



Double Low-Level Jets Drive Vertical Folding and Suspension of Dust Layers over the Taklimakan Desert

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Abstract. Dust-boundary layer interaction is critical for regulating regional climate and the global dust cycle, yet the lack of high-resolution vertical profiling has long hampered mechanistic understanding, especially over complex terrain. Here, ground-based lidar measurements collected in the hinterland of the Taklimakan Desert (TD) from 2023 to 2025 were analysed to reveal a previously overlooked coupling regime: a Double Low-Level Jet (DLLJ) structure. DLLJ comprises a nocturnal low-level jet (NLLJ) characterised by eastward winds near the surface and a synoptic-system-related low-level jet (SLLJ) associated with northwesterly winds at approximately 600 hPa. We demonstrate that their convergence dynamically facilitates the large-scale vertical folding of the dust layer (VFDL), effectively injecting coarse-mode desert dust from the surface directly into the residual layer and above. SLLJ was attributed to the convergence related to Central Asian cold air descent and ascending airflow at the terminal of NLLJ, which not only produces distinct optical stratifications and source but also sustains a dense dust reservoir aloft under high-topography forcing. Climatologically, DLLJs and VFDLs occur with frequencies of approximately 19% and 36% during warm season, respectively, with a co-existence frequency of 9%. Notably, 47% of VFDL events were associated with DLLJ-inducing northwestern low-pressure systems. These findings offer the first observation evidence of how DLLJ modulate the vertical distribution of dust over complex terrain, revealing that current reanalyses and climate models substantially underestimate elevated dust layers. Globally, similar datasets of vertical distribution can offer a stringent observational benchmark for improving dust-cycle representation in global climate projections.



1. Introduction

45 The atmospheric boundary layer (ABL) plays a crucial role in the exchange of energy and materials between the free atmosphere and the Earth's surface (Stull, 1988). The convective boundary layer (CBL) affects local aerosol transport, aerosol vertical distribution, cloud formation processes, rainfall, and strong convective weather (Garcia-Carreras et al., 2015; Chen et al., 2022; Nakamae and Takemi, 2022; Tang et al., 2018). In general, CBL height is typically between 2 and 3 km. However, in arid and semi-arid regions such as the Sahara and Taklimakan/Gobi Deserts, it can exceed 4 km and occasionally reach 5–
 50 6 km; this is referred to as a deep CBL (Zhang and Wang, 2008; Zhang et al., 2011; Marsham et al., 2008; Gamo, 1996; Huang et al., 2014). With strong solar radiation and extremely dry surface conditions, sensible heat flux is rapidly partitioned from surface net radiation, promoting deep CBL development (Zhao et al., 2011; Maronga and Raasch, 2013). In addition, strong winds and wind shear enhance turbulent diffusion and entrainment, facilitating upward transport of sensible heat and creating a favourable dynamic environment for deep CBL development (Ao et al., 2017; Cuesta et al., 2009). The existence of a residual
 55 layer is crucial for the formation of a deep CBL, as it serves as an elevated reservoir that provides additional energy (Blay-Carreras et al., 2014; Freire and Dias, 2013). Thus, the deep CBL is a product of complex boundary layer processes and a critical link between local weather and regional climate, with important implications for atmospheric material cycling and energy balance over desert regions.

With CBL decay following sunset, a layer with residual properties of the CBL forms above the nocturnal boundary layer,
 60 which is referred to as the residual layer (Stull, 1988; Huang et al., 2010). The residual layer is usually distinguishable over desert areas during the daytime and plays a critical role in dust transport (Parker et al., 2005; Song et al., 2024). As the CBL develops, it gradually erodes the residual layer and entrains its stored potential energy, thereby further promoting CBL growth (Zhao et al., 2018; Zhang et al., 2019b; Ma et al., 2022; Zhang et al., 2022). However, CBL development can transport dust particles to higher altitudes through vertical mixing, thereby affecting the vertical aerosol distribution in the residual layer (Su
 65 et al., 2020; Takemi et al., 2005; Wang et al., 2016; Su et al., 2008). In addition, externally sourced aerosols can be transported into the residual layer through short-distance advection or long-range atmospheric circulation (Zhou et al., 2023b; Liu et al., 2020). Therefore, understanding the vertical distribution of aerosols in the residual layer is essential for accurately characterising the evolution of the deep CBL.

Low-level jets (LLJs) are important factors influencing the transport of atmospheric substances (Zhang and Meng, 2019).
 70 The LLJs can be classified into two types: boundary layer low-level jets (BLJs) formed by the dominance of mechanically coherent structures at the boundary layer scale after sunset, and synoptic-system-related low-level jets (SLLJs), which occur in the low levels of the free troposphere (Van De Wiel et al., 2010; Chen et al., 1994). The vertical overlap of the BLJs and SLLJs is referred to as double low-level jets (DLLJs). Currently, research on DLLJs is limited to studies related to their impact on precipitation in South China. The overlap between convergence near the terminus of the BLJs and divergence near the



75 entrance of the SLLJs played a critical role in the initiation of warm-sector heavy rainfall over the coastal regions of southern China (Du and Chen, 2018, 2019). The DLLJs can transport water vapour and provide dynamic forcing in Southern China, thereby creating favourable conditions for the formation of heavy rainfall events (Zhang et al., 2016; Zhang et al., 2019a). Nocturnal low-level jets (NLLJs), a typical subtype of BLJs, are a common phenomenon over arid and semi-arid areas. Many previous studies have mainly focused on the impact of NLLJs on dust activity over source areas (Knippertz and Todd, 2012; 80 Fiedler et al., 2013; Ge et al., 2016). Dust particles retained in the atmosphere can be transported by NLLJs over long distances (Todd et al., 2008). After sunrise, the downward momentum of the NLLJs can be transferred from the atmosphere to the ground, enhancing dust emissions (Wang et al., 2026). The Taklimakan Desert is the second largest desert in the world, located in a deep basin surrounded by high mountains on three sides. Under complex terrain, this area exhibits a unique temporal-spatial distribution of dust, as well as complex structures and processes in the boundary layer. Consequently, the influence of 85 Taklimakan Desert dust extends far beyond its source and surrounding areas, even reaching a global scale (Uno et al., 2009), regardless of whether a sandstorm occurs (Song et al., 2024). Over the Taklimakan Desert, these atmospheric boundary layer processes and dust activities are closely related to NLLJs. Nevertheless, our understanding of NLLJs behaviour over complex terrain remains inadequate owing to the scarcity of high-resolution vertical profile observations. More importantly, the role of DLLJs in regulating the transport and vertical distribution of dust aerosols has not yet been systematically documented.

90 In summary, this study reports the first identification of the DLLJ phenomenon in the Taklimakan Desert and explores its characteristics, formation mechanisms, and impact on the vertical dust distribution using long-term ground-based lidar observations and reanalysis datasets. Section 2 describes the dataset and methods. In Section 3, we present the spatial-temporal characteristics, formation mechanism, and impact on the vertical distribution of dust of the DLLJs, based on a special continuous clear-sky case during 27–30 July 2024. The large-scale backflow of the dust layer is analysed and discussed in 95 Section 4, and the conclusions are presented in Section 5.

2. Data and Methods

2.1 Study area

The Taklimakan Desert is located in the arid region of northwest China, with the southern part adjacent to the Tibetan Plateau, the Tianshan Mountains to the north, and the Pamir Plateau to the west. The Taklimakan Desert, which is the main 100 area of the Tarim Basin, is the second-largest dust source globally. The basin covers an area of 530,000 km² and has an average altitude of 1100 m. This basin has a warm-temperate climate with rare precipitation and high evaporation (Zhou et al., 2023c). Cold-air intrusion and thermal low-pressure systems in the basin provide dynamic conditions for the generation and persistence of dusty weather (Ma et al., 2007). Suspended dust weather occurs frequently during the warm season in the Taklimakan Desert and persists for 20–200 days annually (He and Zhao, 1997). The Tazhong station (39.00°N, 83.70°E, 1107 m a.s.l) is located



105 in the hinterland of the Taklimakan Desert, approximately 220 km from the edge of the desert, where dust activity is frequent and intense, and flowing sand dunes account for more than 80% (Zhou et al., 2023a; Jia et al., 2011). The mean annual precipitation is less than 30 mm, and an east wind prevails in this area. Arid lands contribute to the formation of strong NLLJs and deep CBL under clear-sky conditions, which is the ideal experimental field for studying dust-boundary layer interactions.

2.2 Instruments and dataset

110 The lidar system at the Tazhong station, developed by Lanzhou University, began measurements in May 2019. The system employed an Nd:YAG laser emitting at 532 and 1064 nm with a pulse repetition rate of 10 Hz. As the laser travels through the atmosphere, it interacts with the atmospheric particles. Backscattered signals were collected using a Cassegrain telescope with a 400 mm aperture (Zhang et al., 2023). The system detects the perpendicular and parallel component signals at 532 nm and the total signal at 1064 nm, with a temporal resolution of 2 min and vertical resolution of 7.5 m. The lidar had a blind zone of
 115 approximately 380 m. The raw data were corrected and pre-processed through background noise, range-squared, and overlap corrections (Xie et al., 2017; Zhou et al., 2021; Huang et al., 2025). Additionally, the observation products comprised the aerosol backscatter intensity (INT) and aerosol extinction coefficients (EXT) at 1064 and 532 nm, the linear volume depolarisation ratio at 532 nm, and the colour ratio of backscatter intensity at 1064 nm to that at 532 nm. EXT was derived using Fernald's method with a lidar ratio of 50 sr (Fernald, 1984). In this study, the INT at 532 and 1064 nm in the early
 120 morning was used to determine vertical folding of the dust layer (VFDL) from the aerosol vertical profile, defined by the presence of a distinct aerosol-layer peak above the CBL.

The ERA5 reanalysis dataset from the European Centre for Medium Weather Forecast assimilates multiple satellite and radiosonde datasets and includes various datasets from the World Meteorological Organisation's Global Telecommunications System (Hersbach et al., 2020). The horizontal resolution was $0.25^\circ \times 0.25^\circ$, and the temporal resolution was 1 h. In terms of
 125 the accuracy of the ERA5 reanalysis data, previous studies have indicated that the surface sensible heat flux (SSHf), atmospheric boundary layer height (ABLH), vertical velocity, surface latent heat flux (SLHF), and meteorological parameters used in this study have good accuracy (Huang et al., 2021; Xin et al., 2022). In this study, NLLJs were identified using the ERA5 datasets. NLLJs generally refer to a strong, narrow airflow within the lower atmosphere, with strong vertical wind shear above and below the core of maximum wind speed. Based on Ge et al. (2016) and Wang et al. (2026), NLLJs over the
 130 Taklimakan Desert are defined as wind profiles below 600 hPa satisfying the following conditions: maximum wind speed greater than 6 m/s, with a height lower than 600 hPa, and the wind speed must decrease by at least 3 m/s from the height of the wind maximum to that of the wind minimum. For SLLJs, Du and Chen (2018) combined the Taklimakan desert conditions and defined it as a wind profile within 700–450 hPa with a maximum wind speed greater than 8 m/s. To exclude the impacts of external synoptic systems, the maximum wind speed must be lower than 15 m/s and occur below the 450 hPa level.

135 The Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) reanalysis product is the



latest atmospheric reanalysis dataset provided by NASA's Global Simulation and Assimilation Office for 2017 (Molod et al., 2015). The MERRA-2 dataset provides the dust aerosol optical depth (DAOD) and dust mixing ratios used in this study. The spatial resolution of the dataset was $0.625^\circ \times 0.5^\circ$, and the temporal resolutions of the DAOD and dust mixing ratios were 1 h and 3 h, respectively.

140 The Moderate Resolution Imaging Spectrometer (MODIS) Aerosol Optical Depth (AOD) product derived from NASA Terra satellite imagery can be used to determine the spatial and spectral optical characteristics of aerosols. In this study, the MOD08_D3 product with a $1^\circ \times 1^\circ$ horizontal resolution and a Worldview-derived MODIS true-colour image with a 250-m resolution were used. Furthermore, the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by the National Oceanographic and Atmospheric Administration (NOAA) in collaboration with Australia's Bureau of
145 Meteorology, was employed to determine the backward trajectories of air masses (Stein et al., 2015).

The COST733 circulation-type classification software was used to classify the weather and circulation types. This study mainly adopted T-mode obliquely rotated principal component analysis (PCT) for objective synoptic classification of the data. The principle of this method is to decompose the original high-dimensional data into a principal component matrix and a loading matrix, select several principal components with large variance contributions, perform oblique rotation on them, and
150 finally classify the synoptic pattern at each time step according to the loading magnitudes. Specifically, the data matrix $Z = (z_{ij})$ is expressed as the product $Z = FA^T$, where the principal component matrix and loading matrix are $F = (f_{im})$ and $A = (a_{jm})$, respectively; i denotes the grid point index, and j and m denote date indices. The loadings are the eigenvectors of the data correlation matrix, scaled by the square root of the corresponding eigenvalues, which represent the variance explained by a specific component. Principal components are sorted by eigenvalue magnitude, and only those associated with larger
155 eigenvalues are retained. Oblique rotation is performed on the retained principal components, and each time step is classified according to the pattern with the highest loading. This method has been widely applied in relevant studies of the Taklimakan Desert, based on Zhang et al. (2025), variables at 850 hPa, including wind field (u : 30°N – 45°N , 70°E – 110°E ; v : 25°N – 45°N , 70°E – 110°E), temperature (25°N – 60°N , 60°E – 120°E), and geopotential height (35°N – 60°N , 50°E – 110°E) that are significantly correlated with desert dust, were selected for synoptic typing.

160 3. Results and discussion

3.1. Overview of continuous clear-sky case

Under continuous clear-sky conditions, NLLJs and deep CBL phenomena are more likely to occur (Wang et al., 2019). Here, a continuous clear-sky case during 27–30 July 2024 is selected, as shown in Fig. 1. Daily DAOD increased over time, with a more pronounced increase in the central Taklimakan Desert. MODIS observations showed a similar increasing trend
165 and spatial distribution pattern in AOD, although the values were slightly lower. The vertical distribution of dust loading



through the Tazhong area during this period is shown in Fig. 2. High dust loading was concentrated primarily in the central meridional region of the Taklimakan Desert. High dust loading had greater spatial variations in the zonal zone. It can be seen that the ABLHs were all above 3 km over the entire basin, and high dust loading was concentrated below the ABLH.

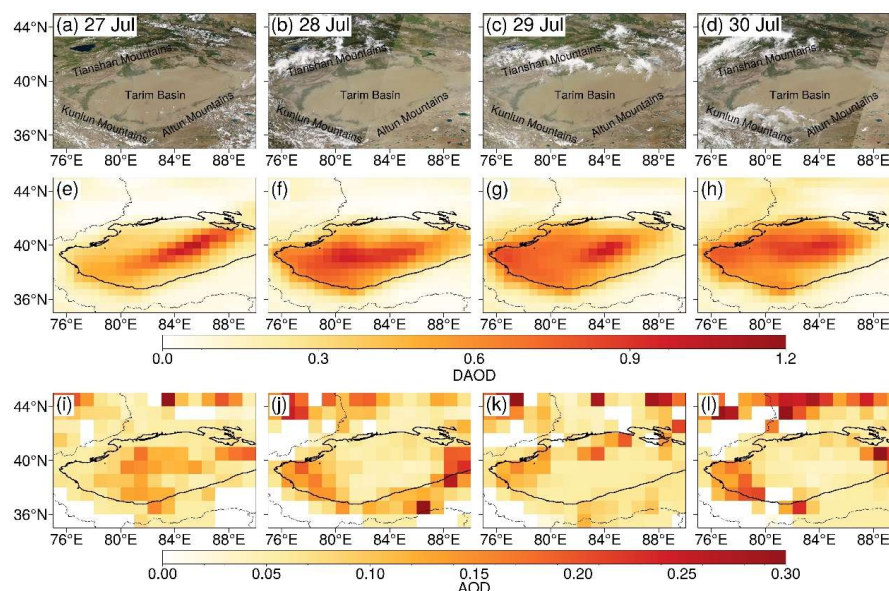


Fig. 1. Continuous clear-sky case during 27–30 July 2024. (a–d): MODIS true-colour image; (e–h): MERRA-2 daily average dust aerosol optical depth (DAOD), and (i–l): MODIS daily aerosol optical depth (AOD). The thick black solid line in (e–l) is the isoline at an altitude of 1500 m in the Tarim Basin (TB) area, and the interior is the main area of the TB (similarly hereinafter).

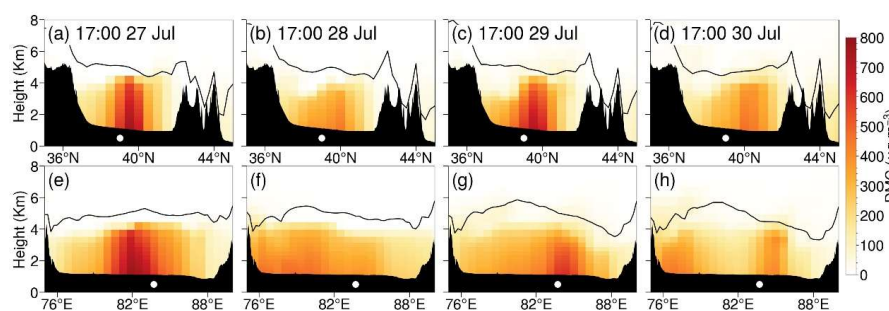
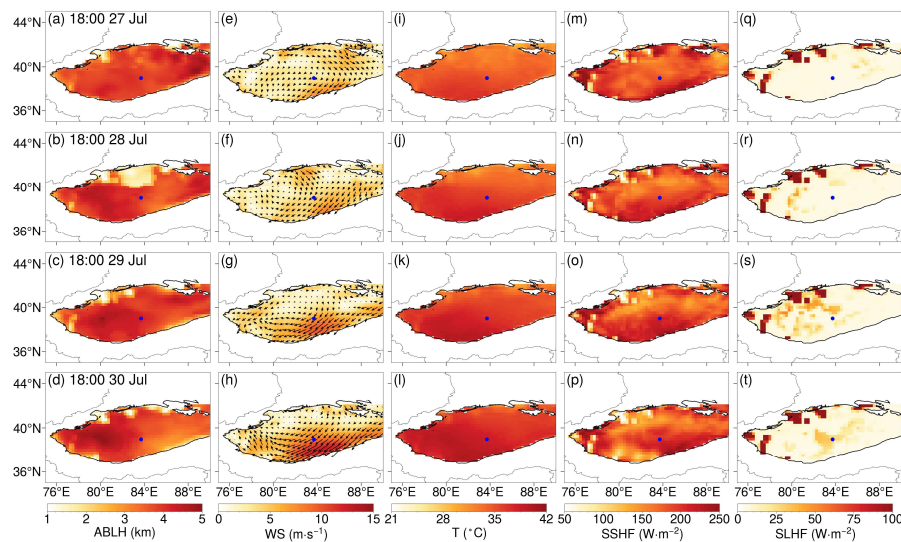


Fig. 2. Vertical distribution of dust mass concentration (DMC) in the meridional (top panel) and zonal (bottom panel) zones passing through Tazhong (white point) at 17:00 Beijing time (BJT) during 27–30 July 2024. The black areas and lines represent the terrain and ABLH, respectively.

Thermal instability and turbulence arising from surface heating are the primary thermodynamic drivers of ABLH formation and variability (Wan et al., 2017). The SSHF warms the near-surface air, enhancing thermal convection and turbulent mixing, which are the primary factors driving the development and elevation of the CBL (Li et al., 2024; Scherf and Roth, 1996). In contrast, SLHF removes surface energy through evaporation, producing a cooling effect that indirectly suppresses surface heating and thus restrains CBL development (Avissar, 1995; Yuan et al., 2017). The ABLH, wind field, temperature field, SSHF, and SLHF are given when the ABLH peaks at 18:00 Beijing time (BJT) in Fig. 3. In this case, the maximum



ABLH beyond 4 km mainly occurred in the eastern Taklimakan Desert on 27 July, and the ABLH exceeded 4 km over a
 185 considerable area to the west of the desert during 28–30 July. The temperature and wind speed at the 850 hPa level increased
 in intensity and spatial scales. Wind speed in the southeastern part of the desert and temperature in the western part of the
 desert both increased, exceeding 10 m/s and 35 °C, respectively. During this period, the wind field was dominated by easterly
 winds in the southern part, forming an anticyclonic circulation under the influence of topography. The SSHF exceeded 150
 $\text{W}\cdot\text{m}^{-2}$ across most of the desert but showed no significant long-term increase. Its spatial distribution was weakly correlated
 190 with ABLH. The SLHF was generally low, remaining below $75 \text{ W}\cdot\text{m}^{-2}$ across most areas except for regions along the desert
 margin, which had little impact on CBL development. SLHF increased in the western part of the desert during the first three
 days and was mainly distributed in the central part of the desert on 30 July.

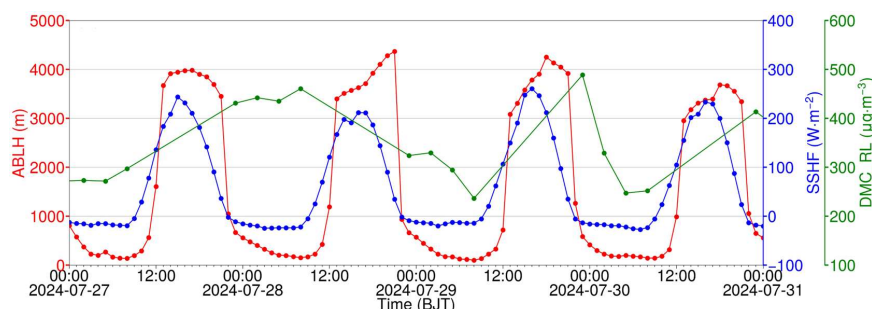


195 **Fig. 3. Spatiotemporal evolution of atmospheric states at 18:00 Beijing time (BJT) during 27–30 July 2024. (a–d): ABLH; (e–h): Wind field at 850 hPa; (i–l): Temperature at 850 hPa; (m–p): SSHF; (q–t): SLHF. The blue point represents the location of the Tazhong site.**

The SSHF during the daytime and dust loading in the residual layer significantly affect the development of the CBL (Ma
 et al., 2020; Scherf and Roth, 1996). Specifically, we examined the time series of some atmospheric states at the Tazhong
 station. As shown in Fig. 4, the maximum ABLH at Tazhong was approximately 4 km during this period, with a small variation
 200 range of ABLH peaks, which is a typical deep CBL scenario. The SSHF peaks all fell between 200 and $300 \text{ W}\cdot\text{m}^{-2}$, which
 cannot provide sufficient energy for deep CBL formation in the hinterland of the Taklimakan Desert. A large number of dust
 particles remaining in the residual layer can also provide additional energy for the formation of a deep CBL (Wang and Zhang,
 2022; Xu et al., 2018). Both of these were continuous clear-sky conditions, and the other variables in this case all exhibited an
 increasing trend, as shown in Fig. 1–3 of this study. However, the increasing trends in ABLH and dust loading of the residual
 205 layer reported in our previous study were not observed (Song et al., 2024). These results underscore the coupled evolution of
 deep CBL dynamics and residual-layer dust, particularly over complex terrain. However, the poor temporal and spatial



resolution of the reanalysis dataset (Fig. 2) limits fine-scale investigation of residual-layer dust and, consequently, prevents an in-depth understanding of the regional dust cycle.



210 **Fig. 4. Time series of DMC in the residual layer, ABLH, and SSHF at Tazhong during 27–30 July 2024.**

3.2 Vertical distribution of dust from lidar

During this continuous clear-sky period, a more refined vertical distribution of dust over the Tazhong area is shown in Fig. 5. Referring to the vertical distribution of dust during the daytime in Fig. 5a, the ABLH provided by ERA5 can represent the real situation of the CBL. During the nights of 28–30 July, distinct high-altitude suspended dust layers were observed in the residual layer, with a high aerosol extinction coefficient. Below the suspended dust layers, clean air masses with low aerosol extinction coefficients (yellow circles in Fig. 5a) were observed at lower altitudes. Notably, there were clear stratifications (red circles in Fig. 5a) in the upper layer (approximately 3.5 km) of the residual layer on 29 July, which showed a higher extinction coefficient, an inconsecutive depolarisation ratio, and colour ratio than those after the decoupling of the CBL after sunset and in the lower part of the residual layer. Although the dust layer (red circles in Fig. 5a) is still located in the residual layer, these inconsistent physical properties indicate that they undergo different atmospheric processes. A similar pattern was observed on 30 July, but with a thicker and denser dust layer. There is no doubt that these dust layers were involved in the entrainment process during the development of the deep CBL between 12:00 and 14:00 BJT.

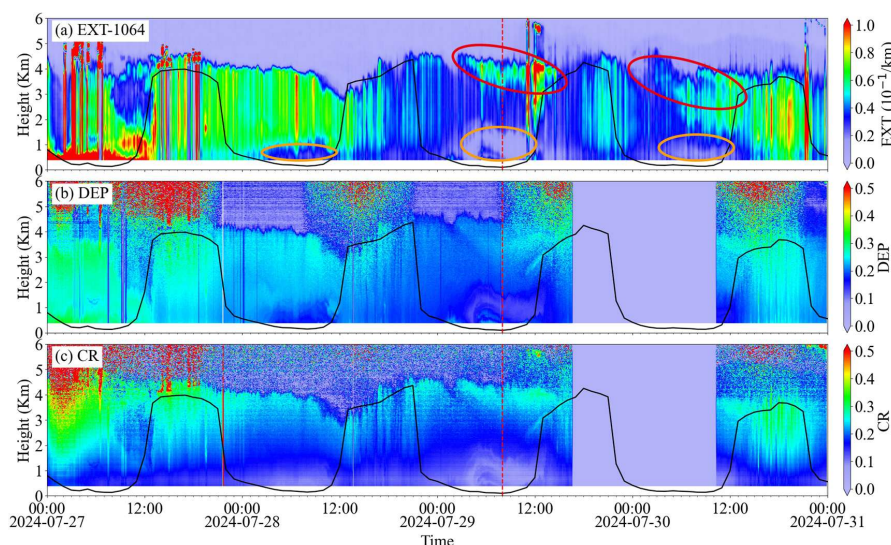


Fig. 5. Time-height cross-section of lidar observations during 27–30 July 2024 in Tazhong. The black lines represent the ABLH from the ERA-5 dataset, the yellow circles indicate clean air masses, the red circles indicate the upper dust layer with a higher extinction coefficient, and the red dashed line represents 08:00 BJT on 29 July.

Furthermore, the vertical profiles of the extinction coefficient, depolarisation ratio, and colour ratio at 08:00 BJT on 29 July are shown in Fig. 6a to view the differences between the upper and lower air masses in the residual layer. The extinction coefficient of the dense residual-layer dust peaked at approximately 3.6 km, close to the corresponding peaks in the depolarisation and colour ratios. The colour ratio indicates that the dust particle size was larger in the upper layer (approximately 3.5 km) than in the lower layer (approximately 1.0 km). The linear volume depolarisation ratio ranged from 0.12 to 0.22, indicating that dust aerosols dominated both layers. Meanwhile, the extinction coefficient in the upper layer was significantly higher than that in the lower layer, reaching approximately $0.26 \times 10 \text{ km}^{-1}$. A low extinction coefficient was observed between 0.7 and 1.3 km. This feature likely explains the vertical differences in dust properties, as it is closely linked to the influence of the NLLJs in the basin. As shown in Fig. 6b–c, the backward trajectories at 0.8 km and 3.54 km revealed that the lower clear air mass originated from the eastern Tarim Basin, whereas the upper air mass originated primarily from the northwestern Tarim Basin. Similar trajectory patterns were observed on 30 July.

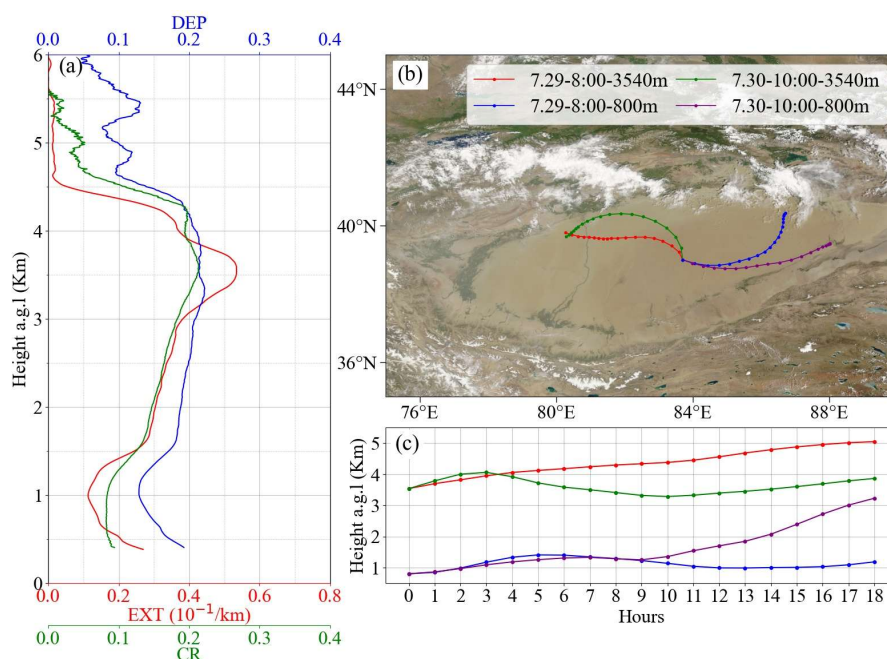


Fig. 6. Vertical profiles of the extinction coefficient (EXT), colour ratio (CR), and depolarisation ratio (DEP) at 8:00 BJT on 29 July 2024. The backward trajectories of the lower and upper layer air masses started at 8:00 BJT on 29 July and 10:00 BJT on 30 July.

3.3 The characteristics and formation of double low-level jets

The trajectories of the aforementioned air masses in both layers may be associated with special circulation at different heights over the Taklimakan Desert. Both horizontal circulation and vertical velocity are crucial factors that drive the three-dimensional distribution of dust in this area. As shown in Fig. 7a, the wind field at low altitudes was predominantly dominated by easterlies, with NLLJs featuring a maximum wind speed exceeding 10 m/s appearing at an altitude of 0.3–1.5 km above the ground. This is in agreement with the vertical distribution of the lower air mass in Fig. 6b. The NLLJs exhibited distinct diurnal variations, occurring between 22:00 and 10:00 BJT. In addition, the SLLJs were detected on 28–30 July, which mainly resided at an altitude of approximately 3 km, with a dominant northerly wind. In addition, SLLJs exhibit an obvious diurnal cycle, mostly occurring between 05:00 and 12:00 BJT. Thus, a DLLJ structure with a pronounced diurnal cycle formed during the continuous clear-sky period, a feature not previously reported in studies of aerosol vertical distribution. As shown in Fig. 7b, the vertical velocity indicates that downdraft air is mostly dominated near 2–3 km during the SLLJ period. Combined with the dust-layer evolution shown in Fig. 5a, the lower clean-air masses and upper dust layers with inconsistent physical properties matched very well with the DLLJ structure.

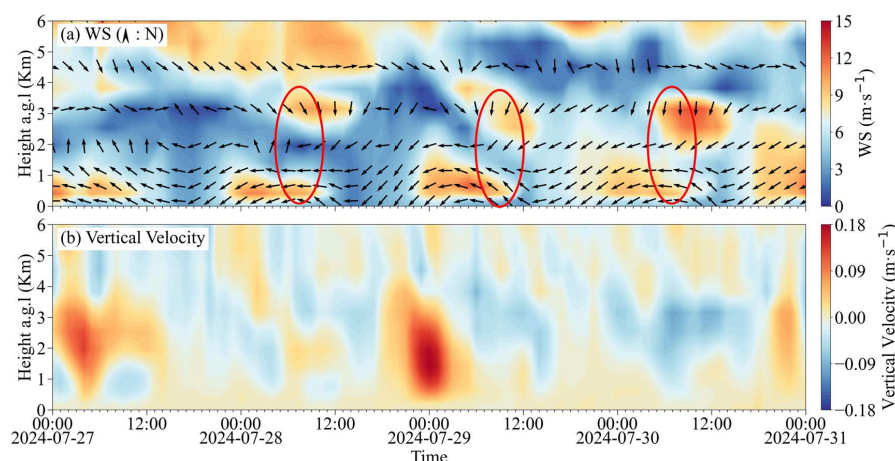


Fig. 7. Time-height cross-sections of the horizontal wind speed (a) and vertical velocity (b) at Tazhong during 27–30 July 2024. Black vector arrows represent the horizontal wind direction. The DLLJs are within the red circle.

To more clearly illustrate the structure of the DLLJs, Fig. 8 shows the horizontal wind fields at 600 hPa and 800 hPa levels at 08:00 BJT during the overlapping period of the SLLJ and NLLJs. At 600 hPa, the Tarim Basin remained under persistent anticyclonic circulation. Tazhong Station was predominantly governed by westerly winds on 27 July and by northwesterly winds over the following three days. At 850 hPa, the NLLJ structure existed throughout the four days, and the wind field was dominated by easterlies, which is the dominant wind direction in the desert. The meridional and zonal wind fields passing through Tazhong are shown in Fig. 9. Comparing the wind field on 27 July with that in the following days, it is clear that regardless of whether the DLLJs occur, the differences in the meridional and zonal cross-sections are quite obvious. As shown in Fig. 9b–d, when the DLLJs occurred on 28–30 July, the meridional wind field showed more pronounced upper-level subsidence over the desert, indicating that larger-scale synoptic conditions may contribute to SLLJ formation in the Taklimakan Desert. Meanwhile, complex terrain generated a region of upward convergence and upper-air turning near the NLLJ exit region (Fig. 8f–h), which, together with the upper-level descending airflow, formed strong SLLJs. Both NLLJs and SLLJs passed directly over the Tazhong area (Fig. 9). From the perspective of dust transportation, NLLJs can advect dust particles and promote their accumulation in the western part of the Taklimakan Desert (Fig. 9f–h). Combining the topographic effects, convergent uplift over the western or northwestern desert creates vertical transport channels for dust (Wang et al., 2026). The uplifted dust particles can then be transported hundreds of kilometres along SLLJs, reaching the central Taklimakan Desert and even extending further eastward. This unique formation process led to a suspended dense dust layer within the residual layer, which we term the large-scale VF DL. This mechanism also explains why the upper dust layer over Tazhong originated from the northwestern part of the desert, as evidenced by the backward trajectories.

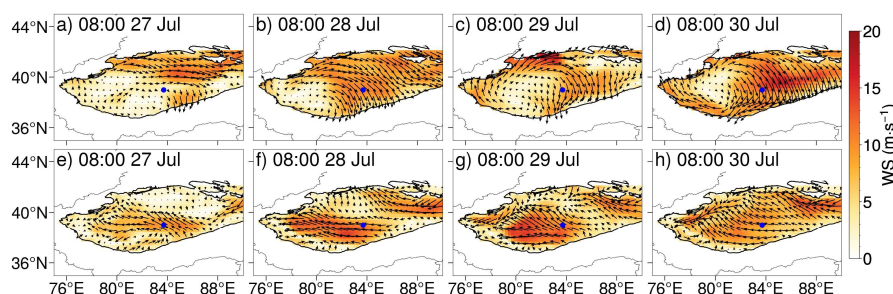


Fig. 8. Spatiotemporal evolution of the horizontal wind field at 600 hPa (a–d) and 850 hPa (e–h) during 27–30 July 2024, when the double low-level jets occurred. The blue point represents the location of the Tazhong site.

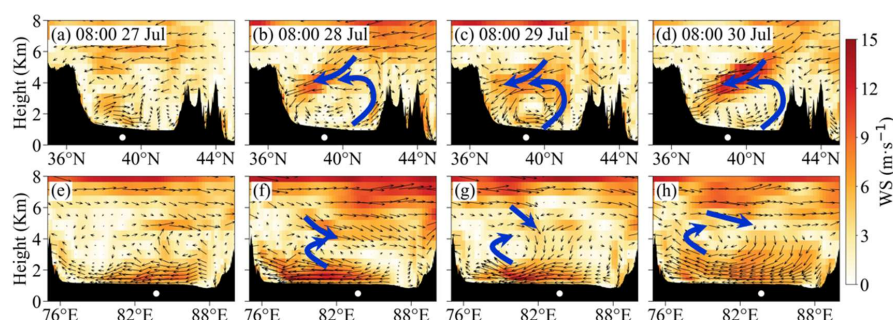


Fig. 9. Meridional and zonal wind fields passing through Tazhong (white point) at 8:00 BJT during 27–30 July 2024.

To explore the mechanism causing the occurrence of the SLLJs, the hourly average horizontal distribution of the geopotential height and wind field at the 500 hPa level and the wind speed at the 600 hPa level during 28–30 July 2024 are shown in Fig. 10. A deep low-pressure system was observed northwest of the Tarim Basin. In the early morning, the low-pressure system gradually moved eastward, reaching northwestern China by 08:00 BJT. The 588-geopotential contour covered the Tazhong region. Widespread cold-air intrusion and subsidence were observed over the northern, central, and eastern Taklimakan Desert, with Tazhong located at the western edge of subsiding airflow. This configuration generated strong northwesterlies at 600 hPa, which coupled with the ascending flow of the NLLJs, producing strong SLLJ development. As shown in Fig. 10c–d, the low-pressure system gradually retreated northward as it moved eastward, while the cold air invading the Taklimakan Desert dissipated. Combined with the evolution of the NLLJs, the diurnal cycle of the low-pressure system further drove the diurnal variation of the DLLJs during this period.

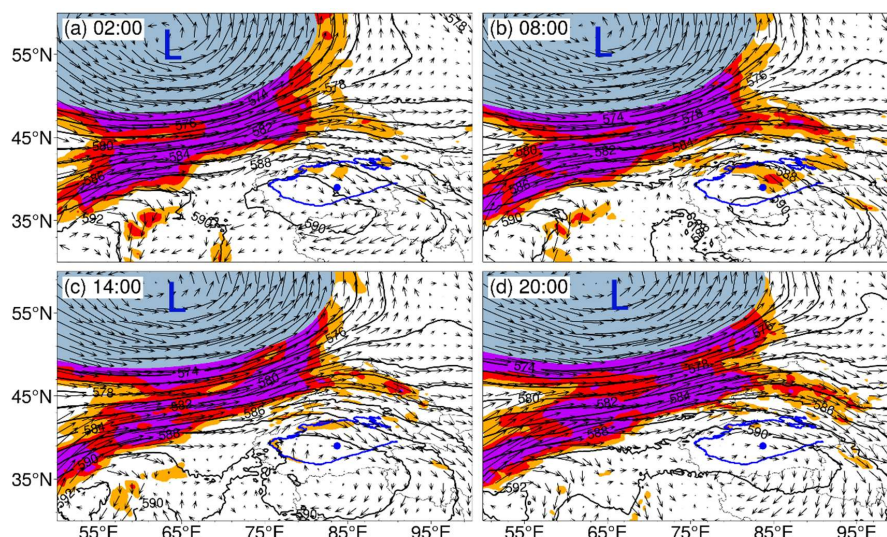


Fig. 10. Hourly mean horizontal wind speed at 600 hPa (orange, red, and purple shading indicate 8, 10, and 12 m/s, respectively), geopotential height (blue shading < 572 dagpm), and wind field at 500 hPa during 28–30 July 2024. The area enclosed by the blue line represents the TB, and the blue dot represents Tazhong Station.

4. Long-term lidar evidence of double low-level jets inducing dust vertical folding

To verify whether DLLJs and VFDLs are widespread in the Taklimakan Desert, based on lidar observations at Tazhong and the ERA5 reanalysis dataset from May to August (2023–2025), the occurrence frequency of DLLJs was approximately 19% (73 days), and that of VFDLs was approximately 36% (133 days), with their co-occurrence frequency being 9% (33 days), indicating that DLLJs are not the sole factor driving VFDLs captured by lidar observations. Once VFDLs occur, high dust loading in the residual layer can affect CBL development. Therefore, analysing the mechanisms that favour VFDL formation enhanced understanding of dust transport channels in the Taklimakan Desert and facilitated the association between dust in the residual layer and the CBL. Thus, the synoptic patterns corresponding to all VFDLs were statistically analysed and further classified into three types using the PCT method: 1) the northwest high-pressure pattern, which refers to high pressure situated to the northwest of the Taklimakan Desert (51 days); 2) the northwest low-pressure pattern, which refers to low pressure situated to the northwest of the Taklimakan Desert (62 days); and 3) the behind the westerly trough pattern, which refers to the westerly trough located to the northeast of the Taklimakan Desert (20 days).

The circulation pattern of the northwest high-pressure type is shown in Fig. 11 a1–f1. On the 500 hPa isobaric surface, there was an obvious high-pressure system to the northwest of the Taklimakan Desert, and the area above the Taklimakan Desert was dominated by westerly airflow south of the high-pressure system. A distinct negative geopotential height anomaly over the northern part of the desert indicated a mid-tropospheric trough over the Altai Mountains. Under the blocking effect of the Tibetan Plateau, the northwest wind behind the trough turned eastward to the entrance of the Tarim Basin (Mao et al., 2019). Influenced by the upper-level synoptic conditions, wind speed increased, enhancing dust emissions. On the 850 hPa isobaric



surface, an anomalously warm high-pressure system was also observed to the northwest of the Taklimakan Desert, and cold air affected by this high-pressure system moved toward the desert. The geopotential height in the desert shows a distribution of high in the north and low in the south, but the pressure gradient is weak. The low-level wind field in all areas of the basin, except for the opening, was relatively weak, particularly in the northern part of the basin. Under the northwest high-pressure pattern, a distinct northwesterly wind anomaly occurs over the northern basin, limiting westward dust transport (Fig. 11 f1). Under these influences, as illustrated in Fig. 12a, dust first accumulated in the southern basin, driven by strong northeasterly winds over its southeastern part. It then forms a vertical transport channel under the topographic forcing of the Tibetan Plateau and is finally transported to the upper atmosphere over Tazhong via upper-level flow turning.

The circulation pattern of the northwest low-pressure type is shown in Fig. 11 a2–f2. Contrary to the northwest high-pressure type, there is a Central Asian cyclonic vortex to the northwest of the basin at the 500 hPa isobaric surface, and the area above the basin is dominated by airflow along the southern flank of the vortex, producing northwesterly winds. The cold air carried by the northwest winds crosses the Pamir and Tianshan Mountains and invades the basin. Meanwhile, there was a negative geopotential height near the Mongolian Plateau in the eastern part of the basin. Under the influence of low-pressure activities in this area, easterly winds were facilitated to enter the basin through the opening (Feng et al., 2023). On the 850 hPa isobaric surface, the geopotential height in the southwest of the basin was relatively low. Under the influence of the strong pressure gradient formed by the high geopotential height area in the northeast of the basin, the entire basin was dominated by northeasterly winds. Simultaneously, a distinct southeasterly wind anomaly over the desert hinterland weakened dust accumulation in the southern part of the basin and facilitated westward dust transport. Similar to the case during 27–30 July 2024, dust accumulated and lifted in the western basin and was ultimately transported to the central basin under the influence of a strong upper-level cold-air invasion (Fig. 12b).

The large-scale circulation associated with the westerly trough is shown in Fig. 11. a3–f3. At 500 hPa, the area to the northwest of the basin is dominated by an abnormally strong warm high pressure, creating a pronounced "high-in-the-north and low-in-the-south" geopotential gradient. The westerly trough was positioned over the Mongolian Plateau and the area north of the basin, whereas a high-pressure ridge extended to the northwest of the basin. The Taklimakan Desert, situated ahead of the ridge and behind the trough, is consequently controlled by the northwesterly flow. Through positive vorticity advection and baroclinic instability, the westerly trough facilitates the southward transport of low-level cold air, which in turn promotes trough development and the eastward progression of surface high pressure, thereby intensifying wind speeds at the basin opening. Meanwhile, the northwesterly flow over the basin remained relatively weak, favouring dust retention within the basin (Zhu et al., 2023). At the lower level (850 hPa), the area northwest of the Taklimakan Desert is governed by an abnormally strong thermal high pressure, with geopotential heights exceeding the climatic mean. This high-pressure system forms a steep pressure gradient with a thermal low over the central basin, generating strong easterly winds across the eastern basin. Under



the influence of this low-level easterly flow, dust was advected toward the northwestern basin, where it was lifted and subsequently transported to the central basin by the weak upper-level northwesterlies (Fig. 12c).

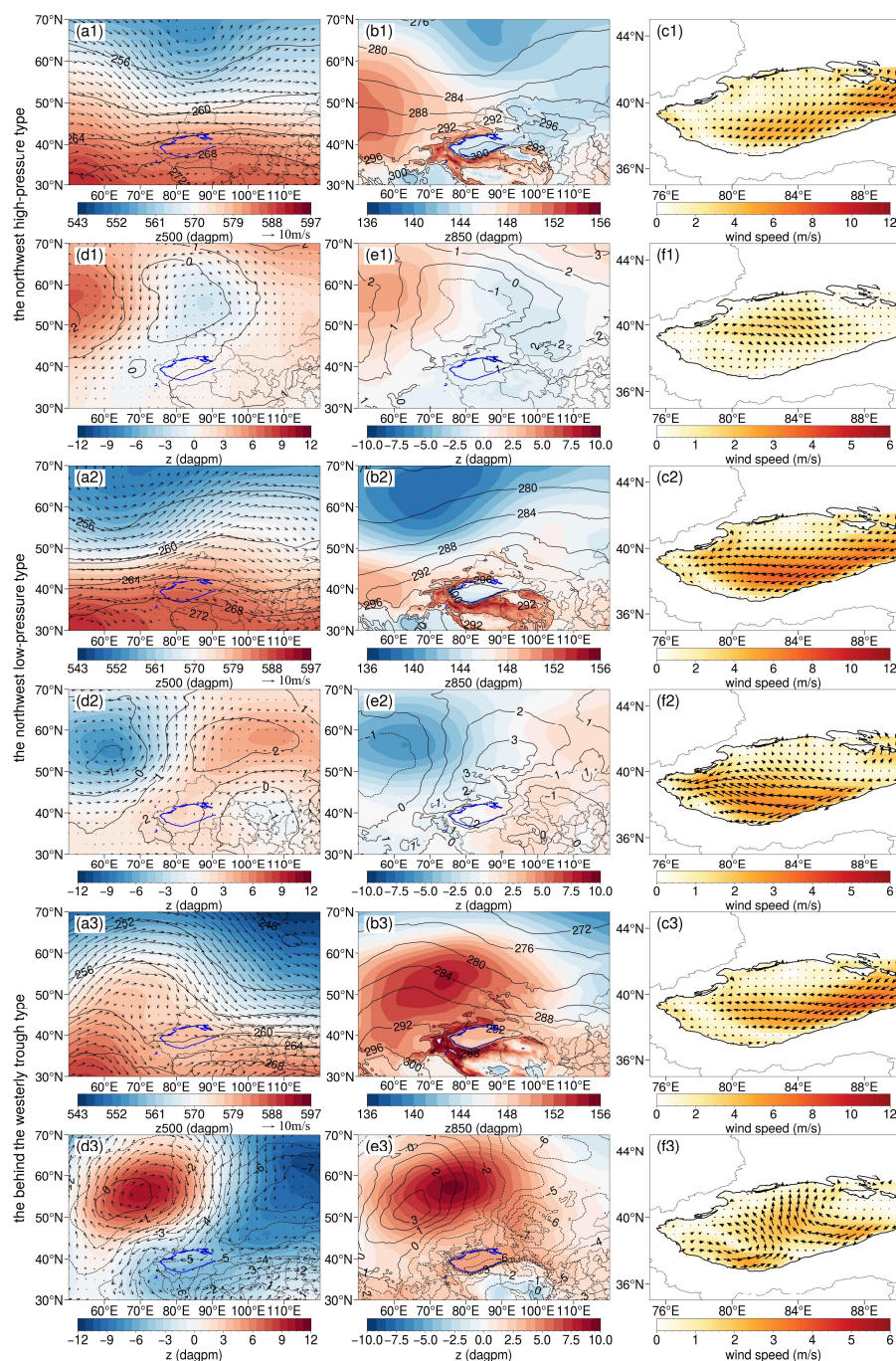


Fig. 11. Circulation patterns of the three synoptic types. (a) 500 hPa synoptic fields: black contours denote temperature, shading denotes geopotential height, and black vectors denote wind field; (b) 850 hPa synoptic fields: black contours denote temperature and shading denotes geopotential height; (c) 850 hPa wind field; (d) 500 hPa geopotential height anomaly (shading), temperature anomaly (black contours), and wind anomaly; (e) 850 hPa geopotential height anomaly



355 and temperature anomaly; (f) 850 hPa wind anomaly.

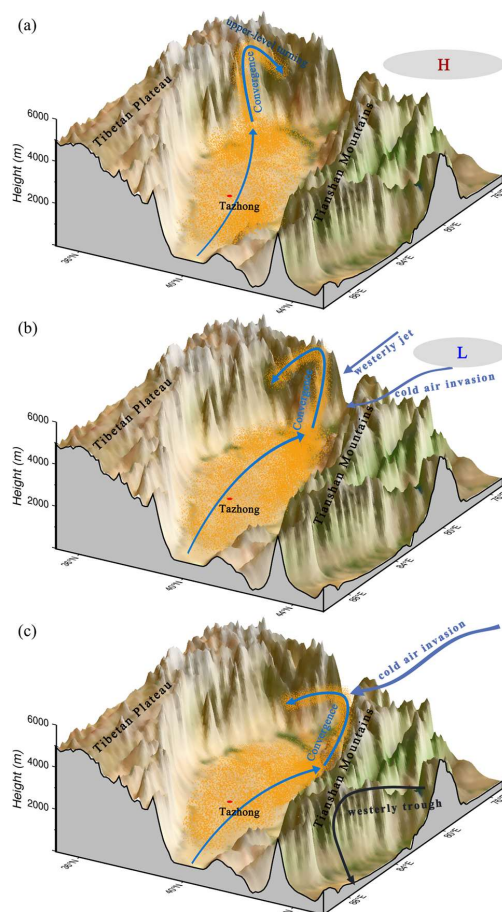


Fig. 12. Schematic diagram of three synoptic patterns: (a) northwest high-pressure type, (b) northwest low-pressure type, and (c) behind the westerly trough type.

5. Discussion

360 This study systematically revealed the DLLJ structure over the Taklimakan Desert and its driving mechanism for the VFDL based on high-resolution lidar observations. To some extent, the comparative analysis highlights the complementary strengths and weaknesses of ground-based lidar observations and the MERRA-2 reanalysis dataset, which differ in their ability to resolve features across temporal and spatial scales because of inherent differences in resolution. The intrinsically coarse spatiotemporal resolution of the MERRA-2 reanalysis dataset constrains its capacity to resolve detailed dust processes in global climate models (Gelaro et al., 2017; Randles et al., 2017; Yao et al., 2020; Wang et al., 2020; Xu et al., 2020; Li et al., 2026).
 365 In other words, inadequate representation of regional dust transport and three-dimensional structure can introduce substantial uncertainties into estimates of the regional dust cycles. Furthermore, these regional-scale uncertainties may propagate through coupled dust–radiation–weather–climate interaction processes, potentially affecting climate simulations at the global scale (Lu



et al., 2023; Tindan et al., 2023; Liu et al., 2022; Li et al., 2025). Polar-orbiting satellites generally overpass a given region only once or twice per day and are thus unable to capture complete and detailed information on atmospheric processes on a daily scale. Geostationary satellites enable continuous monitoring of regional aerosol distribution and transport; however, they fail to accurately analyse the detailed vertical structure of aerosols. Single-station lidar measurements cannot characterise wide spatial variations and therefore provide only limited constraints on the model biases. However, long-term continuous measurements with high spatiotemporal resolution can serve as a critical supplementary approach to the MERRA-2 reanalysis dataset for depicting regional dust evolution processes associated with the atmospheric boundary layer, especially over complex terrains, providing a robust benchmark for model evaluation and refinement. In particular, the distinct diurnal evolution and fine vertical stratification structure of the VFDL identified in this study cannot be resolved by either satellite products or reanalysis data, filling the gap of high-frequency vertical observations of dust-boundary layer coupling in desert basins. However, a significant amount of information remains unmonitored. For instance, the spatial extent and distribution of DLLJs and VFDLs may have eluded detection by lidar stations. In addition, the spatial extent over which these VFDLs extend and how they can be more comprehensively characterised remain unknown. From this perspective, substantial knowledge gaps remain in our understanding of aerosol processes at the regional scale, as revealed by synergistic analyses of observations and reanalysis datasets.

Low-level jets are widely observed across diverse climatic regimes worldwide and occur over a broad range of underlying surfaces, including plains, coastal regions, mountainous terrain, and basins, with some areas of complex topography exhibiting particularly high frequencies of low-level jet activity (Rife et al., 2010; Weide Luiz and Fiedler, 2024). When low-level flows impinge on high-mountain barriers, mechanical blocking and topographic channelling can induce flow deflection and acceleration (Acosta and Huber, 2017). These flows can generate pronounced low-level convergence and ascent over windward slopes, mountain-front regions, and jet-exit or deceleration zones (Wu et al., 2021; Wang et al., 2026). Thus, an important vertical aerosol transport channel is established. As a regional-scale heat source, high mountain terrain is likely to perturb regional circulation during summer. This perturbation favours the formation of a high–low-level configuration that promotes vertical coupling between low-level jets and higher-level divergence, potentially producing a DLLJ structure similar to that described in this study. Over complex terrains, DLLJs act as a key dynamical bridge connecting horizontal aerosol transport near the surface and transboundary transport in the free troposphere (Ratnam et al., 2018; Caton Harrison et al., 2021; Song et al., 2024). In addition, strong wind speeds and shear within the DLLJ trigger alternating convergence, ascent, subsidence, and turbulence around the jet cores. These processes redistribute dust among the surface layer, residual layer, and lower free troposphere, forming a unique vertically folded transport pathway. For example, in this study, the VFDLs were typically located near or slightly below the maximum mixed-layer height. The downward momentum during the mid-morning period due to the decay of the NLLJ and dust from the residual layer entrained and vertical mixing during the development of the mixed layer



400 after sunrise would rapidly increase the concentration of air pollutants on the surface (He et al., 2023). DLLJs simultaneously promote high concentrations at low altitudes and the formation of elevated polluted layers. Ground-based in-situ monitoring is unable to capture these frequent and periodic elevated polluted layers. As a result, they are often overlooked because of limitations in current monitoring methods (Zhou et al., 2024; Lin et al., 2026). Meanwhile, the sources and characteristics of elevated polluted layers in the residual layer vary across terrain types, leading to substantial differences in their effects on
 405 boundary layer development on the following day. However, the underlying mechanisms governing these terrain-dependent differences remain unclear.

In this study, ground-based lidar observations during 2023–2025 at Tazhong in the hinterland of the Taklimakan Desert were used to explore DLLJs and clarify the full mechanisms driving suspended dense VFDs in the residual layer. To our knowledge, this study provides the first ground-based lidar evidence linking DLLJs to VFDs over the Taklimakan Desert and
 410 surrounding regions within the framework of the Global Climate and Environmental Observation Network over the dust belt (Huang et al., 2024). Similarly, existing global lidar networks span the world, with EARLINET covering Europe, AD-Net covering East Asia, and LALINET covering Latin America, in addition to the global-scale MPLNET. Many of these network stations are situated in regions such as plateaus, mountains, coastal regions, and basin systems, providing ideal natural experimental platforms for studying aerosol processes over complex terrains that are poorly represented by low-resolution
 415 reanalysis datasets. Their potential for investigating terrain-induced aerosol uplift and vertical redistribution remains insufficiently explored, especially for the diurnal evolution of aerosol-boundary layer interactions. The observation and analysis framework established in this study can be extended to stations across these networks, facilitating comprehensive studies of boundary layer dynamics and processes, dust aerosols, air pollution, and other phenomena under varying topographic and climatic conditions. Such observations worldwide will provide stronger constraints on climate models and help mitigate
 420 resolution-related uncertainties in refining aerosol radiative forcing and ice-nucleating particle budgets in global climate projections.

6. Conclusion

In summary, this study analysed continuous clear-sky conditions with a deep CBL during 27–30 July 2024 by combining ground-based lidar observations and reanalysis datasets. The phenomenon of DLLJs over the Taklimakan Desert was first
 425 reported based on lidar observations. Its effects on the vertical dust distribution, formation mechanism, and diurnal variability were then analysed. Moreover, DLLJs and VFDs were identified, and the synoptic patterns favourable for the occurrence of VFDs were further analysed. The results showed that the dust concentration in the residual layer varied substantially during 27–30 July, whereas the CBL height remained steady at approximately 4 km. The two variables did not follow the typical positive feedback relationship under continuous clear-sky conditions, indicating that the dust–ABL interaction is highly



430 complex over the Taklimakan Desert. Analysis of the lidar observations in Tazhong revealed the presence of VFDLs in the early morning. The lower layer was affected by NLLJs, whereas the upper layer was influenced by northwesterly SLLJs. The unique vertical dust distribution was affected by multiple factors: NLLJs transported and accumulated dust in the western part of the Taklimakan Desert. Dust is then vertically transported to the upper layer through the convergent upward area generated by topographic effects. Meanwhile, the upper-level low-pressure system in the northwest of the Taklimakan Desert resulted in
 435 sinking airflow caused by cold air invasion, which, coupled with the airflow ascending to the upper air of the basin through convergence driven by the NLLJs, formed SLLJs and transported dust to the RL over Tazhong. The DLLJs exhibited pronounced diurnal variations and occurred at approximately 8:00 BJT. Furthermore, a statistical analysis of lidar and wind field data at Tazhong from May to August (2023–2025) revealed that both DLLJs and VFDLs occurred, accounting for 19% and 36% of the data, respectively, with 9% occurring simultaneously. This indicates that the DLLJs over the Taklimakan Desert
 440 are not the sole factor driving the VFDLs phenomenon. Synoptic classification of VFDL events showed that the northwest low-pressure pattern (the case in this study) was the most favourable for VFDL occurrence (47%), followed by the northwest high-pressure pattern (38%), and the pattern behind the westerly trough was the least favourable (15%).

These findings on DLLJs and VFDLs provide a new perspective for studying dust-boundary layer interactions over complex terrain. However, some limitations still exist. First, ground-based lidar observations and reanalysis datasets were used
 445 only to explore the selected continuous clear-sky case and to conduct statistics on VFDLs and DLLJs. Second, seasonal differences and annual variations in the DLLJ and VFDL remain to be explored. Third, the physical mechanism proposed in this study lacks quantitative verification through high-resolution numerical simulations. Future studies should combine these observations with model simulations to assess the impacts of the VFDL phenomenon on deep CBL and the regional dust cycle.

450 **Author contributions**

Tian Zhou: Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Data curation, Conceptualisation. Xiaokai Song: Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. Zhongwei Huang: Software, Resources, Methodology, Investigation, Formal analysis, Data curation. Zikai Lin: Software, Resources, Methodology, Investigation, Formal analysis. Keyu Zhang: Software, Resources,
 455 Methodology, Investigation, Formal analysis. Yonghong Gu: Methodology, Resources, Software, Data curation. Dongsheng Wu: Software, Resources, Methodology, Data curation. Xingran Li: Software, Resources, Methodology, Data curation. Qili Gao: Software, Resources, Methodology, Data curation.

Competing interests



The authors declare that they have no competing interests.

460 **Data availability**

The ERA5 dataset can be found at <https://cds.climate.copernicus.eu>. The HYSPLIT data is sourced from NOAA and can be accessed at <https://www.arl.noaa.gov/hysplit/>. The MERRA-2 datasets presented in this study are openly available at <https://giovanni.gsfc.nasa.gov>, and MODIS observations are openly available at <https://ladsweb.modaps.eosdis.nasa.gov/>. The Cost733class software can be obtained at <http://cost733.met.no/>.

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