the major role in megadune formation mechanisms (Lou et al., 1962; Sun et al., 1964; Wang, 1990; Zhang and Wang, 2005). Dong et al. (2004, 2009) observed regular height-spacing correlations between simple dunes and wind ripples, reporting that megadunes are predominantly wind-formed. Chen et al. (2004, 2006) studied moist sand beneath dry surface layers, suggesting groundwater plays a central role in megadune formation and maintenance. Considerable attention has also focused on wind regimes. Wang et al. (2005) calculated DP-based wind data from 1998 to 2001, concluding the BJD was in a low-energy wind environment. Yang et al. (2011) showed directional variability differs greatly on BJD margins, indicating regional topography's influence. Zhang et al. (2015) used wind data from seven BJD stations to analyze wind regimes, finding DP decreases from north (N) to south (S) and that dominant winds controlling sand dune formation are northwesterly, northeasterly, and southwesterly.

Limited detailed analysis of dune geomorphology in terms of wind-sand interactions has been conducted in the BJD due to scarce wind data. Although aforementioned studies yielded important results, natural conditions and traffic/communication limitations have created a lack of inner desert wind data. Knowledge of wind-sand activities in this area is mostly based on surrounding stations, which do not accurately reflect actual desert hinterland conditions. The effect of wind regimes on dune morphology also remains unclear. Therefore, detailed wind regime information based on field measurements is required to explain sand dune formation mechanisms. Four meteorological stations that are part of Lanzhou University's scientific field station network were established in the southeastern BJD, enabling detailed wind regime data collection.

This study aimed to (1) analyze recent wind regimes to determine characteristics of wind-blown sand and dynamic environments in the desert hinterland, and (2) discuss correlations between dune morphology near stations and wind environments based on meteorological wind data and wind regime analysis. These results will be useful for interpreting megadune formation in the BJD and are significant for future dune geomorphology studies aimed at controlling wind-blown sand damage.

## 2.1 Study Area

The BJD (99°54' -104°34' E, 39°20' -41°19' N) lies on the Alxa Plateau in western Inner Mongolia Autonomous Region, China. Its southern and eastern parts are bordered by the Beida Mountain and Yabrai Mountain, respectively, while its northern and northwestern parts are bounded by the Guezihu wetland and lower reaches of the Heihe River (Fig. 2 [Figure 2: see original paper]). Covering  $4.92 \times 10^4$  km<sup>2</sup> (Dong et al., 2004), BJD elevation gradually decreases from 1800 m in the southeast (SE) to 1000 m in the northwest (NW). The south-

eastern desert contains many tall compound sand dunes with relative heights of 300–400 m and a maximum dune height of 453 m (Niu et al., 2021). At dune bottoms, 110 perennial lakes can be observed, most less than 1 km<sup>2</sup> in size (Wang et al., 2016). Migrating dunes occupy over 80% of the BJD’s total area. Primary dune types include reticulate dunes, transverse megadunes, star dunes, barchan dunes, barchanoid chains, and megadunes. Dune formation is mainly influenced by northwesterly winds, with sand dunes oriented in the NNE (north-northeast) direction of 10°–40° (Ning et al., 2013). The area experiences an extreme continental desert climate, with annual mean air temperature ranging from 9.5°C to 10.3°C, increasing from south to north with decreasing elevation (Dong et al., 2004). Average annual precipitation ranges from 90.1 to 115.4 mm in the southern desert and from 35.2 to 42.9 mm in the northern part. Precipitation is highly concentrated, with over half falling from May to September and generally dominated by light rain (Ma et al., 2011; Wang et al., 2013). Main plant species include *Artemisia ordosica*, *Agriophyllum arenarium*, and *Nitraria tangutorum*.

## 2.2 Wind Data

Wind data were obtained from four meteorological stations in the BJD hinterland (Fig. 2 [Figure 2: see original paper]). Cherigele (CRGL) and Wuertabulage (WETBLG) stations are located in lake basins, while Yikeri (YKR) and Sumujilin (SMJL) stations are located on sand dune tops. Stations used the MAWS-301 model produced by Vaisala, Finland. Wind direction data are expressed by azimuth angles ranging from 0° to 360°. At each observation station, wind data were measured by self-recording anemometers at 10-minute intervals and at 3 m above ground, except for YKR station (measured at 10 m above ground). The wind direction measurement range was 0°–359° with data output every 30 minutes. Data passed quality control inspection. Station locations and measurement durations are listed in Table 1 .

### 2.3.1 Calculation of Sand-Driving Wind Velocity

Threshold velocity required to move sand grains is a fundamental concept in dune geomorphology (Bagnold et al., 1974). This study considered the mean threshold velocity for sand movement at 10 m height to be 6.0 m/s based on Wang et al. (2005). A simplified exponential wind velocity profile formula was used to convert wind velocity at 3 m above ground to velocity at 10 m above ground (Wang et al., 2020). The equation is as follows:

$$U_z = U_1 \left( \frac{z}{z_1} \right)^\alpha$$

where  $U_z$  is wind velocity at height  $z$  (m/s),  $\alpha$  is the shear index (0.12 in desert areas) (Li et al., 2011), and  $U_1$  is wind velocity at height  $z_1$  (m/s). The equation for converting wind velocity from 3 m to 10 m above ground is:

$$U_{10} = 1.15 \times U_3$$

where  $U_{10}$  is wind velocity at 10 m (m/s) and  $U_3$  is wind velocity at 3 m (m/s). Wind velocity data  $\geq 6.0$  m/s were selected and converted to velocity data at 10 m height. Subsequently, 16 azimuths of N, NNE (north-northeast), NE (northeast), ENE (east-northeast), E (east), ESE (east-southeast), SE, SSE (south-southeast), S, SSW (south-southwest), SW (southwest), WSW (west-southwest), W (west), WNW (west-northwest), NW, and NNW (north-northwest) were used to present all sand-driving wind directions. Frequencies of sand-driving winds at different azimuths were calculated, distributions of sand-driving wind directions were analyzed, and monthly and seasonal variations in sand-driving wind velocities were determined. Seasons were divided as follows: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February of the following year).

### 2.3.2 Calculation of the Drift Potential (DP)

We calculated wind energy environment parameters using the method described by Fryberger and Dean (1979). The equations are as follows:

$$DP = (U - U_t)^2 \times t$$

$$C = \sum (DP \times \sin \theta)$$

$$D = \sum (DP \times \cos \theta)$$

$$RDD = \arctan \left( \frac{C}{D} \right)$$

$$RDP = \sqrt{C^2 + D^2}$$

where  $DP$  represents sand-driving wind's ability to transport sand within a time period (vector units, VU),  $U$  is wind velocity above threshold (m/s),  $U_t$  is threshold wind velocity (6.0 m/s in this case, with all velocities converted to knots where 1.0 knot = 0.5 m/s),  $t$  is the proportion of time during which wind velocity exceeds sand-driving wind threshold (%),  $RDD$  is resultant drift direction ( $^\circ$ ) representing sand transport direction,  $C$  and  $D$  are parameters used to calculate  $RDD$ ,  $\theta$  is the angle measured clockwise from  $0^\circ$  (N), and  $RDP$  is resultant drift potential (VU) reflecting net sediment transport capacity. The  $RDP/DP$  ratio represents directional variability, reflecting wind direction combinations in a region.

Sand roses were plotted to represent sand drift patterns, with each rose including arms corresponding to DP from all directions and an arrow reflecting net RDP direction. Wind energy environment classification is shown in Table 2 .

### 3.1 Sand-Driving Wind

Figure 3 [Figure 3: see original paper] shows sand-driving wind roses based on data from four BJD stations (2017-2018). Minimum sand-driving wind frequency (0.8%) was detected at CRGL station, with primary and secondary wind directions being W (27.8%) and WNW (23.9%), respectively. At WETBLG station, sand-driving wind frequency was 1.3%, with dominant NE (17.8%) and secondary N (11.3%) directions. At YKR station, frequency was 9.0%, with primary WNW (31.0%) and secondary W (29.5%) directions. At SMJL station, maximum frequency was 16.4%, with primary NW (29.5%) and secondary WNW (25.7%) directions. Generally, the most common wind direction was NW, making northwesterly winds the main factor causing sand movement toward the SE. WETBLG station recorded northeasterly winds resulting from local circulation caused by thermodynamic contrast between megadunes and lowlands. Due to tall sandy dune barriers, average sand-driving wind velocities at CRGL (6.9 m/s) and WETBLG (6.8 m/s) stations were lower than at YKR (7.5 m/s) and SMJL (8.2 m/s) stations. Annual mean sand-driving wind velocity was highest at SMJL (8.2 m/s) and lowest at WETBLG (6.8 m/s).

Wind directions differed by station and season (Table 3 ; Fig. 4 [Figure 4: see original paper]). Highest sand-driving wind frequencies occurred in spring at CRGL, YKR, and SMJL stations (63.2%, 41.1%, and 34.9% of total frequency, respectively). At WETBLG station, highest frequency occurred in summer (56.4%). Lowest frequencies occurred in winter at WETBLG, YKR, and SMJL stations (1.6%, 16.3%, and 18.6% of total frequency, respectively). At CRGL station, lowest frequency occurred in autumn (5.0%).

Due to local circulation, wind directions at CRGL and WETBLG stations were more complex across seasons. The most common wind direction was NW at most stations in all four seasons. In summer, low pressure dominates large parts of Asia, making desert winds directionally unstable (Breed et al., 1979). Wind direction varied in summer at all stations but was more concentrated in autumn and winter because temperature changes more obviously with height in summer, the specific heat albedo difference between lake and sand surfaces becomes larger, and dominant wind direction is greatly affected by local topography and microclimate. Higher wind velocities occurred in spring or summer, with lower values typically measured in autumn and winter.

Monthly wind velocity and sand-driving wind frequency variations at different observation stations are presented in Figure 5 [Figure 5: see original paper]. Results indicated sand-driving wind velocity peaked in April at CRGL, YKR, and SMJL stations, with average values of 7.0, 8.2, and 9.3 m/s, respectively.

### 3.2 Sand Drift Potential (DP)

DP is the most important and frequently used index for determining wind energy (Lancaster et al., 1995). DP and RDP distributions from meteorological stations are shown in Figure 6 [Figure 6: see original paper]. Results indicated annual DP, RDP, RDD, and RDP/DP ratio differed across stations. DP correlated with both sand-driving wind strength and direction. Maximum DP occurred at SMJL station (288.14 VU), while minimum DP was at CRGL station (3.35 VU). Based on Table 2 criteria, most BJD hinterland areas belonged to low-energy wind environments, except SMJL station (intermediate-energy). High DP values originated mainly from W, WNW, NW, and NE directions. RDP spatially varied among stations, following a pattern similar to DP variation. RDD pointed toward the SE quadrant (ranging from  $97^\circ$  to  $128^\circ$ ), implying sand transport from NW to SE.

The RDP/DP ratio exceeded 0.30 in most desert areas (except WETBLG station), with most areas exhibiting unimodal or bimodal wind regimes. The lowest RDP/DP ratio occurred at WETBLG station (0.24), revealing high directional variability and a complex wind regime.

Sand DP and its direction varied seasonally. Seasonal wind regime shifts would influence sand dune morphology. DP calculations for different seasons showed highest DP values in spring for CRGL, YKR, and SMJL stations (2.14, 49.96, and 156.86 VU, respectively) and in summer for WETBLG station (2.91 VU), with smallest DP values in autumn for all stations (Fig. 7 [Figure 7: see original paper]). RDP was also largest in spring, indicating highest wind activity generally occurs in this season. Wind mostly blew from NW in different seasons at CRGL, YKR, and SMJL stations, whereas the main wind direction was NE at WETBLG station. RDD differed across stations and seasons, but the overall direction was mainly SE. The RDP/DP ratio in summer was lower than in other seasons at all stations, implying wind direction was most variable in summer. Specifically, in summer, low pressure dominates much of Asia, and desert wind becomes weaker and more directionally unstable (Breed et al., 1979). Figure 8 [Figure 8: see original paper] shows monthly DP, RDP, RDD, and RDP/DP ratio values. DP and RDP were highest in April. RDD at each station was concentrated between  $90^\circ$  and  $180^\circ$ , indicating sand transport toward the SE. The RDP/DP ratio exceeded 0.30 at all stations each month, with low to intermediate directional variability.

### 3.3 Sand Dune Morphology

Morphological characteristics of sand dunes are key to understanding their types. Google Earth provides fine spatial resolution images that can be used to calculate dune pattern parameters, including dune orientation and spacing, using geographical information system software. Examples were selected where winds measured at meteorological stations were representative of regional wind environments. Figure 9 [Figure 9: see original paper] shows Google Earth images

of representative transverse sand dune types at the four stations.

Transverse dunes were the most dominant and widespread dune types in the study area, indicating unlimited positive sand supply sources. Transverse dune intervals at CRGL station were 20–30 m, with dune direction perpendicular to RDD. Transverse dunes at WETBLG station showed NE–SW trends, being nearly parallel to RDD with 18–30 m intervals. At YKR station, transverse dunes trended N–S, nearly perpendicular to RDD. At SMJL station, transverse dunes appeared as secondary dunes superimposed on star dunes. Star dunes formed earlier, while transverse dunes formed later. SMJL station wind regimes could only explain the secondary transverse dunes, not the star dunes. The windward slope was convex and gentle while the leeward slope was concave and steep. Distance between sand dunes was 15–20 m. Sand dune ridgeline orientation was  $210^{\circ}$ – $225^{\circ}$ , with the angle between dune crests and RDD being  $82^{\circ}$ – $97^{\circ}$ , vertical to sand transport potential direction.

#### 4 Discussion

Wind activity involved in sand transport differed across meteorological stations, partially attributed to local topography, peripheral sand dune barrier functions, and surface variations underlying the stations. The latter factor may be significant because CRGL and WETBLG stations were within semi-closed depressions while YKR and SMJL stations were on higher-elevation sand dunes. Topographical variations can accelerate, decelerate, or otherwise control near-surface air or wind-blown sand flow, thereby controlling sediment transport (Xiao et al., 2015).

Previous studies showed that lake basin zone airflows are accelerated by megadunes (Wilson, 1973; Wang et al., 2016). Megadunes influenced wind regimes at lake basin stations in two ways. First, megadunes greatly weakened wind force and exerted considerable physical blocking and thermodynamic effects. Stations positioned between megadunes were clearly affected by secondary flows and sheltering effects. Second, megadunes changed wind velocity and direction near lakes, concentrating sand flow activities mainly on megadunes. Therefore, local circulation caused by thermodynamic contrast between megadunes and lakes influenced wind regimes (Zhang et al., 2013a, 2017). Specifically, sand reflectivity was higher than lake water reflectivity (0.30 and 0.25, respectively), and lake water specific heat was approximately 4.35 times that of sand ( $0.97 \times 10^3$  J/(kg · °C) for sand vs.  $4.20 \times 10^3$  J/(kg · °C) for lake water). These marked differences in reflectivity and specific heat altered air temperature and pressure fields, increasing local circulation (Zhang et al., 2013a, b). Thus, wind velocities and directions recorded at lake basin stations (CRGL and WETBLG) differed from those recorded at dune top stations (YKR and SMJL). Dominant wind directions on dune tops were W and NW, while lake basin stations recorded more complex directions, mostly W, NW, and NE. Sand-driving wind frequency and average velocity at lake basin stations were lower than at dune top stations, indicating stronger wind

activity intensity at dune top stations.

During the observation period in the BJD hinterland, sand-driving wind frequency, average wind velocity, and sand DP height were greatest in spring, making spring the main season for wind activities. This agrees with seasonal changes in BJD surrounding areas and most sandy areas in northern China (Dong et al., 2004; Wang et al., 2015; Zhang et al., 2015; Tian et al., 2021). Research on wind regimes surrounding the BJD showed prevailing wind directions were NW and NE on northwestern and northeastern desert edges, respectively, and SE in eastern and southeastern parts (Liu et al., 2010; Zhang et al., 2015). Although the BJD contains China's largest megadunes, it is not the region with strongest sand transport activity among Chinese deserts (Wang et al., 2005). Most BJD areas are characterized by low-energy wind environments, with high-energy environments occurring only in some northern parts (Guaizi Lake and Bayinnuoergong) (Dong et al., 2004; Zhang et al., 2015). This study showed the desert hinterland was dominated by westerly, northwesterly, and northeasterly winds. DP ranged from 135.58 to 288.14 VU at dune top stations, higher than in western (73.8–116.4 VU) and northern (90.6 VU) parts but lower than in southern (168.7–286.3 VU) and northeastern (448.2–733.4 VU) parts (Zhang et al., 2015). Most hinterland areas are in low-energy wind environments, consistent with surrounding desert wind environments. These observations agree with Lancaster et al. (2013), who reported major global sand seas formed in low-energy wind environments, suggesting BJD dunes formed under such conditions that favored long-term sand deposition. Wind direction variability at most stations exceeded 0.30, representing low to medium variability. RDD was SE, consistent with sand transport direction in other desert areas and overall dune movement direction (Chen et al., 2011).

Complex local and regional wind regimes control sand dune pattern variations (Yang et al., 2020). Fryberger et al. (1979) suggested barchan chains and transverse dunes are generally associated with unimodal wind regimes (higher RDP/DP ratios), indicating lower wind direction variability. Wind regimes at CRGL, YKR, and SMJL stations correlated with local sand dune types. WETBLG station showed highly variable wind direction, with high directional variability (RDP/DP = 0.24) and RDD reflective of transverse dune differences. Dune morphology at WETBLG station was not closely related to wind regimes, possibly because sand dunes are small and cannot truly reflect wind regimes. However, this is not the only study showing weak relationships between dune morphology and wind regimes. Some previous studies demonstrated most Chinese sandy desert dunes are transverse and linear, usually consistent with wind regimes (e.g., Wang et al., 2005), while other deserts show no close relationship between dune morphology and regional wind direction distribution (e.g., Wang et al., 2005). Wind regimes, in conjunction with vegetation and sand supply, affect overall dune morphology (Wasson and Hyde, 1983; Gao et al., 2015). Figure 9 shows almost no vegetation at all stations, indicating wind regimes and sand availability are key factors for dune geomorphology development. BJD sand sea sediments originated mainly from Quaternary and modern alluvial-lacustrine

deposits from the Heihe River drainage system and fine sediment from Gulunai Lake grassland (Dong et al., 2004; Zhang et al., 2015). However, this study did not discuss sand supply due to lack of detailed data.

$^{14}\text{C}$  dating of rhizoconcretions from beneath megadunes (Yang et al., 2000) and organic sediments from lake floors (Yang et al., 2003) showed megadune and lake ages (e.g., SMJL lake) are  $31,750 (\pm 485)$  and  $8390 (\pm 30)$  BP, respectively, indicating long-term harmonious lake-dune coexistence. This pattern appears in most global deserts, including 422 lakes in China's Tengger Desert (Yan et al., 2001), Lake Frome in Australia's Strzelecki Desert (Fitzsimmons et al., 2007), Dunhuang Oasis's Crescent Moon Spring (Zhang et al., 2013b), Kumtag Desert's Crescent Moon Spring (Li et al., 2014), and Sahara Desert's Lake Qarun (Wahed et al., 2015). Lake-megadune coexistence in desert environments is controlled not only by groundwater but also by local circulation where wind can blow sand between lakes and megadunes. First, in lake basins, relative relief between megadunes and inter-dunes generates mountain-valley winds. Specifically, air is heated mainly by long-wave radiation from the ground. During daytime, air above mountain slopes obtains more heat from sandy surfaces than air in valleys at the same height, causing mountain-slope air to rise faster than valley air, creating low pressure near mountain surfaces and relatively high pressure near valley surfaces. Pressure differences generate valley winds; the opposite occurs at nighttime (Zhang et al., 2017). Second, local circulation arises from thermodynamic property differences between lakes and megadunes. Wind blows from lakes to megadunes during daytime and from megadunes to lakes at nighttime (Zhang et al., 2013a, b). Lake-land breeze and valley breeze have superposition effects, and local circulation may be enhanced by coupling between lake-land breeze and megadune valley breeze. Furthermore, lake warm and cold effects influence local circulation (Zhang et al., 2014). Third, aeolian sand transport balance is controlled by alternating daytime, nighttime, and seasonal wind directions, which determine lake survival or extinction. In different seasons, wind alternately offsets faint local wind erosion and related deposition phenomena, resulting in overall stable and balanced landscape dynamics. This phenomenon is influenced by local terrain, regardless of wind direction relative to annular sand hills that create whirlwinds, slide sand ridges, and mountain-top conditions. This characteristic of sandstorm activity makes the sand-lake relationship symbiotic. Sandstorm activities around lake stations were weak, reducing sand quality entering lakes. Weakening wind activities from dune tops to lake basins affected aeolian sand deposit spatial distribution and prevented lakes from being buried by mobile dunes. This indirectly explains BJD lake-dune coexistence, which affects sand mountain height maintenance (Dong et al., 2013), though these effects' patterns and extents require further study. In summary, although local circulation and wind regime effects on lakes and megadunes provide means to interpret lake-dune pattern coexistence, more evidence is needed for full understanding.

To control wind-blown sand damage, near-surface wind regime characteristics must be understood. Precipitation at CRGL and SMJL stations was 76.7

and 95.7 mm in summer (June–August), accounting for 79.1% and 67.7% of annual precipitation, respectively. Thus, BJD precipitation is mainly concentrated in summer. This area is dominated by desert vegetation such as *Nitraria tangutorum* and *Artemisia sphaerocephala*. This study showed wind activity was greatest in spring. Differences in wind-sand activities and precipitation across time periods, plus lower vegetation cover, have aggravated desert sandstorm frequency and intensity (Pang et al., 2020). Future research should focus on sandstorm disaster prevention, especially in spring. The desert was dominated by two major wind systems (NW and NE). Strong, frequent NW winds were the dominant factor causing SE sand transport. Therefore, local sand transport direction must be considered when establishing engineering measures like sand barriers and shelterbelts during windbreak and sand fixation system construction in the BJD.

## 5 Conclusions

This study analyzed wind regimes in the BJD hinterland and associated sand dune types, discussing correlations between dune morphology and wind regimes using Google Earth images and meteorological observations. Results showed sand-driving wind frequency accounted for 0.8%–16.4% of total annual wind frequency. Sand-driving wind varied notably seasonally and monthly, occurring mostly in spring. Annual average DP values at four meteorological stations ranged from 3.35 to 288.14 VU. Most areas can be classified as low-energy wind environments. The main wind direction controlling dune formation was NW. Except for WETBLG station, all other stations exhibited low or intermediate annual directional wind variability and unimodal or bimodal wind regimes. DP and RDP varied seasonally, with spring being the main season of wind activity. RDD differed across stations and seasons, but the overall direction was SE. Due to sandy mountain barrier functions and local circulation, sand transport activity was weaker in lake basins than on dune tops. Sand transport activity in the desert hinterland correlated with surrounding deserts. Transverse dunes were the most dominant dune types in the study area. Overall, wind regimes were consistent with sand dune types; therefore, wind was the main dynamic factor affecting sand dune formation and development.

This research's novelty lies in analyzing wind regimes in a desert hinterland representing sand dune wind environments. The work revealed local circulation effects on sand transport between lakes and megadunes, indicating more attention should be paid to local circulation in dune geomorphology research. This study provides new BJD wind regime data for analyzing sand dune formation and development. Although preliminary results are provided, further studies are needed. Effects of local topography, vegetation cover, sand particle size, and other factors on sand transport activity intensity should be analyzed in detail. Additionally, research should focus on measures to control sand damage to desert oases by considering wind regime characteristics, providing a theoretical basis for desert ecosystem restoration and protection.

**Acknowledgements:** This research was funded by the National Natural Science Foundation of China (41871021) and the Desert and Glacier Field Scientific Observation and Research Station of Lanzhou University (lzujbky-2021-sp16). We thank Prof. ZHANG Zhengcai and Prof. CHENG Hongyi for helpful comments and suggestions.

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