



Multi-level tower estimates of friction velocity in the Taklimakan Desert: sensitivity to height selection, wind direction, and causal controls

Yifei Wang^{1,2,3,4,5} Wen Huo^{1,3,4,5}, Mayibaier Maihamuti^{1,2,3,4,5}, Yisilamu Wulayin^{1,3,4,5}

¹Institute of Desert Meteorology, China Meteorological Administration, Urumqi 830002, China

²Xinjiang Branch of China Meteorological Administration Training Centre, Urumqi 830013, China

³National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang, Urumqi 830002, China

⁴Taklimakan Desert Meteorology Field Experiment Station, China Meteorological Administration, Urumqi 830002, China

⁵Xinjiang Key Laboratory of Desert Meteorology and Sandstorm, Urumqi 830002, China

Corresponding author: Wen Huo (huowenpet@idm.cn)

Abstract. Friction velocity (u^*) underpins estimates of dust emission, but profile-derived values may depend on measurement height, wind direction and site conditions. We analysed multilevel tower observations from Tazhong (TZ) and Xiaotang (XT) during March–July 2024, together with ERA5 data and convergent cross mapping (CCM). TZ had greater terrain ruggedness than XT (TRI, 3.0 versus 1.4) and a slightly higher mean daily u^* (0.24 versus 0.21 m s^{−1}). The monthly maximum frequency of hourly u^* above 0.30 m s^{−1} was 57.23% at TZ and 48.46% at XT. Across seven height configurations, H01 (1, 2, 4, 10 and 20 m) gave the lowest RMSE and highest Pearson correlation for both fitting approaches. Against an ERA5-derived neutral-profile reference, finite-L H01 fits had RMSEs of 0.186 and 0.191 m s^{−1} at TZ and XT, respectively, with correlations of 0.195 and 0.261. Neutral-only H01 fits had RMSEs of 0.118 and 0.129 m s^{−1} and correlations of 0.396 and 0.417. Directional differences were more pronounced at TZ, where the high-level H05 configuration generally produced larger median u^* than lower-level configurations across wind sectors. CCM cross-map skill for 10 m wind speed was similar at both sites (maximum $\rho = 0.24$), whereas net-radiation skill was higher at TZ (0.44) than XT (0.25). Surface–air temperature contrast showed a similar site difference (0.38 versus 0.22), while air–temperature contrast was comparable (0.40 at both sites). These results show that height configuration and wind direction shape profile-derived estimates, while thermal associations vary between sites.

1 Introduction

Dust storms are among the most destructive natural hazards in arid and semi-arid regions, posing substantial threats to ecosystems and human society. They can intensify soil erosion, suppress vegetation growth, and accelerate land degradation and desertification, thereby perturbing regional ecosystem structure and functioning (Z. Dong et al., 2020; Lee & Gill, 2015; Middleton, 2017). Dust-related air pollution, often accompanied by strong winds, can increase the incidence of respiratory illnesses and exacerbate cardiovascular conditions (D’Amato & Akdis, 2022; Goudie, 2014; Tong et al., 2017; Zhang X.-X.



et al., 2018). In addition, dust storms disrupt infrastructure and economic activities by degrading visibility and elevating traffic-
 accident risk, while also damaging farmland and reducing crop yields (Ahmadzai et al., 2023; MalAmiri et al., 2025; Miri &
 Middleton, 2022; Zhang H. & Zheng X., 2025). They occur frequently across arid and semi-arid regions, particularly over the
 Taklimakan Desert and the Gobi Desert along the Mongolian border. These events are most common in spring and can affect
 35 large populations downwind (Chen et al., 2017; Sun & Gao, 2022; Xing et al., 2024; Xu L. et al., 2020; Yang B. et al., 2024).
 u^* is a key dynamical parameter in dust-storm research, determining whether wind forcing is sufficient to dislodge surface
 particles and entrain them into the atmosphere, while also governing the estimation of particle-mobility thresholds, dust
 emission fluxes, and sediment transport rates (Du H. et al., 2024; Dupont, 2020; Kok et al., 2012; Shao Y. et al., 2020).
 Classical aeolian-transport theory suggests that the sand transport rate scales approximately with the cube of friction velocity,
 40 highlighting the central role of u^* in aeolian sediment transport (Zhibao Dong et al., 2002; Kok et al., 2012). In addition, u^*
 controls the efficiency of vertical dust transport and the atmospheric residence time of suspended particles, thereby shaping
 the spatial extent and duration of dust storms.

Existing approaches for estimating u^* can be broadly grouped into two categories. The first is the logarithmic wind-profile
 method, which derives u^* by fitting wind-speed profiles measured at multiple heights. This method is most applicable under
 45 neutral or near-neutral stability conditions; it is straightforward and has been widely used. Grounded in Monin–Obukhov
 similarity theory, it has been extensively adopted in studies of dust storms and wind erosion. For example, Gillette and Passi
 (1988) applied this approach to estimate u^* and examine dust-emission thresholds under different surface conditions; Krasnov
 et al. (2014) further proposed an improved threshold-wind-speed formulation based on this method, which has been widely
 used in subsequent aeolian-dynamics models. The second category is the turbulent momentum-flux method, which relies on
 50 high-frequency wind measurements and generally provides higher accuracy, but requires stringent instrumentation and
 observational conditions; it is therefore most often used at fixed stations or in wind-tunnel experiments. Dupont et al. (2021)
 employed the turbulent-flux method to monitor wind-erosion processes in the semi-arid southern United States, demonstrating
 its reliability for capturing dynamically evolving dust emission. In addition, recent studies have explored wavelet-transform
 techniques to estimate u^* at 1-min and 10-s resolutions, extending the toolkit for investigating high-frequency dust-storm
 55 dynamics. For instance, Zhang and Zheng (2025) extracted high-frequency wind signals using wavelet analysis and
 successfully captured abrupt u^* transitions during the outbreak stage of dust storms.

Research on the multi-factor controls of u^* remains relatively limited. On the one hand, many studies approximate u^* using
 near-surface wind speed or directly adopt reanalysis-derived diagnostics, making the resulting inferences highly sensitive to
 wind variability and thus hindering a clear separation of the modulating roles of non-wind factors—such as net radiation, near-
 60 surface temperature gradients, and soil moisture—on surface-layer momentum exchange (Chakravarty et al., 2021; Hersbach
 et al., 2020; Leung et al., 2024; Zeng Y. et al., 2020). On the other hand, these approaches tend to emphasize wind-speed
 magnitude while downplaying the effects of wind direction and vertical-structure differences. Consequently, how wind-speed
 characteristics under different wind-direction regimes and across different height combinations influence the estimation and
 interpretation of u^* has not yet been systematically examined. This issue is particularly relevant for dune-dominated deserts,



65 where surface roughness, topographic relief, and fetch conditions may vary strongly with wind direction. Therefore, evaluating the stability of u^* retrievals under different height combinations and wind-direction sectors is necessary for improving the interpretation of tower-based friction-velocity estimates.

Accordingly, this study combines multi-level tower observations at TZ and XT with hourly ERA5 reanalysis to characterize u^* over the Taklimakan Desert during March–July 2024. We focus on three questions: (1) how the intra-annual variability and
70 site contrast of profile-derived u^* differ between TZ and XT, and why March–July is selected as the focus period for subsequent process-oriented analysis; (2) whether u^* computed from different tower height pairs and wind-direction sectors shows clear height- and direction-dependence, and how these patterns correspond to local terrain conditions quantified by the Terrain Ruggedness Index (TRI); and (3) how station-scale relationships between u^* and key meteorological variables differ between the two contrasting tower sites.

75 **2 Study area, data, and methods**

2.1 Study area and observation sites

The TD (Fig. 1) lies in the central Tarim Basin of southern Xinjiang, northwestern China. It is the world's second-largest shifting-sand desert (Sun and Liu, 2006), bounded by the Tian Shan to the north, the Kunlun Mountains to the south, and the Pamir Plateau to the west. Its extensive mobile dunes and hyper-arid climate support frequent dust emissions. Modeling studies
80 identify the Taklimakan as one of the most persistent dust-emission source regions in East Asia (Laurent et al., 2006). The desert also exhibits pronounced spatial variability in elevation and surface relief. To represent this terrain contrast, two observation sites were selected: XT, characterized by relatively flat terrain with limited local relief, and TZ, located in markedly undulating dune terrain. This paired-site design provides a natural framework for assessing how terrain heterogeneity modulates near-surface airflow and friction velocity.

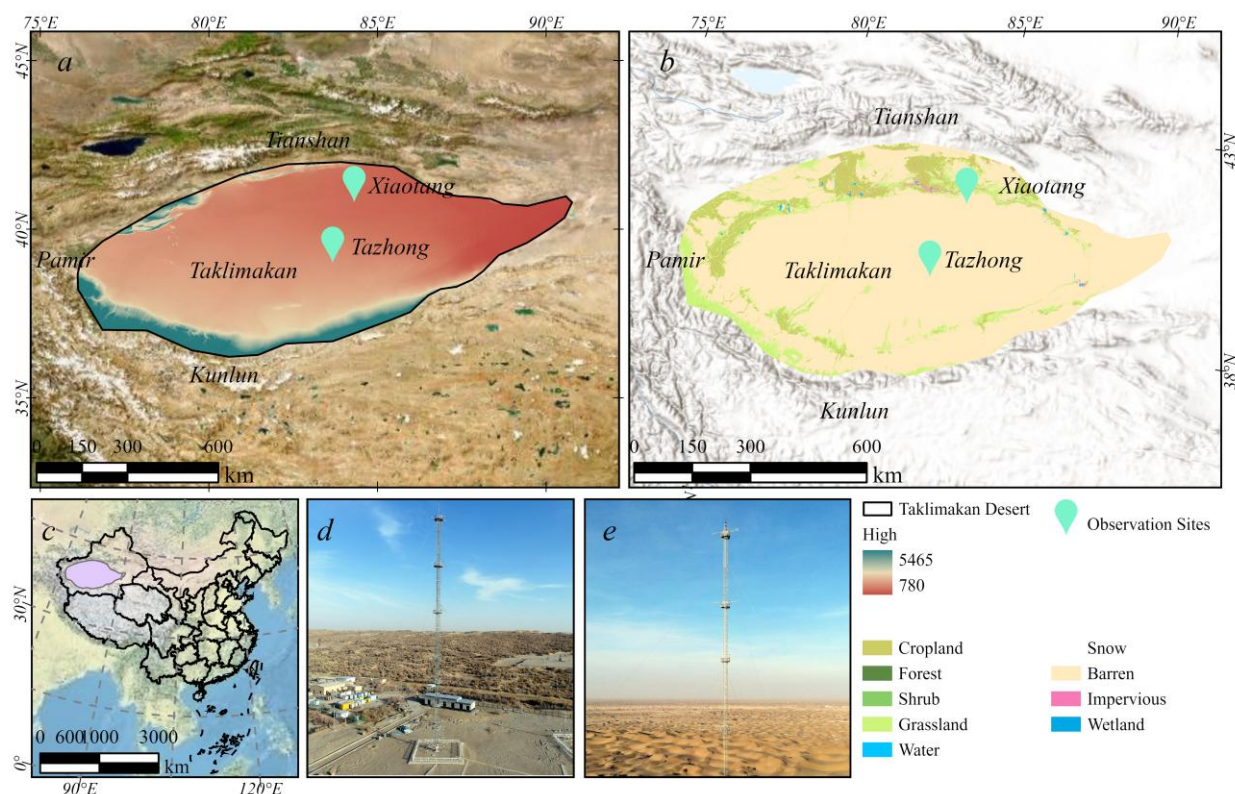


Fig. 1. Overview of the study area and observation sites in the Taklimakan Desert. (a) Topography and locations of the observation sites; (b) land-cover types; (c) geographical location of the study area in China; (d) Xiaotang observation site; and (e) Tazhong observation site.

2.2 Tower observations and auxiliary measurements

90 The observational dataset was obtained from two gradient meteorological towers: the 80 m TZ tower in the desert interior (38.97°N, 83.66°E) and the 100 m XT tower on the northern margin of the Taklimakan Desert (40.80°N, 84.30°E). The TZ tower is located in an interdune valley surrounded by high dunes, whereas the XT tower is situated in a relatively flat desert–oasis transition zone with sparse vegetation.

Both towers measure air temperature, relative humidity, water vapor pressure, horizontal wind components, wind speed, and wind direction at multiple levels. For the wind-profile analysis, wind-speed observations at 1, 2, 4, 10, 20, 32, 47, 63, and 80 m were examined. To identify a reference near-surface wind-profile configuration, seven height combinations were quantitatively evaluated using ERA5-based and eddy-covariance (EC)-based comparisons. The H01 combination (1–2–4–10–20 m) was selected as the reference configuration because it showed the most stable performance among the tested configurations, with the highest Pearson correlation and lowest root-mean-square error (RMSE) at TZ ($r = 0.336$, RMSE = 0.210 m s⁻¹) and XT ($r = 0.157$, RMSE = 0.256 m s⁻¹). This combination also retained large valid samples and directly represented the lower tower levels. In contrast, higher-level combinations, particularly H05 (32–47–63 m) and H06 (47–63–



80 m), produced much larger positive biases and RMSE values, indicating stronger sensitivity to upper-level profile distortion. Therefore, H01 was used as the reference near-surface profile, while the remaining combinations were retained for height-sensitivity and wind-direction analyses. The detailed quantitative comparison among the tested height combinations is provided in Supplementary Table S1. The tested combinations were H01 (1–2–4–10–20 m), H02 (2–4–10–20 m), H03 (1–2–4–10–20–32 m), H04 (1–2–4–10–20–32–47–63 m), H05 (32–47–63 m), H06 (47–63–80 m), and H07 (1–2–4–10–20–32–47–63–80 m).

EC systems provide high-frequency fluctuations of three-dimensional wind and temperature/water vapor, enabling the calculation of turbulent fluxes, including u^* , sensible heat flux, and latent heat flux. In addition, both sites simultaneously record surface shortwave and longwave radiation, net radiation, surface and soil temperature, soil moisture, precipitation, air pressure, and other meteorological variables.

To assess the reliability of the observational basis, we further examined tower records from the broader 2023–2025 period. The data completeness and the proportion of quality-controlled valid records varied substantially among years. For the H01 profile-derived u^* based on the 1–2–4–10–20 m height combination, the valid hourly records in 2024 reached 7135 h at TZ and 7046 h at XT, corresponding to valid rates of 81.2% and 80.2%, respectively. These values were higher than those in 2023 and much higher than those in 2025, when the valid rates decreased to 40.8% at TZ and 30.2% at XT because of more frequent missing records and quality-control failures. Therefore, the main analysis focuses on March–July 2024, during which both stations provided relatively complete and comparable observations for the active dust season. The multi-year data availability and quality-control statistics are summarized in Supplementary Table S2. To illustrate the seasonal evolution of u^* the daily mean profile-derived u^* values were smoothed using a 30-day centered moving average, and the resulting curves are shown as solid lines in Fig. 3.

2.3 Reanalysis data

We use the ERA5 reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 provides global atmospheric fields at $0.25^\circ \times 0.25^\circ$ horizontal resolution with hourly temporal resolution (C3S, 2018; Hersbach et al., 2020). Radiosonde evaluations at Tazhong found that ERA5 generally outperformed four other reanalysis products in representing vertical temperature and wind fields during summer, although errors were largest near the surface (Huang et al., 2021). ERA5 10 m wind data have also been used to characterize wind regimes and sand-transport patterns across the Taklamakan Desert and to examine their relationship with dune morphology (Sun and Gao, 2022). In this study, we extract hourly ERA5 data from 1 March to 31 July 2024 over $32\text{--}45^\circ\text{N}$ and $72\text{--}95^\circ\text{E}$, including near-surface winds, air temperature and humidity, boundary-layer height, soil variables, and surface radiative fluxes. The data are available from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels>).

ERA5 near-surface variables were evaluated against tower and EC observations to establish a regional reference for the subsequent profile analyses. Specifically, ERA5 10 m wind speed (WS_{10}), 2 m air temperature (T_{2m}), and ERA5-derived u^* were compared with tower-observed WS_{10} , tower-observed T_{2m} , and EC-observed u^* at hourly, daily, and monthly scales.



135 Daily correlations for WS_{10} were 0.844 at TZ and 0.843 at XT, while daily correlations for T_{2m} exceeded 0.99 at both sites; ERA5-derived u^* correlated with EC-observed u^* at 0.560 and 0.782, respectively. The detailed statistics are provided in Supplementary Tables S3–S4. The air-temperature difference was defined as $\Delta T_a = T_{10m} - T_{2m}$, and the surface–air temperature difference as $\Delta T_s = T_{s,0m} - T_{2m}$. These variables were calculated from hourly measurements at both TZ and XT.

2.4 Friction velocity estimation

140 In this study, u^* was retrieved within the Monin–Obukhov similarity theory (MOST) framework by combining the eddy-covariance-derived Monin–Obukhov length L with multi-level wind-speed profiles. The Monin–Obukhov length L was obtained from the EC system, where it was calculated from turbulent momentum and sensible heat fluxes after quality control, rather than being recalculated from the profile-derived u^* . Therefore, L was introduced as an external stability constraint in the profile-fitting procedure.

145 The nondimensional stability parameter was calculated as $\zeta = z/L$, and the surface-layer stability regime was classified as unstable ($\zeta < -0.05$), near-neutral ($-0.05 \leq \zeta \leq 0.05$), or stable ($\zeta > 0.05$). The corresponding stability correction for momentum, ψ_m , was then applied according to the stability regime. The Businger–Dyer formulation was used under unstable conditions, a linear correction was adopted under stable conditions, and ψ_m was set to zero under near-neutral conditions. The wind-speed profile can be expressed as:

150
$$U(z) = \frac{u_*}{\kappa} \left[\ln \left(\frac{z-d}{z_0} \right) - \psi_m \left(\frac{z-d}{L} \right) + \psi_m \left(\frac{z_0}{L} \right) \right]$$

where $U(z)$ is the mean wind speed at height z , κ is the von Kármán constant, z_0 is the aerodynamic roughness length, and d is the zero-plane displacement height. For the desert surface considered here, d was approximated as 0.

Although vegetation is sparse at both sites, the effective displacement height at TZ may also be influenced by dune-scale topography. We therefore treated $d = 0$ m as a baseline approximation rather than as a physically exact value. To characterize
 155 the effect of the displacement-height treatment, the profiles were additionally fitted with prescribed d values of 0.25 and 0.5 m using the observed stability input. For H01, the median u^* decreased by 8.4% and 18.3% at TZ and by 8.8% and 19.0% at XT for $d = 0.25$ and 0.5 m, respectively, relative to the $d = 0$ baseline. The corresponding height-combination results are summarized in Supplementary Table S6. Because the available observations do not provide an independent estimate of d , we used 0.25 and 0.5 m as sub-metre sensitivity scenarios rather than as estimates of the actual displacement height. A $d = 1$ m
 160 scenario was not applicable to height combinations containing a 1 m measurement level, because $z - d$ would equal zero at the lowest level; Table S6 therefore reports $d = 1$ m only for combinations whose lowest measurement height exceeds 1 m.

The response also varied systematically with stability. At $d = 0.5$ m, the median H01 decrease in u^* was 22.6% under unstable conditions, compared with 6.1% under stable conditions at TZ; the corresponding values at XT were 22.7% and 7.2%. Wind-direction-specific results are provided in Supplementary Table S7, and the joint stability dependence of the H01 response and
 165 fitted z_0 is reported in Supplementary Table S8.



In the retrieval procedure, z_0 was not prescribed as a constant but was treated as an unknown parameter jointly constrained with u^* from the observed wind-speed profiles. Under a given stability state, the wind-speed difference between two heights was first used to reduce the direct dependence on z_0 and obtain an initial estimate of u^* . The two-height form can be written as:

$$U(z_2) - U(z_1) = \frac{u_*}{\kappa} \left[\ln \left(\frac{z_2 - d}{z_1 - d} \right) - \psi_m \left(\frac{z_2 - d}{L} \right) + \psi_m \left(\frac{z_1 - d}{L} \right) \right]$$

The retrieved u^* was then substituted back into the profile equation to estimate z_0 , and the solution was iteratively refined until convergence. In this way, z_0 was treated as a time- and stability-dependent diagnostic variable rather than a prescribed constant, which allowed the profile-derived u^* to remain comparable under different stability conditions.

For accepted H01 fits, median z_0 was 0.0356 m at TZ and 0.0179 m at XT; the middle 50% of estimates spanned 0.00618–0.2354 m and 0.00200–0.1767 m, respectively (Supplementary Table S10). The pooled distributions were concentrated around these central values, with longer upper tails (Supplementary Fig. S2a). Estimates of $z_0 \geq 1$ m accounted for only 2.89% of accepted fits at TZ and 2.06% at XT. Thus, most fitted values were below 1 m, although a small fraction extended to higher values. We therefore treat z_0 as an effective profile-derived parameter whose distribution varies across flow conditions, rather than as a single, time-invariant physical roughness length.

The directional and stability summaries show that fitted z_0 varies systematically across flow regimes. The stability-specific distributions and the associated u^* response are given in Supplementary Table S8, while the 45° wind-direction summaries are given in Supplementary Table S7. A further fixed- z_0 comparison is provided in Supplementary Tables S9a–S9b; these results quantify how constraining z_0 changes the height-combination statistics and the directional H01 estimates.

As described in Section 2.1, the H01 combination (1–2–4–10–20 m) was used as the reference near-surface wind-profile combination in the main analysis. The extended and high-level combinations were retained to evaluate the sensitivity of profile-derived u^* to tower-level selection and to diagnose the influence of upper-level wind structure and direction-dependent profile distortion. Detailed comparison statistics for the height combinations are provided in the Supplementary Material.

2.5 Convergent Cross Mapping analysis

We used Convergent Cross Mapping (CCM), implemented with the rEDM package in R, to evaluate directional associations between hourly meteorological variables and profile-derived friction velocity (u^*). For each site, records were ordered by observation time and assigned a sequential time index, as in the analysis code. The screened input series contained 3,160 records at TZ and 3,165 at XT. The embedding dimension was set to $E = 3$ based on preliminary hourly EmbedDimension screening. CCM is a nonlinear time-series method grounded in state-space reconstruction: when two variables are dynamically coupled, information about one variable can be recovered from the reconstructed manifold of the other. Cross-map skill is evaluated across progressively larger libraries, and convergence provides evidence of a directional association (Sugihara et al.,



2012). Because convergence can also be affected by shared drivers and other data properties, CCM results are interpreted here as directional associations rather than definitive proof of causation.

200 The common drivers examined at both sites were WS_{10} , net radiation (R_n), the air-temperature difference (ΔT_a), the surface–air temperature difference (ΔT_s), and bias-corrected ERA5 soil moisture in the first soil layer (SM). For each driver, CCM was run with columns set to the driver and target set to u^* , using library sizes $L = 200, 500, 1,000, 1,500$, and $2,000$, 100 random library samples per size, and random sampling enabled. The output column $u^*:\text{driver}$ is the cross-map skill obtained by reconstructing the driver from the u^* manifold; under CCM, its convergence with increasing L is the diagnostic for a driver-to- u^* association. The reciprocal driver: u^* mapping was also calculated to assess directional asymmetry. We report the cross-map correlations (ρ) across library sizes and describe their largest values, without treating them as standalone proof of causation.

205 2.6 Cross-reference assessment of height-combination selection

210 Because the original benchmark analysis compares profile-derived u^* with EC-observed u^* , we performed a complementary cross-reference analysis to separate the role of the comparison target from the role of the stability input. First, the finite- L profile estimates were compared with a nearest-grid ERA5-derived neutral-profile u^* , with EC-observed u^* excluded from both the comparison target and the sample filter. In parallel, neutral-only profile fits were recalculated from the cleaned tower wind profiles without using EC-derived L or EC-observed u^* in the fitting or screening procedure. The procedures and full height-combination statistics are reported in Supplementary Table S5.

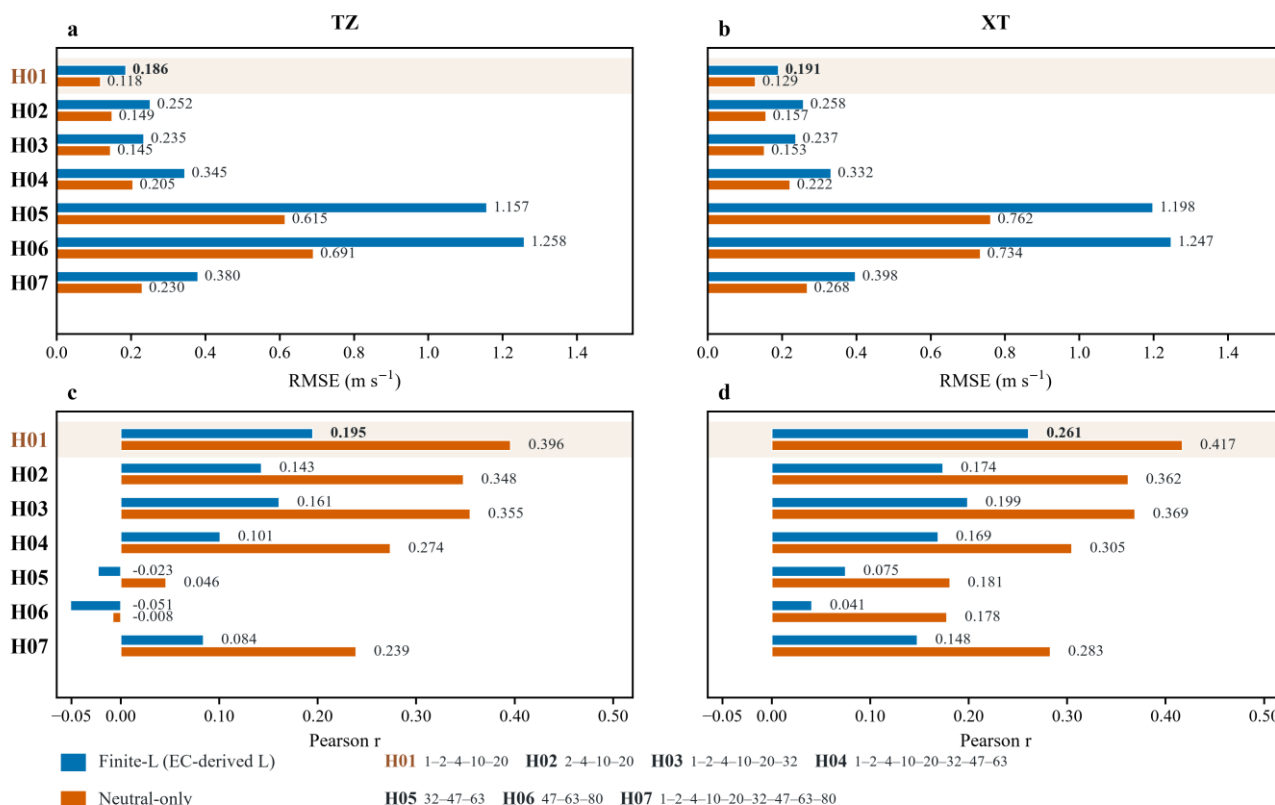


Fig. 2. Comparison of friction-velocity estimates obtained from finite-L and neutral-only profile fits across seven tower-height combinations at Tazhong (TZ) and Xiaotang (XT) during March–July 2024. Blue and orange bars represent the finite-L and neutral-only estimates, respectively. Panels (a) and (b) show the root-mean-square error (RMSE), whereas panels (c) and (d) show Pearson’s correlation coefficient. Panels (a) and (c) correspond to TZ, while panels (b) and (d) correspond to XT. H01–H07 denote, respectively, the height combinations 1–2–4–10–20 m, 2–4–10–20 m, 1–2–4–10–20–32 m, 1–2–4–10–20–32–47–63 m, 32–47–63 m, 47–63–80 m, and 1–2–4–10–20–32–47–63–80 m. All estimates are evaluated against the nearest-grid ERA5-derived neutral-profile reference.

Supplementary Fig. S5. Height-combination performance against the nearest-grid ERA5-derived neutral-profile reference. Panels (a)–(b) show RMSE and panels (c)–(d) show Pearson correlation at TZ and XT, respectively. Blue bars indicate finite-L estimates using EC-derived L; orange bars indicate neutral-only estimates.

The ERA5-reference comparison consistently identifies H01 as the strongest low-level configuration. Under the finite-L retrieval, H01 produced RMSE values of 0.186 m s^{-1} at TZ and 0.191 m s^{-1} at XT, compared with 1.157 and 1.198 m s^{-1} for H05 and 1.258 and 1.247 m s^{-1} for H06, respectively. The corresponding Pearson correlations for H01 were 0.195 at TZ and 0.261 at XT, whereas H05 and H06 yielded negative or weak correlations (−0.023 and −0.051 at TZ; 0.075 and 0.041 at XT). The neutral-only analysis showed the same ordering: H01 had RMSE values of 0.118 m s^{-1} at TZ and 0.129 m s^{-1} at XT, while H05–H06 yielded 0.615–0.691 m s^{-1} at TZ and 0.734–0.762 m s^{-1} at XT. H01 also had the highest Pearson correlations in the neutral-only comparison (0.396 at TZ and 0.417 at XT).



230 For continuity with the EC benchmark used in the original analysis, the profile estimates were additionally compared with EC-
observed u^* using the same cleaned tower records. These results are provided in Supplementary Table S5b. In the finite-L
comparison, H01 gave RMSE values of 0.233 m s⁻¹ at TZ and 0.213 m s⁻¹ at XT, with Pearson correlations of 0.203 and
0.214, respectively. The corresponding high-level combinations H05–H06 produced RMSE values of 1.661–2.160 m s⁻¹ at
TZ and 1.539–1.667 m s⁻¹ at XT. In the neutral-only comparison, H01 again gave the lowest RMSE at both stations (0.214
235 m s⁻¹ at TZ and 0.194 m s⁻¹ at XT) and the highest Pearson correlations within the tested combinations (0.016 at TZ and
0.081 at XT). The H05–H06 RMSE values were 0.754–0.861 m s⁻¹ at TZ and 0.726–0.727 m s⁻¹ at XT.
Across the ERA5-based and EC-based comparisons, H01 consistently showed the most stable performance among the tested
height combinations. Because the EC-derived u^* is not fully independent of the stability information used in the finite-L profile
fitting, the EC comparison was not used alone to define the reference configuration. The finite-L estimates incorporated EC-
240 derived L as the stability constraint, whereas the neutral-only estimates were obtained directly from the observed wind profiles
without applying an EC-derived stability correction. H01 was therefore selected as the primary near-surface configuration for
the subsequent analyses.



3 Results

3.1 Regional background and local contrasts in friction velocity

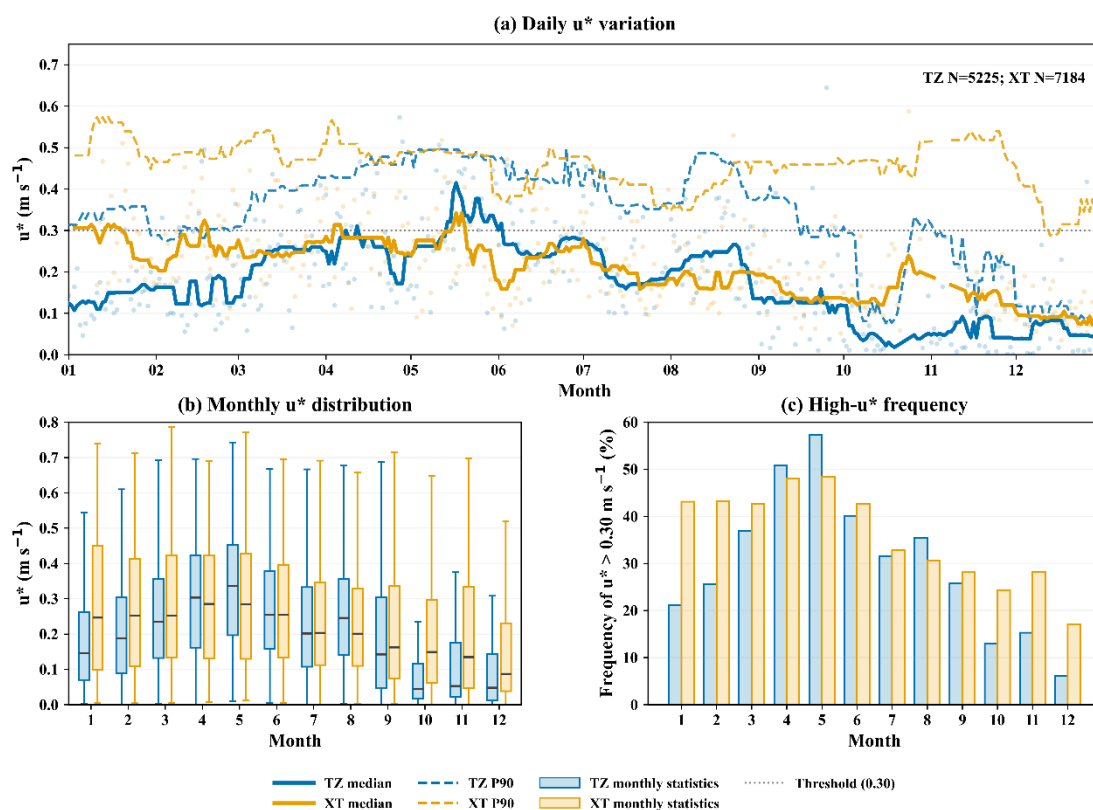


Fig. 3 Annual variation of profile-derived friction velocity at TZ and XT in 2024. (a) Daily variation of profile-derived u^* , with dots indicating daily mean values and solid lines indicating 30-day centered moving averages. (b) Monthly distribution of hourly profile-derived u^* . (c) Monthly frequency of hourly u^* exceeding 0.30 m s⁻¹.

Fig. 3 shows the annual variation of profile-derived u^* at the TZ and XT towers in 2024. Both stations exhibit pronounced day-to-day fluctuations and clear seasonal variability, but their intra-annual patterns differ between the two sites. At XT, u^* remains relatively high during the early part of the year, especially from January to April, and the monthly distributions indicate a higher central tendency in several months. In contrast, TZ shows a more distinct enhancement from spring to early summer, with stronger episodic peaks and a marked increase in high- u^* occurrence during the warm season. The frequency of hourly u^* exceeding 0.30 m s⁻¹ increases notably from March and reaches its annual peak during April–June, with maximum monthly frequencies of 57.23% at TZ and 48.46% at XT. This suggests that both stations frequently reached conditions associated with enhanced near-surface momentum exchange during this period, while TZ shows a stronger episodic response.

These annual features suggest that the inter-site contrast cannot be described as a simple year-round dominance of either station. XT tends to maintain a relatively higher background u^* during parts of the year, whereas TZ exhibits stronger episodic

enhancement and a more pronounced warm-season response, consistent with the rougher and more topographically complex surface around the interior dune site. Considering the enhanced u^* , frequent threshold exceedance, active dust season in the Taklimakan Desert, and relatively complete valid observations at both towers, March–July 2024 was selected as the focus period for the subsequent analyses of height-combination sensitivity, wind-direction dependence, and site-scale controlling factors.

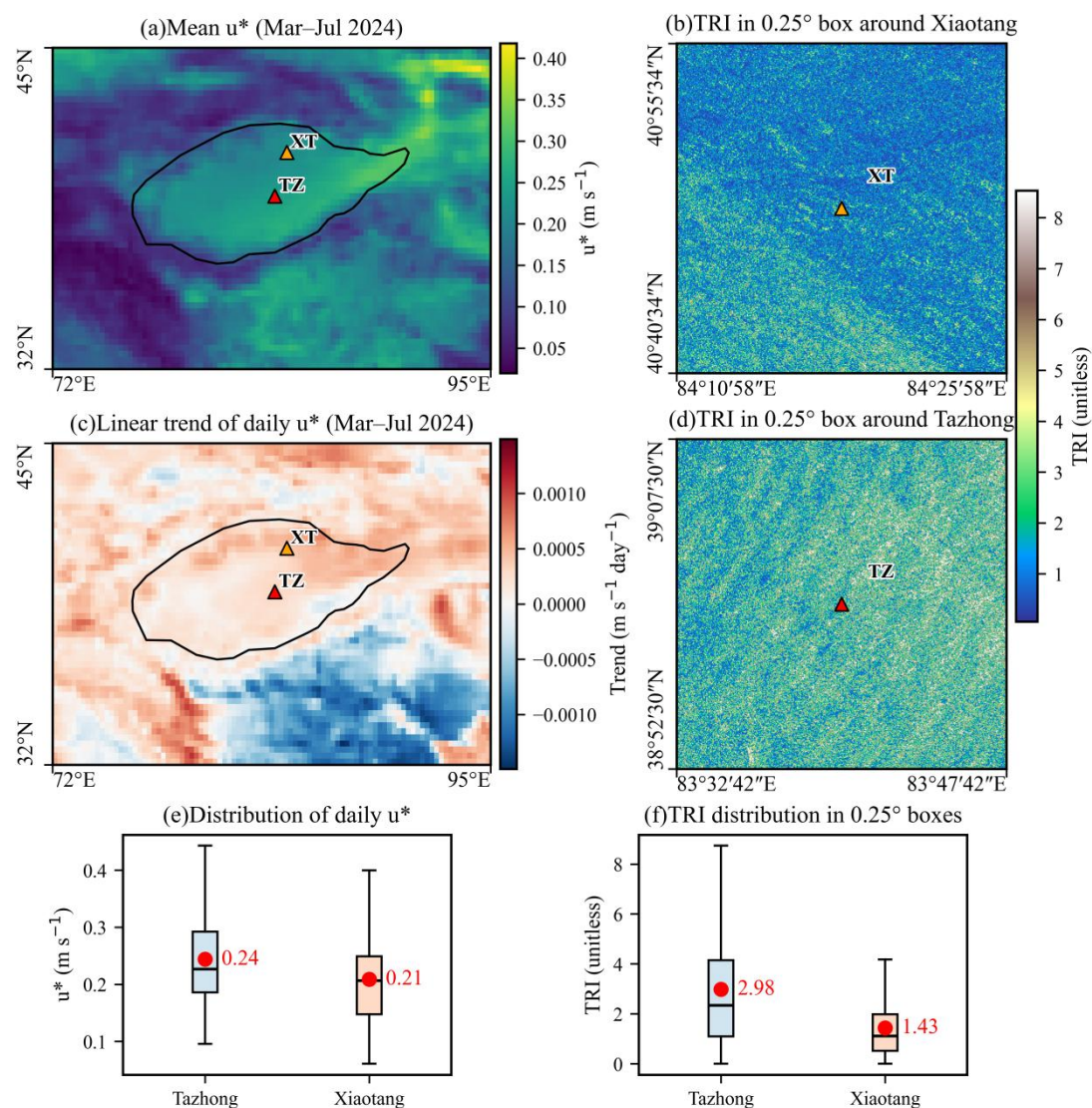


Fig. 4 Spatial patterns of regional u^* and terrain ruggedness (TRI) over the Taklimakan Desert during March–July 2024. (a, c) ERA5 mean u^* for March–July and the linear trend of daily u^* , respectively. (b, d) Distribution of 30 m TRI within the $0.25^\circ \times 0.25^\circ$ grid cell centered on XT and TZ, respectively. (e) Boxplots of daily mean u^* at the two sites, and (f) the corresponding boxplots of TRI within the associated 0.25° grid cells; red dots denote the mean values.



On the regional maps, both observation towers are located within a corridor of relatively high u^* across the northern and western Taklimakan Desert, whereas u^* is weaker over the southern basin (Fig. 4a). From March to July 2024, daily mean u^* at both sites shows a slight upward tendency, indicating a modest seasonal strengthening of near-surface momentum exchange (Fig. 4c).

Although the two towers share a similar regional background, their local surfaces differ markedly: TZ is surrounded by closely spaced dune ridges and exhibits much stronger topographic relief, whereas the XT surroundings are flatter and smoother (Fig. 4b,d). To quantify this contrast, we use the Terrain Ruggedness Index (TRI), a simple metric that summarizes small-scale elevation variability within a grid cell; higher TRI indicates a more rugged surface. The 0.25° grid cell containing TZ has a mean TRI of ~ 3.0 , approximately twice that of the XT grid cell (~ 1.4) (Fig. 4f). Consistent with this, TZ shows a slightly higher mean daily u^* and stronger day-to-day variability than XT (0.24 vs. 0.21 m s^{-1}) (Fig. 4e).

3.2 Site-scale attribution of u^* variability using Convergent Cross Mapping

Figure 5 shows the CCM cross-map skill (ρ) between hourly u^* and the five candidate drivers across library sizes. A comparison of the two sites shows that the association between WS_{10} and u^* was similar, with a maximum ρ of approximately 0.24 at both sites. By contrast, the association with R_n was stronger at TZ (maximum $\rho = 0.44$) than at XT (0.25), as was the association with ΔT_s (0.38 at TZ versus 0.22 at XT). The site contrast was therefore more pronounced for R_n and ΔT_s than for WS_{10} . In comparison, the association with ΔT_a was nearly identical at the two sites (maximum $\rho = 0.40$ at both TZ and XT). Soil moisture had low cross-map skill at both sites, with maximum ρ values of 0.11 at TZ and 0.065 at XT.

These results suggest that the detected associations of wind speed and air-temperature contrast with u^* were comparable between the sites, whereas those of net radiation and surface–air temperature contrast were stronger at TZ. The relatively low soil-moisture skill indicates a weaker association with u^* in the analyzed records, particularly at XT. The stronger cross-map skill for R_n and ΔT_s at TZ is consistent with greater covariation between surface thermal conditions and u^* at the dune-dominated site. However, CCM skill does not quantify causal-effect magnitude or, on its own, identify the physical processes underlying these site differences.

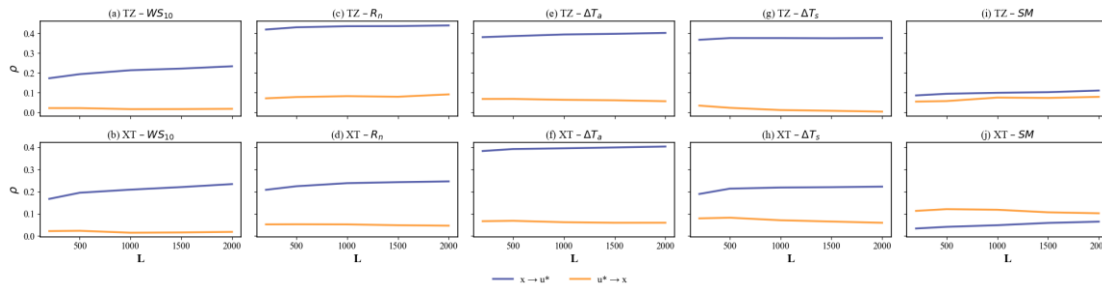


Fig. 5. Panels (a)–(j) show the CCM convergence curves (ρ – L) between hourly u^* and the candidate drivers (WS_{10} , R_n , ΔT_a , ΔT_s , and SM) at the TZ and XT sites for March–July 2024.



3.3 Directional dependence of u^* and sensitivity to height combinations

The comparison further characterizes the directional dependence of profile-derived u^* across the tested height combinations. Figure 6 compares the directional distributions of u^* at TZ and XT across wind-direction sectors and evaluates their consistency with ERA5. Overall, the estimates derived from different height combinations show strong agreement at both sites, with most curves clustering within individual sectors and exhibiting similar azimuthal variations. This consistency indicates that the inferred directional structure of u^* is generally stable across the available wind-profile configurations, while the magnitude of the estimates remains sensitive to the selected tower levels.

At TZ (Fig. 6a), median u^* exhibits pronounced directional dependence, with marked enhancement under the western to northwestern sectors, especially for the high-level combination and generally weaker values in the southerly sectors. Notably, the high-level combination (32–47–63 m) yields systematically larger medians across nearly all wind directions and shows stronger directional anisotropy, suggesting that u^* estimates relying primarily on higher-level winds are more susceptible to influences from aloft flow structure, profile shape, and directionally varying acceleration and roughness contrasts induced by dune topography. By comparison, multi-level combinations that include near-surface measurements, particularly H01–H04 combining lower and middle tower levels, produce more moderate and mutually consistent medians, indicating that incorporating near-surface information helps constrain shear estimates and reduces the risk of potential overestimation under strong wind-direction regimes.

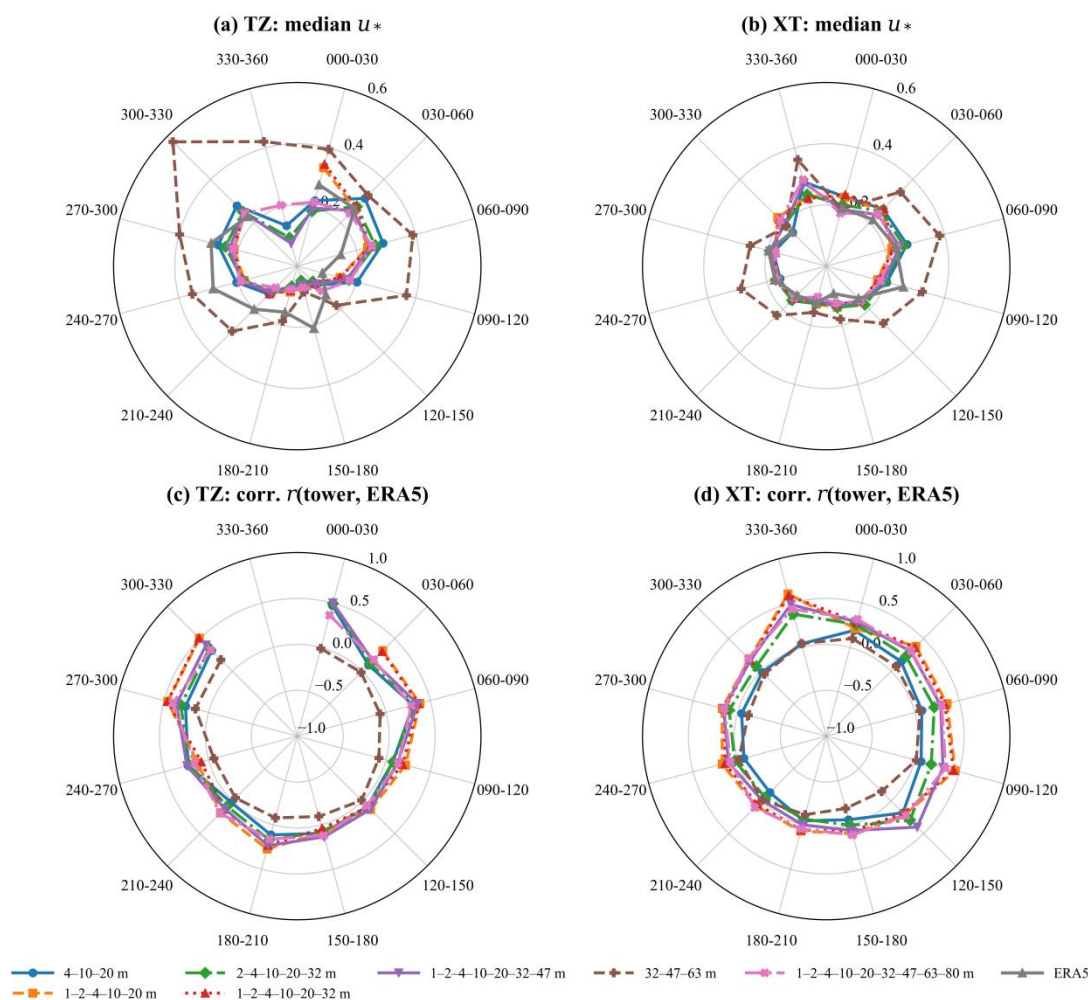


Fig. 6. Directional dependence of tower-derived friction velocity (u^*) and its agreement with ERA5 at TZ and XT.

At XT (Fig. 6b), directional contrasts are also evident but generally smoother than at TZ. Median u^* still varies with wind direction, but the spread among H01–H04 remains relatively limited compared with the high-level H05 combination. This is consistent with the more homogeneous surface at the desert-margin site and a weaker imprint of wind-direction-dependent flow distortion. Nevertheless, the 32–47–63 m combination remains generally higher than the other combinations, indicating that the tendency for “high-level combinations to overestimate” is present at both sites.

Panels in the lower row (Fig. 6c–d) show the correlation coefficients between tower-derived u^* and ERA5-derived u^* across wind-direction sectors. Correlations are generally positive, although their strength varies among sectors and between the two stations. More importantly, combinations spanning near-surface and middle tower levels tend to yield more stable correlations in several wind sectors, whereas the differences among H01–H04 are generally smaller than those between H01–H04 and the high-level combination. In contrast, the high-level 32–47–63 m combination does not consistently improve the agreement with



ERA5 and can deviate from the lower- and multi-level combinations in some sectors, suggesting that shear signals inferred primarily from higher-level winds may contain a larger contribution from sub-grid processes, such as dune-scale flow acceleration and direction-dependent roughness effects, that are not fully resolved by reanalysis. Overall, the choice of height combination mainly affects the magnitude of u^* and its directional anisotropy, particularly at TZ. Among the tested configurations, combinations including near-surface and middle tower levels provide more stable wind-direction signals and better agreement with ERA5.

4 Summary and Discussion

The annual overview of profile-derived u^* shows that TZ and XT differ not only in mean magnitude but also in the form of variability. XT maintains relatively high background u^* during part of the year, whereas TZ exhibits stronger episodic enhancement, a heavier upper-tail distribution, and a more pronounced warm-season response. During March–July, the mean daily u^* is slightly higher at TZ than at XT (0.24 vs. 0.21 m s^{-1}), and the maximum monthly frequency of hourly u^* exceeding 0.30 m s^{-1} reaches 57.23% at TZ and 48.46% at XT. These results suggest that the dune-dominated interior site more frequently enters a high-momentum-exchange regime, which is consistent with the stronger roughness and topographic complexity around TZ. The higher terrain ruggedness at TZ, with a mean TRI of about 3.0 compared with about 1.4 at XT, further supports the interpretation that local surface morphology modulates the response amplitude of u^* under a similar regional dynamical background.

The CCM analysis showed similar associations between WS_{10} and u^* at the two sites, while associations with net radiation and the surface–air temperature contrast were stronger at TZ. The association with SM was comparatively weak at both sites. These patterns indicate site-dependent covariation in the hourly records; the CCM analysis alone does not identify the physical mechanisms behind it.

The site-scale CCM results further show that the difference between TZ and XT is not mainly controlled by the strength of the wind background alone. Near-surface wind provides a comparable dynamical background at both stations, but radiative and surface-thermal processes are more efficiently translated into u^* variability at TZ. In particular, the CCM skill of net radiation is stronger at TZ than at XT, whereas soil moisture remains the weakest driver at both sites. This suggests that, under arid desert conditions, wind forcing provides the basic momentum background, while local thermal coupling and surface morphology jointly regulate how strongly that forcing is expressed in hourly u^* variability.

The main analysis uses quality-controlled observations from March–July 2024, selected after screening the 2023–2025 tower records because this period provided the most complete and comparable records at both stations. For the H01 profile-derived u^* series, 2024 provided 7,135 and 7,046 valid hourly records at TZ and XT, corresponding to record availabilities of 81.2% and 80.2%, respectively, compared with 40.8% and 30.2% in 2025. This period therefore provides a consistent basis for examining height-combination sensitivity, wind-direction dependence and site-scale differences in profile-derived u^* . The



355 multi-year record availability, quality-control statistics and ERA5–tower comparisons are summarized in Supplementary
Tables S2–S4.

Code and data availability

The ERA5 hourly single-level reanalysis data used in this study are publicly available from the Copernicus Climate Change
Service Climate Data Store at <https://doi.org/10.24381/cds.adbb2d47>. The observational tower and EC datasets used in this
360 study are maintained by the Institute of Desert Meteorology, China Meteorological Administration, Urumqi, China. Because
these in situ observational datasets are subject to institutional data-management regulations, they are not publicly downloadable.
Researchers who wish to use the observational data may submit a formal data-application request to the Institute of Desert
Meteorology, China Meteorological Administration, specifying the research purpose, requested variables, time period, and
planned scope of use; access will be granted upon approval in accordance with the institute’s data-sharing policies. The
365 processed statistical tables and analysis scripts used to generate the figures and statistics in this manuscript will be archived in
a public repository before publication.

Author contributions

Yifei Wang: Conceptualization, Methodology, Formal analysis, Data curation, Visualization, Writing – original draft. Wen
Huo: Conceptualization, Methodology, Supervision, Project administration, Resources, Writing – review and editing.
370 Mayibaier Maihamuti: Investigation, Data curation, Validation, Writing – review and editing. Yisilamu Wulayin: Investigation,
Resources, Validation, Writing – review and editing. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare there are no conflicts of interest for this manuscript.

375 Disclaimer

Copernicus Publications adds a standard disclaimer: “Copernicus Publications remains neutral with regard to jurisdictional
claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. While
Copernicus Publications makes every effort to include appropriate place names, the final responsibility lies with the authors.
Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher.”



380 Financial support

This research was funded by the Tianshan Talent Project of Xinjiang (Grant No. 2023TSYCCX0075), the Xinjiang Uygur Autonomous Region Natural Science Foundation for Outstanding Young Scientists (Grant No. 2025D01E64), the Key Project of the Innovation and Development Special Program of the China Meteorological Administration (Grant No. CXFZ2026J007), the China Meteorological Administration Young Innovative Team Project (Grant No. CMA2024QN13), and the S&T Development Fund of the Chinese Academy of Meteorological Sciences (Grant No. 2021KJ034). We gratefully acknowledge the Institute of Desert Meteorology, China Meteorological Administration, for providing and maintaining the observational tower and EC datasets used in this study. We also thank the Taklimakan Desert Meteorology Field Experiment Station and the National Observation and Research Station of Desert Meteorology, Taklimakan Desert of Xinjiang, for field observation support. We thank the College of Geography and Remote Sensing Science, Xinjiang University, for technical and academic support.

References

- Ahmadzai, H., Malhotra, A., & Tutundjian, S. (2023). Assessing the impact of sand and dust storm on agriculture: Empirical evidence from Mongolia. *PLOS ONE*, 18(2), e0269271. <https://doi.org/10.1371/journal.pone.0269271>
- C3S. (2018). ERA5 hourly data on single levels from 1940 to present [Data set]. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). <https://doi.org/10.24381/CDS.ADBB2D47>
- Chakravarty, K., Vincent, V., Vellore, R., Srivastava, A. K., Rastogi, A., & Soni, V. K. (2021). Revisiting Andhi in northern India: A case study of severe dust-storm over the urban megacity of New Delhi. *Urban Climate*, 37, 100825. <https://doi.org/10.1016/j.uclim.2021.100825>
- Chen, S., Huang, J., Qian, Y., Zhao, C., Kang, L., Yang, B., et al. (2017). An overview of mineral dust modeling over East Asia. *Journal of Meteorological Research*. <https://doi.org/10.1007/s13351-017-6142-2>
- D'Amato, G., & Akdis, C. A. (2022). Desert dust and respiratory diseases: Further insights into the epithelial barrier hypothesis. *Allergy*, 77(12), 3490–3492. <https://doi.org/10.1111/all.15392>
- Dong, Z., Brahney, J., Kang, S., Elser, J., Wei, T., Jiao, X., & Shao, Y. (2020). Aeolian Dust Transport, Cycle and Influences in High-Elevation Cryosphere of the Tibetan Plateau Region: New Evidences from Alpine Snow and Ice. *Earth-Sci. Rev.*, 211, 103408. <https://doi.org/10.1016/j.earscirev.2020.103408>
- Dong, Zhibao, Liu, X., & Wang, X. (2002). Wind initiation thresholds of the moistened sands. *Geophysical Research Letters*, 29(12). <https://doi.org/10.1029/2001GL013128>
- Sun J. & Liu T. (2006). The age of the Taklimakan Desert. *Science*, 312(5780), 1621. <https://doi.org/10.1126/science.1124616>
- Laurent B., Marticorena B., Bergametti G. & Mei F. (2006). Modeling mineral dust emissions from Chinese and Mongolian deserts. *Global and Planetary Change*, 52(1–4), 121–141. <https://doi.org/10.1016/j.gloplacha.2006.02.012>



- Du H., Liu X., Ding R., Fan Y., & Liu X. (2024). New insights into dust emission mechanism in natural environments based on a series of field observations. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2024.169888>
- Dupont, S. (2020). Scaling of Dust Flux With Friction Velocity: Time Resolution Effects. *Journal of Geophysical Research: Atmospheres*, 125(1), e2019JD031192. <https://doi.org/10.1029/2019JD031192>
- 415 Dupont, S., Rajot, J. -L., Lamaud, E., Bergametti, G., Labiadh, M., Khalfallah, B., et al. (2021). Comparison Between Eddy-Covariance and Flux-Gradient Size-Resolved Dust Fluxes During Wind Erosion Events. *Journal of Geophysical Research: Atmospheres*, 126(13), e2021JD034735. <https://doi.org/10.1029/2021JD034735>
- Gillette, D. A., & Passi, R. (1988). Modeling dust emission caused by wind erosion. *Journal of Geophysical Research: Atmospheres*, 93(D11), 14233–14242. <https://doi.org/10.1029/JD093iD11p14233>
- 420 Goudie, A. S. (2014). Desert dust and human health disorders. *Environment International*, 63, 101–113. <https://doi.org/10.1016/j.envint.2013.10.011>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Kok, J. F., Parteli, E. J. R., Michaels, T. I., & Bou Karam, D. (2012). The physics of wind-blown sand and dust. *Reports on Progress in Physics*, 75(10), 106901. <https://doi.org/10.1088/0034-4885/75/10/106901>
- 425 Krasnov, H., Katra, I., Koutrakis, P., & Friger, M. D. (2014). Contribution of dust storms to PM₁₀ levels in an urban arid environment. *Journal of the Air & Waste Management Association*, 64(1), 89–94. <https://doi.org/10.1080/10962247.2013.841599>
- Lee, J. A., & Gill, T. E. (2015). Multiple causes of wind erosion in the Dust Bowl. *Aeolian Research*, 19, 15–36. <https://doi.org/10.1016/j.aeolia.2015.09.002>
- 430 Leung, D. M., Kok, J. F., Li, L., Mahowald, N. M., Lawrence, D. M., Tilmes, S., et al. (2024). A new process-based and scale-aware desert dust emission scheme for global climate models – Part II: Evaluation in the Community Earth System Model version 2 (CESM2). *Atmospheric Chemistry and Physics*, 24(4), 2287–2318. <https://doi.org/10.5194/acp-24-2287-2024>
- MalAmiri, N., Rashki, A., Al-Dousari, A., & Kaskaoutis, D. G. (2025). Socioeconomic and Health Impacts of Dust Storms in Southwest Iran. *Atmosphere*, 16(2), 159. <https://doi.org/10.3390/atmos16020159>
- 435 Middleton, N. J. (2017). Desert dust hazards: A global review. *Aeolian Research*, 24, 53–63. <https://doi.org/10.1016/j.aeolia.2016.12.001>
- Miri, A., & Middleton, N. (2022). Long-term impacts of dust storms on transport systems in south-eastern Iran. *Natural Hazards*, 114(1), 291–312. <https://doi.org/10.1007/s11069-022-05390-z>
- 440 Shao Y., Zhang J., Ishizuka M., Mikami M., Leys J., & Huang N. (2020). Dependency of particle size distribution at dust emission on friction velocity and atmospheric boundary-layer stability. *Atmospheric Chemistry and Physics*. <https://doi.org/10.5194/acp-20-12939-2020>
- Sugihara, G., May, R., Ye, H., Hsieh, C.-h., Deyle, E., Fogarty, M., & Munch, S. (2012). Detecting causality in complex ecosystems. *Science*, 338(6106), 496–500. <https://doi.org/10.1126/science.1227079>



- 445 Sun, W., & Gao, X. (2022). Geomorphology of sand dunes in the Taklamakan Desert based on ERA5 reanalysis data. *Journal of Arid Environments*, 207, 104848. <https://doi.org/10.1016/j.jaridenv.2022.104848>
- Huang J., Yin J., Wang M., He Q., Guo J., Zhang J., Liang X., & Xie Y. (2021). Evaluation of five reanalysis products with radiosonde observations over the Central Taklimakan Desert during summer. *Earth and Space Science*, 8, e2021EA001707. <https://doi.org/10.1029/2021EA001707>
- 450 Tong, D. Q., Wang, J. X. L., Gill, T. E., Lei, H., & Wang, B. (2017). Intensified dust storm activity and Valley fever infection in the southwestern United States. *Geophysical Research Letters*, 44(9), 4304–4312. <https://doi.org/10.1002/2017GL073524>
- Xing, Y., Chen, Y., Yan, S., Cao, X., Zhou, Y., Zhang, X., et al. (2024). Dust storms from the Taklamakan Desert significantly darken snow surface on surrounding mountains. *Atmospheric Chemistry and Physics*, 24(9), 5199–5219. <https://doi.org/10.5194/acp-24-5199-2024>
- 455 Xu L., Fukushima S., Sobanska S., Murata K., Naganuma A., Liu L., et al. (2020). Tracing the evolution of morphology and mixing state of soot particles along with the movement of an Asian dust storm. *Atmospheric Chemistry and Physics*. <https://doi.org/10.5194/acp-20-14321-2020>
- Yang B., Liu Y., & Qu J. (2024). Consistency between the distributions for the two phases in aeolian sand transport: Impact of sand on wind. *AIP Advances*. <https://doi.org/10.1063/5.0235476>
- 460 Zeng Y., Wang M., Zhao C., Chen S., Liu Z., Huang X., & Gao Y. (2020). WRF-Chem v3.9 simulations of the East Asian dust storm in May 2017: Modeling sensitivities to dust emission and dry deposition schemes. *Geoscientific Model Development*. <https://doi.org/10.5194/gmd-13-2125-2020>
- Zhang H. & Zheng X. (2025). Wavelet analysis of the coupling between turbulence, particles and electrostatics in dust storms. *Journal of Fluid Mechanics*. <https://doi.org/10.1017/jfm.2025.112>
- 465 Zhang X.-X., Sharratt B., Liu L.-Y., Wang Z.-F., Pan X.-L., Lei J.-Q., et al. (2018). East Asian dust storm in May 2017: Observations, modelling, and its influence on the Asia-Pacific region. *Atmospheric Chemistry and Physics*. <https://doi.org/10.5194/acp-18-8353-2018>