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## Near-surface wind field characteristics of the desert-oasis transition zone in Dunhuang, China postprint

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### Abstract

The desert-oasis transition zone (DOTZ) functions as a buffer area between desert and oasis environments. Understanding its wind field characteristics is crucial for the prevention and control of aeolian disasters in oases. In this study, meteorological data from 2013-2019, collected by portable meteorological stations at five sites (site A at the oasis edge, sites B, C, and D within the DOTZ, and site O in the desert) in Dunhuang, China, were utilized to analyze near-surface wind field characteristics and their underlying causes, and to elucidate the critical protective role of the DOTZ. The results demonstrated that mean wind speed, sand-driving wind frequency, and wind directional variability decreased from west to east within the DOTZ, with wind speed being significantly influenced by air temperature. Terrain features affected regional prevailing winds, which originated primarily from the northeast and southwest. Only certain areas adjacent to the oasis were dominated by southeasterly winds. These findings indicate that near-surface wind field characteristics in the DOTZ arise from the combined effects of local terrain and surface hydrothermal differences. At site D, the annual drift potential (DP) was 24.95 vector units (VU), indicating a low wind energy environment, while the resultant drift direction (RDD) exhibited pronounced seasonal variations. Furthermore, the DOTZ played a crucial buffering role between desert and oasis. Compared to the desert, mean wind speed in the oasis decreased by 64.98%, with prevailing wind directions becoming more concentrated. The results of this study will be valuable for interpreting aeolian activity in the Dunhuang DOTZ.

## Full Text

### Preamble

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### Near-surface wind field characteristics of desert-oasis transition zone in Dunhuang, China

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## Abstract

The desert-oasis transition zone (DOTZ) serves as a critical buffer area between desert and oasis ecosystems. Understanding its wind field characteristics is of great significance for the prevention and control of aeolian disasters threatening oasis stability. In this study, we analyzed meteorological data from 2013-2019 collected at five portable meteorological stations in Dunhuang, China: site A on the oasis edge, sites B, C, and D within the DOTZ, and site O in the desert. Our analysis focused on near-surface wind field characteristics, their underlying causes, and the key protective role of the DOTZ. Results showed that mean wind speed, frequency of sand-driving wind, and directional variability all decreased from west to east within the DOTZ, with wind speed significantly influenced by air temperature. Regional terrain shaped the prevailing wind directions, which were primarily from the northeast and southwest, though some areas adjacent to the oasis experienced southeasterly winds. This indicates that near-surface wind field characteristics in the DOTZ result from combined effects of local terrain and surface hydrothermal differences. At site D, the annual drift potential (DP) was 24.95 vector units (VU), indicating a low wind energy environment, while the resultant drift direction (RDD) exhibited obvious seasonal differences. The DOTZ played an important buffering role between desert and oasis: compared with the desert, mean wind speed in the oasis decreased by 64.98%, and prevailing wind directions became more concentrated. These results will be useful for interpreting aeolian activity in the Dunhuang DOTZ.

**Keywords:** desert-oasis transition zone; near-surface wind field; hydrothermal difference; sand-driving wind; aeolian environment; Dunhuang

## 1 Introduction

Oases are unique landscapes distributed along the margins of deserts and Gobi regions in arid and semi-arid areas worldwide, providing essential water resources and living spaces for local people, plants, and animals [?, ?]. The desert-oasis transition zone (DOTZ) refers to the narrow strip of land surrounding the periphery of an oasis, lying between desert and oasis ecosystems. This zone serves as a critical link for interaction and transformation between these two systems [?, ?, ?] and plays a vital role in maintaining oasis ecosystem stability while preventing aeolian erosion [?, ?, ?]. However, climate change and human activities have intensified aeolian activity and increased desertification risk in some DOTZs, thereby weakening their protective and buffering effects on oases [?]. Understanding the aeolian environment of the DOTZ and implementing effective aeolian disaster prevention and control measures are therefore necessary to ensure oasis ecological security.

Previous DOTZ research has primarily focused on soil physical and chemical properties [?, ?], plant communities [?, ?, ?, ?], microclimate [?, ?], and hydrology [?, ?]. Although many studies have comprehensively evaluated the ecological effects of DOTZs, research on their aeolian environment remains relatively scarce.

Near-surface wind field characteristics, particularly wind speed and direction, are key factors in aeolian environmental research. They not only control the development of aeolian geomorphology but also profoundly impact sand flow transport processes [?, ?]. Many researchers have used near-surface wind field characteristics to evaluate regional aeolian environmental status and evolution patterns [?, ?, ?]. For example, Zu et al. [?] studied the near-surface wind field of the Taklimakan Desert and found prevailing winds from the northeast (NE) and northwest (NW), with local wind regimes showing unimodal or bimodal features. Liu et al. [?] supplemented this work, indicating that wind speed has decreased most significantly in spring and in the eastern part of the desert since 1965, with drift potential (DP) changes primarily controlled by winds from NW, north (N), and NE. Cui et al. [?] analyzed temporal variations in the near-surface wind field of the Mu Us dune field, revealing generally decreasing wind speeds during 1960–2014, especially in autumn and winter, along with reduced DP. These studies have focused on large-scale regions such as deserts; however, small-scale regions with special landscapes have rarely been studied, despite exhibiting significant differences in near-surface wind field characteristics compared with large-scale regions.

In large-scale regions, the near-surface wind field is primarily controlled by atmospheric circulation and surrounding terrain, which affect the aeolian environment and local landforms [?, ?, ?]. In contrast, the near-surface wind field in small-scale regions is mainly influenced by local terrain and hydrothermal characteristics, which in turn affect local aeolian activity [?]. Changes in aeolian activity characteristics may increase aeolian disaster risk; therefore, research

in these regions should focus on understanding these characteristics and implementing appropriate preventive measures [?].

Dunhuang is a historic city in Gansu Province and an important hub on the Silk Road, home to world-class cultural and natural heritage sites including the Mogao Grottoes, Mingsha Mountain, and Yardangs that attract numerous tourists and researchers [?, ?, ?]. The natural landscape of Dunhuang comprises desert, oasis, and DOTZ, with the DOTZ having a decisive impact on urban development and landscape patterns [?, ?, ?]. The DOTZ serves as a special landscape between desert and oasis that can effectively protect the oasis and prevent desert aeolian invasion [?, ?]. In recent years, Dunhuang has faced severe ecological problems due to climate change and human activities, which have caused frequent strong winds and sandstorms, leading to oasis shrinkage and desertification intensification that threaten local residents and natural and cultural heritage [?, ?, ?]. In this context, the DOTZ plays a crucial role as both a natural barrier restraining aeolian activity invasion and a preferred location for future oasis expansion and desert transformation, providing possibilities for Dunhuang' s ecological civilization construction [?, ?, ?]. Therefore, studying near-surface wind field characteristics of the Dunhuang DOTZ is key to exploring the aeolian environment and revealing the protective effect of the DOTZ on the oasis.

Many researchers have studied the aeolian environment in Dunhuang. Shen et al. [?] conducted a detailed comparative analysis of main wind erosion factors affecting dust emissions using observational data from the Gobi desert and oasis, showing that different cropland types had different dust emission rates, with plowed croplands emitting hundreds of times more dust than the Gobi desert. Li et al. [?] evaluated responses of three typical plant species to wind erosion in the Mogao Grottoes shrub zone, indicating that the optimal shrub configuration for resisting wind erosion consists of two parallel rows perpendicular to the main wind direction. Zhang et al. [?] verified star dune development on Mingsha Mountain using long-term observational data, showing that topographic barrier was the main reason for complex mega-dune formation. Additional scholars have conducted in-depth studies on landscape changes [?] and dynamic dune changes [?, ?] in Dunhuang' s desert and oasis.

While previous studies have yielded important results regarding Dunhuang' s aeolian environment, comprehensive meteorological data have been lacking, causing research on the DOTZ aeolian environment to be largely overlooked. This knowledge gap has limited our understanding of aeolian processes in the DOTZ and their effects on oasis protection, compromising the effectiveness of local wind-blown sand control measures. Therefore, we conducted a detailed analysis of the near-surface wind field in the DOTZ based on observed meteorological data to fill this gap. Exploring the influence of DOTZ wind field characteristics on the aeolian environment will not only help protect the oasis but also provide valuable insights for sand-blown control strategies in other similar areas.

The specific aims of this study were to: (1) analyze near-surface wind field

characteristics and causes in the Dunhuang DOTZ to systematically evaluate its aeolian environment; and (2) reveal the key role of the DOTZ in oasis protection. The results will be useful for interpreting aeolian activity in the DOTZ and providing guidance for prevention and mitigation of aeolian sand hazards in the Dunhuang oasis.

## 2.1 Study Area

Dunhuang is an important segment of the Hexi Corridor, located in northwestern China (92°15' -95°30' E, 39°40' -41°35' N; Fig. 1a [Figure 1: see original paper]), covering an area of approximately  $3.12 \times 10^4$  km<sup>2</sup>. It is flanked by Mingsha Mountain to the south (S) and the oasis to the north (N), where elevation is low and forests and towns are distributed. Terrain decreases from south to north, with a mean elevation of approximately 1100 m. The climate is continental and arid, with scarce and uneven precipitation throughout the year. Mean annual precipitation is less than 40 mm, while mean annual evaporation reaches 2488 mm. Strong winds and sandstorms are frequent and intense, particularly in spring. Natural vegetation is sparse and dominated by *Alhagi sparsifolia*, *Haloxylon ammodendron*, *Caragana korshinskii*, and *Populus euphratica*.

## 2.2 Data Sources

Meteorological data from 2013 to 2019 were obtained from five portable meteorological stations located in the desert, oasis, and DOTZ of Dunhuang. The desert and oasis each had one station, while the DOTZ had three stations. All portable meteorological stations were produced by HOBO (Onset, USA). To evaluate near-surface wind field characteristics and causes of the DOTZ and reveal its key role in oasis protection, we selected five sites corresponding to the station locations: site A on the oasis edge; sites B, C, and D within the DOTZ; and site O in the desert. Vegetation coverage declined markedly along the oasis-desert gradient at each site (Fig. 1b1-b3). All stations were erected at 2.0 m above ground surface in flat, open terrain. Wind cups and vanes measured wind speed and direction from 16 directions: N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, and NNW. Data were collected at 10-min intervals and averaged daily, with accuracies of 0.10 m/s and 3°. We used complete-year meteorological data (1 January 2016 to 31 December 2016) to calculate mean air temperature, mean wind speed, sand-driving wind, and DP. To ensure data quality, we removed outliers based on previous studies in this area [?, ?, ?] and used linear interpolation with meteorological data from other years to fill missing values.

## 2.3 Calculation of the Data

Using air temperature and wind data from the portable stations, we calculated mean wind speed, mean air temperature, and sand-driving wind in the desert,

oasis, and DOTZ at different time scales. We also estimated DP for each DOTZ site across time scales.

The threshold wind speed for sand movement, generally referred to as sand-driving wind, is an important parameter reflecting regional wind conditions [?, ?]. The desert, oasis, and DOTZ in Dunhuang have small spatial scales with no significant difference in threshold sand-driving wind speed among them [?, ?]. Therefore, we set the threshold sand-driving wind speed to 5.00 m/s for all sites.

DP is a key parameter indicating the potential maximum sand transport rate expressed in vector units (VU), reflecting wind energy environment in a specific area [?, ?, ?, ?]. We used the formula proposed by Fryberger and Dean [?] for calculating DP:

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

where  $DP$  is drift potential (VU);  $V$  is sand-driving wind speed at 2 m height (m/s);  $V_t$  is threshold sand-driving wind speed (m/s); and  $t$  is duration of sand-driving wind, usually calculated by frequency (%). Classification criteria for wind energy environment are listed in Table 1 .

Resultant drift potential ( $RDP$ ; VU) and resultant drift direction ( $RDD$ ; °) are vector sums of DP and direction for each azimuth, respectively. The formulas are as follows [?]:

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

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

where

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

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

$C$  and  $D$  are parameters for calculating  $RDP$  and  $RDD$ , respectively; and  $\theta$  is the angle measured clockwise from 0° (N), in degrees.

Additionally, the ratio  $RDP/DP$  is regarded as an important indicator for describing directional variability of wind [?, ?]. Classification criteria for directional variability are listed in Table 1.

**Table 1** Classification criteria of wind energy environment and directional variability of wind

Wind energy environment	Directional variability
High: >400 VU	Narrow: RDP/DP >0.8
Intermediate: 200-400 VU	Intermediate: 0.3-0.8
Low: <200 VU	Wide: <0.3

*Note: Classification criteria based on Fryberger and Dean (1979). DP, drift potential; VU, vector units; RDP, resultant drift potential.*

## 2.4 Statistical Analysis

We calculated all parameters using Excel according to the above formulas. Linear regression analysis explored correlations between mean air temperature and mean wind speed, performed using Origin 2021 (OriginLab, Northampton, USA). Figures were created using ArcMap 10.7 (Esri, Redlands, USA), Surfer 15 (Golden Software, Golden, USA), and Origin 2021.

## 3.1 Mean Air Temperature

Figure 2 [Figure 2: see original paper] shows mean annual air temperature across the DOTZ and surrounding sites. Temperatures ranged between 11.4°C and 13.0°C, with the highest values in the desert and lowest in the DOTZ. The central DOTZ formed a low-temperature center for the region. Most areas exhibited temperatures below 13.0°C with small spatial variation (1.6°C difference). However, isotherm density analysis revealed denser spacing between desert and DOTZ than between oasis and DOTZ, indicating a smaller temperature difference between oasis and DOTZ. The temperature increase relative to the low-temperature center was less than 0.5°C.

Local temperature distribution resulted from combined effects of oasis effect, urban heat island effect, and other factors. The oasis effect, arising from hydrothermal differences between desert and oasis surfaces, causes heat transfer from desert to oasis [?, ?, ?], significantly reducing oasis air temperature relative to desert [?]. However, rapid urbanization in Dunhuang, accompanied by population growth and industrial activities, influenced the desert-oasis hydrothermal difference [?, ?]. The urban heat island effect exacerbated this contrast, considerably weakening the oasis effect and making oasis temperature declines less noticeable [?, ?]. Furthermore, the DOTZ's adjacency to the Danghe River (Fig. 1) created a regulatory effect that slowed local air temperature increase, making it the coldest area in the region [?, ?]. This caused near-surface air pressure in the DOTZ to be higher than surrounding areas, forming convection due to uneven pressure gradients that generated airflow diverging from the DOTZ to surrounding areas [?].

### 3.2 Mean Wind Speed

Wind speed showed a gradually decreasing trend from west to east in the DOTZ, with large spatial differences (Fig. 3 [Figure 3: see original paper]). Mean annual wind speed at site B (westernmost DOTZ) was 3.39 m/s, 1.64 m/s higher than at site D (easternmost DOTZ, 1.75 m/s). This pattern related to local air temperature distribution. As previously shown, hydrothermal differences significantly affected temperature distribution across desert, oasis, and DOTZ, as well as the near-surface wind field environment. Site D's proximity to the oasis meant that the oasis's regulatory effect lowered its hydrothermal difference and wind speed, consistent with Liu et al. [?]. The region exhibited large spatial variation in mean annual wind speed: desert values reached 2.97 m/s, while oasis values were only 1.04 m/s. Wind speed is an important indicator for characterizing dynamic wind environments [?]. This phenomenon was influenced by both oasis-desert microclimate effects and DOTZ blocking effects, which together effectively weakened wind speed, resulting in a 64.98% reduction in mean annual wind speed [?, ?, ?, ?].

To further explore wind speed-temperature relationships, we fitted mean monthly wind speed against mean monthly air temperature at sites A, D, and O (oasis, DOTZ, and desert, respectively; Fig. 4a [Figure 4: see original paper]). The oasis correlation coefficient was only 0.09, while desert and DOTZ coefficients exceeded 0.50, with wind speed showing slight increasing trends with temperature. This indicated no obvious correlation between wind speed and temperature from desert to oasis. Fitting data for DOTZ sites B, C, and D (Fig. 4b) yielded correlation coefficients of 0.69, 0.88, and 0.54, respectively, indicating that DOTZ wind speed tended to increase with air temperature, most significantly at site C. Although site D displayed the highest slope, its fit was poorest, likely due to proximity to the oasis.

A plausible explanation is that local microclimates of both desert and oasis influenced wind speed, with the oasis deepening differences through modulation [?, ?, ?]. This suggests a “wind-heat synchronization” phenomenon similar to desert interiors occurred in the DOTZ [?, ?]. Thus, hydrothermal difference was the main factor causing wind speed changes in the DOTZ. In contrast, although wind speed decreased from desert to oasis, it showed no significant correlation with air temperature, making the DOTZ the primary factor determining wind speed. This underscores the DOTZ's effectiveness in mitigating potential aeolian hazards [?, ?].

### 3.3 Sand-driving Wind

Sand-driving wind roses for Dunhuang's desert, oasis, and DOTZ are shown in Figure 5 [Figure 5: see original paper]. In the DOTZ, sand-driving wind frequency decreased gradually from west to east. At site B (westernmost DOTZ), frequency was 29.80%, while at site D (easternmost DOTZ), it was only 6.00%. Frequency also differed significantly along the north-south direction: annual

sand-driving wind events numbered 10,676 in the desert, 3,007 in the DOTZ, and 1,842 in the oasis. Compared with the desert, the oasis experienced an 82.75% reduction in sand-driving wind events, demonstrating the DOTZ' s important buffering role in oasis protection and its effectiveness in reducing regional aeolian activity intensity.

Wind direction in the desert, oasis, and DOTZ is an indispensable indicator for evaluating local near-surface wind field environments. While local airflow was mainly driven by hydrothermal differences between underlying surfaces, causing divergence from the DOTZ to both desert and oasis, actual wind direction was more complex due to local terrain influences [?, ?]. Vegetation in the DOTZ and forests/buildings in the oasis greatly increased surface roughness, significantly weakening wind speed [?, ?, ?], resulting in minimal northwesterly wind impact across most DOTZ areas. Additionally, sandy hills on the southern side blocked winds from that direction. Consequently, only site D at the DOTZ' s eastern end was significantly affected by southeasterly winds, while other sites were mainly influenced by NE and SW winds. However, site D' s proximity to the oasis meant vegetation disturbance and obstruction made it less affected by northeasterly winds [?]. The DOTZ' s good blocking effect led to single prevailing wind directions for both desert (southeasterly) and oasis (easterly) [?].

Wind direction differences between the DOTZ and adjacent areas were reflected in frequency distributions at each site. Table 2 presents frequencies for two wind direction groups (E+SE+SSE and S+SW+WSW) across sites A, D, and O from north to south, and two groups (NE+ENE and SW+WSW) across sites B, C, and D from west to east. Results showed significant easterly wind frequency decreases from north to south, while southerly wind frequency increased in the opposite direction. From west to east in the DOTZ, northeasterly wind frequency decreased while southwesterly wind frequency increased significantly.

**Table 2** Changes in prevailing wind directions in the study area

Location	E+SE+SSE (%)	S+SW+WSW (%)	NE+ENE (%)	SW+WSW (%)
Site A	45.2	12.8	-	-
Site D	38.7	18.5	-	-
Site O	32.1	25.3	-	-
Site B	-	-	28.4	15.2
Site C	-	-	22.1	21.7
Site D	-	-	16.8	28.9

*Note: E, east; SE, southeast; SSE, south-southeast; S, south; SW, southwest; WSW, west-southwest; NE, northeast; ENE, east-northeast.*

Based on previous analysis, site D' s wind energy environment between desert and oasis can reflect DOTZ conditions, revealing its key role in oasis protection. Annual and seasonal DP variations from 2013-2019 (Fig. 6 [Figure 6: see

original paper]) show a low annual DP of 24.95 VU, indicating a low wind energy environment. Seasonal DP ranged from 2.98 to 9.47 VU, highest in spring (9.47 VU) and lowest in winter (2.98 VU). Both spring and winter DP values indicated low wind energy environments, showing that seasonal DP differences in the DOTZ were not significant. RDP at site D showed no clear seasonal differentiation, with only 2.32 VU difference between maximum and minimum values. However, RDD showed significant seasonal differences:  $8.0^\circ$  and  $37.5^\circ$  in summer and winter, respectively, and  $338.4^\circ$  and  $356.7^\circ$  in spring and autumn, respectively. This indicated southwesterly sand drift directions in summer and winter, but southeasterly directions in spring and autumn.

To further examine wind direction combinations within the DOTZ, we analyzed inter-annual and seasonal RDP/DP trends at sites B, C, and D. Figure 7 [Figure 7: see original paper] depicts RDP/DP changes across time scales. Analysis revealed that RDP/DP gradually increased from west to east in the DOTZ. At site B (westernmost), annual RDP/DP was 0.23, indicating high directional variability, while at site D (easternmost), it was 0.43, indicating intermediate variability. Significant seasonal differences in RDP/DP distribution were observed: sites B and C displayed large seasonal variations, while site D remained relatively constant across seasons. For instance, site C's RDP/DP was 0.22 in summer (high variability) and 0.46 in autumn (intermediate variability), whereas site D's values remained between 0.30 and 0.60 in all seasons (intermediate variability). Overall, directional variability in the DOTZ showed significant temporal differences and a clear increasing trend along the east-west direction, closely related to increasing surface roughness and blocking effects of sandy hills [?, ?, ?].

## 4 Conclusions

This study fills a gap in understanding the aeolian environment of the DOTZ and its key role in oasis protection by analyzing near-surface wind field characteristics in Dunhuang based on 2013-2019 meteorological data. Wind patterns within the DOTZ exhibited a distinct spatial gradient from west to east, characterized by decreasing wind speed, sand-driving wind frequency, and directional variability at eastern sites. Wind speed was positively correlated with air temperature and influenced by surface hydrothermal differences. Sand hills, forests, and buildings on both sides of the DOTZ modified the near-surface wind field, mitigating northwesterly wind impacts while enhancing influences from NE and SW winds. Consequently, prevailing regional winds were from NE and SW, though southeasterly winds primarily affected areas adjacent to the oasis. The near-surface wind field in the DOTZ was thus shaped by combined effects of surface hydrothermal differences and local terrain. The region generally showed a low wind energy environment. Compared with the desert, the oasis experienced significant reductions in mean wind speed (64.98%) and annual sand-driving wind events (82.75%). Wind speed-air temperature fitting results for desert and oasis showed that temperature was not the main factor influencing wind

speed variation between them; rather, effective DOTZ blocking caused wind directions to exhibit relative uniformity, with southeasterly winds prevailing in the desert and easterly winds in the oasis. Therefore, the DOTZ acted as a vital buffer between desert and oasis.

Although this study obtained important results regarding near-surface wind field characteristics of the Dunhuang DOTZ, several scientific issues require future investigation. First, systematic analysis of the DOTZ' s impact on near-surface wind field characteristics of both desert and oasis is needed. Second, suitable wind-blown sand control systems should be designed to protect the oasis based on the DOTZ' s aeolian environment.

### **Conflict of interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### **Author contributions**

Conceptualization: PAN Jiapeng, ZHANG Kecun; Methodology: PAN Jiapeng, ZHANG Kecun, AN Zhishan, ZHANG Yu; Formal analysis: PAN Jiapeng, ZHANG Kecun, AN Zhishan, ZHANG Yu; Writing - original draft preparation: PAN Jiapeng, ZHANG Kecun; Writing - review and editing: PAN Jiapeng, ZHANG Kecun; Funding acquisition: ZHANG Kecun; Resources: ZHANG Kecun, AN Zhishan, ZHANG Yu; Supervision: ZHANG Kecun, AN Zhishan. All authors approved the manuscript.

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