



OPEN Windblown dust in the Tarim basin, Northwest China

Xiao-Xiao Zhang^{1,2✉}, Xing-Hua Yang^{3,4}, Fan Yang⁴, Jia-Qiang Lei¹, Mamtimin Ali⁴, Sheng-Yu Li¹, Lian-You Liu^{5,6}, Yi-Bo Xue^{1,7}, Zi-Fa Wang², Wen-Jun Tian^{1,7}, Yong-Dong Wang¹ & Xiao Tang²

Tarim Basin in western China is home to the world's second-largest mobile dune desert, Taklimakan Desert, and it's one of Asia's primary sources of sand and dust storm. Observations of windblown dust are insufficient over this hyper-dry inland region. Here we present a comprehensive study based on consecutive in-situ field observations, meteorological records, environmental monitoring data and satellite measurements over the Tarim Basin for a full year in 2015. The results show that during the severe sand and dust storm events, the observed ambient PM₁₀ (particulate matter with an aerodynamic diameter $\leq 10 \mu\text{m}$) concentration rises rapidly, with a maximum value exceeding 10,000 $\mu\text{g}/\text{m}^3$ per hour, while wind speeds reach 10–30 m/s and visibility is reduced to less than 10 m. Soil particulates can be blown vertically into the atmosphere at a height of 3–12 km. High volumes of dust deposition were measured at environmental monitoring stations, ranging from 1764 to 3800 g/m² yr. Those significant flux levels of ambient particulate matter (PM) concentrations and dust depositions are strongly associated with frequent dust occurrence in the arid environment of the Tarim Basin. Satellite measurements of aerosol optical depths (AOD) show a broad spatial pattern of dust aerosols distribution over the basin, with dense dust remaining suspended for long periods of time (3–5 months in spring and summer seasons). The wind regimes, basin-like topography, thermodynamic condition, and loose sandy surfaces greatly affect the regional aeolian dust environment in the Tarim Basin, which lead to a significantly high dust emission, ambient PM concentration and dust deposition.

Keywords Tarim basin, Sand desert, Wind erosion, Dust aerosol

Airborne dust is one of the important atmospheric constituents which significantly influences the global energy, carbon cycles and solar radiation^{1–3}. These dusts affect the radiative flux directly and indirectly through short-wave and long-wave radiation^{4,5}. The long-range transport of airborne dust and its impacts on biogeochemical cycles have been widely concerned^{6–9}. However, dust aerosols are still inadequately observed over the global source areas^{10–14}. This greatly limits our deep understanding of dust movement on earth surfaces as well as the global dust cycles. Therefore, it requires more measurements and sufficient observations over the data-sparse arid environment.

The Tarim Basin in western China is encircled by the Tianshan Mountains (average altitude above 4000 m a.s.l.), the Pamir Plateau (average altitude above 4500 m a.s.l.), the Kunlun Mountains (average altitude above 5500 m a.s.l.), the Altun Mountains (average altitude above 4500 m a.s.l.), and the Tibetan Plateau (average altitude above 5500 m a.s.l.). The basin distributes the world's second-largest desert of moving sand dunes, the Taklimakan Desert (Fig. 1). Aeolian dust events frequently occur in the dryland area with above 60 d per year^{15,16}. This desert region is consistently recognized as one of the primary sources of spring dust storms in Asia and has received widespread attention^{14,17,18}. It is reported that the soil dust emitted from the Taklimakan Desert can be transported up to 8000 km away to the North Pacific Ocean, Arctic region and the North American continent^{19,20}. Thus, the dynamic processes of windblown dust movement in the Tarim Basin are of interest

¹State Key Laboratory of Ecological Safety and Sustainable Development in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China. ²State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China. ³School of Geographical Sciences, Shanxi Normal University, Taiyuan 030032, China. ⁴Taklimakan National Station of Observation and Research for Desert Meteorology in Xinjiang/Taklimakan Desert Meteorology Field Experiment Station, Institute of Desert Meteorology, China Meteorological Administration, Urumqi 830002, China. ⁵Key Laboratory of Environmental Change and Natural Disaster, Ministry of Education, Beijing Normal University, Beijing 100875, China. ⁶Key Laboratory of Tibetan Plateau Land Surface Processes and Ecological Conservation (Ministry of Education), Qinghai Normal University, Xining 810016, China. ⁷University of Chinese Academy of Sciences, Beijing 101408, China. ✉email: zhangxx@ms.xjb.ac.cn

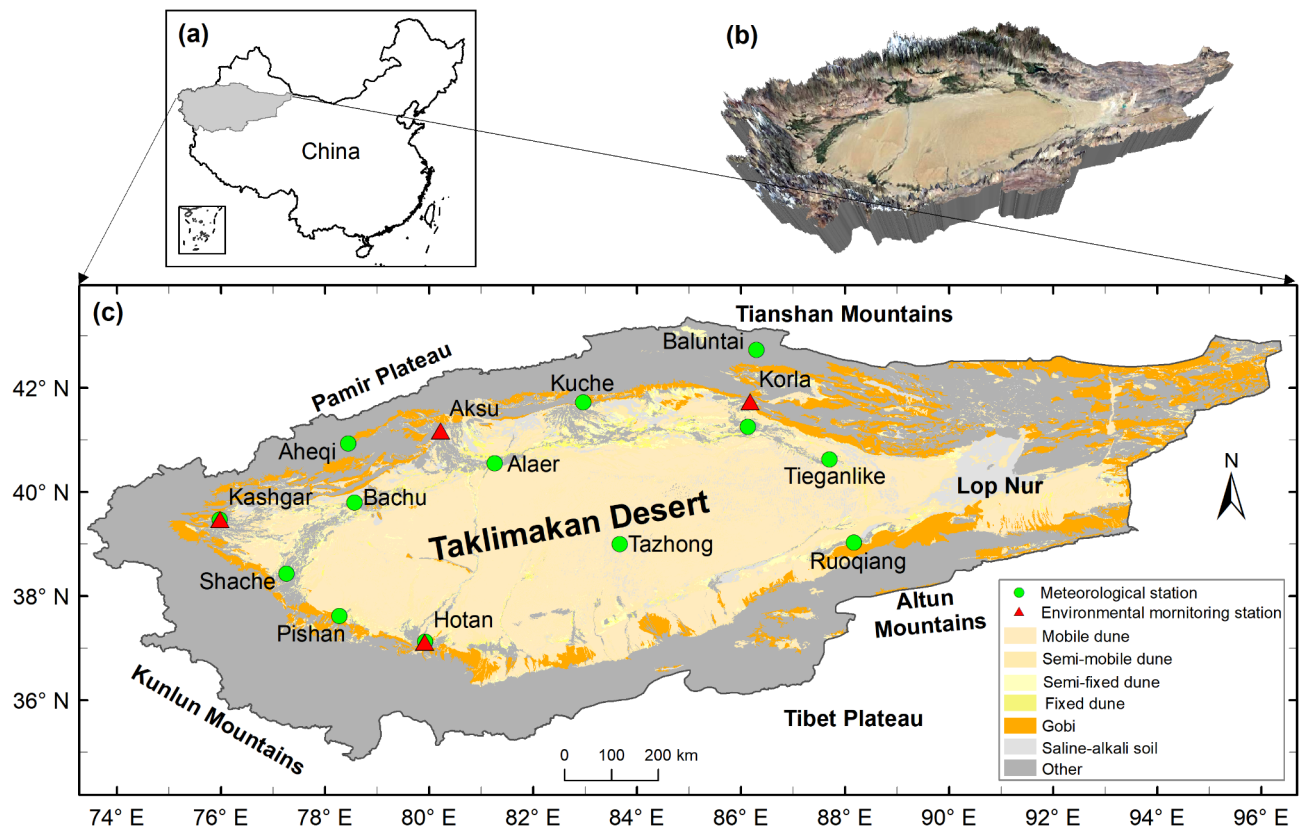


Fig. 1. Location of the Tarim Basin in western China (a). Three-dimensional terrain and satellite image of the Tarim Basin (b). Desert environment in Tarim Basin (c). The environmental monitoring stations and meteorological stations are marked with red triangles and green dots, respectively. Land use types are identified across the Tarim Basin according to Wang et al.⁴⁵. The map was created using ArcGIS 10.6 (<https://www.esri.com/en-us/arcgis/geospatial-platform/overview>).

to the wind erosion, atmospheric physics, and dust research communities. The early modern record on desert landscape and aeolian dust in the Tarim Basin was made by Richthofen²¹. Scientific quantitative studies of windblown dust over the Tarim Basin began in the late twentieth century. Zhang et al.¹⁰ made the first quantitative estimation of dust release in the Tarim Basin based on in-situ observations and numerical calculation. Ginoux et al.¹¹ simulated global dust emissions and suggested uncertainties for the Tarim Basin. Huneeus et al.²² further proposed uncertainties in dust simulation based on outputs from 15 global dust aerosol models. To narrow these uncertainties, physical mechanisms of aeolian dust processes have been studied step by step^{11,13,23–35}. Accurate estimation of dust fluxes requires sufficient multi-source observations, improved parameterization schemes and adequate model validation¹⁴. Laurent et al.³⁶ established a map of the aerodynamic roughness length Z_0 in East Asia from the composition of protrusion coefficient derived from the POLDER-1 bidirectional reflectance distribution function (BRDF), and retrieved erosion thresholds of 7 m/s in the sandy deserts of the Taklimakan. Yang et al.^{15,37,38} determined the wind speed threshold range of 4.9–9.2 m/s based on field experiments in the Tarim Basin, and suggested that soil moisture (relative soil moisture above 0.025) may significantly affect the threshold friction velocity. Li et al.^{39,40} developed a land-use dataset from the latest Land Cover data to improve the simulation capability of the Weather Research and Forecasting model coupled to Chemistry (WRF-Chem) in the Tarim Basin. Meng et al.⁴¹ observed and modeled a severe sand and dust storm event occurring in the Tarim Basin and suggested that more than 51% of the emitted soil dusts is persistently suspended over the atmosphere. The dynamical, thermal, and topographic factors together influence the meridional transport of windblown dust in the Tarim Basin^{15,41,42}. Both meteorological conditions and large-scale circulation affect the aeolian dust activity in the Tarim Basin⁴¹. In addition, the up-and-down terrains of sand-dune landscapes may considerably impact regional dust emissions and the micrometeorological environment^{37,38}. The large uncertainty in the current estimates of dust emission, transport, and deposition fluxes over source regions, reflects one aspect that, could be attributed to the shortage of surface observational data^{11,14}. Ground-based observations in the Tarim Basin are sporadic and inadequate. Space-borne satellite measurements make up this situation to some extent and provide a timely way to portray the synoptic process of aeolian dust events. Various satellite instruments, such as the Multi-angle Imaging Spectroradiometer (MISR), the Ozone Monitoring Instrument (OMI), the Total Ozone Mapping Spectrometer (TOMS), the Moderate-resolution Imaging Spectroradiometer (MODIS), and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), allow the detection and monitoring of the spatiotemporal variation of atmospheric dust aerosols over a large area and with a high

observation frequency. The dust aerosol optical depth (AOD) and the Ångström exponent (AE) measured by the above satellite instruments are helpful to reflect the aeolian dust activities, in particular the horizontal and vertical dust distribution and dust transport^{1,41,43,44}. Current monitoring measurements via space satellites have their limitations in estimating aeolian dust, e.g., the relative coarse resolution of space-grid observations, insufficient detection due to abundant cloud cover, and discontinuous sampling. Therefore, there is an urgent need for quantitative analysis and multi-source observations in dust measurements.

Ground-based observations are still limited in the desolate desert regions of western China¹⁴. Continuous and long-term multi-source observations contribute to our further insight into the characterization of aeolian dust activities over the hyper-dry areas. This study presents an investigation based on consecutive in-situ field observations, meteorological records, environmental monitoring data, and satellite products in the Tarim Basin for a full year in 2015. The spatiotemporal variability of airborne dust and its associated influences (e.g., wind regimes, precipitation, atmospheric circulation, etc.) are analyzed and discussed. It is intended to give a detailed context of the windblown environment in this specific Asian dust source region. Meanwhile, we hope to provide insights into aeolian dust activities over complex basin terrain and improve dust simulation and model validation.

Materials and methods

Study area

The Tarim Basin in western China has an area of more than 4×10^5 km². Mobile dunes, oases, yardangs, gravel Gobi, and saline and alkaline soil crusts are widely distributed over the basin. It has the world's second-largest mobile dune desert, the Taklimakan desert (Fig. 1), with area of 3.3×10^5 km²¹⁵. In the sand desert, there are various types of sand dunes, e.g., barchan dune, longitudinal dune, and pyramid dune, etc. This region suffers from perennial climatic drought, aeolian land desertification, and severe sand and dust storms³⁸. The average annual precipitation is less than 100 mm in the desert areas, while its potential evapotranspiration (PET) can exceed 3000 mm/yr¹⁴. It's a hyper-dry continental arid basin with intense wind erosion, dust emission and aeolian dust storms^{30,46}. Windblown sand and dust storms dominate the Tarim Basin throughout the year¹⁵.

Ground-based observation data

Surface observation data in the Tarim Basin were mainly collected from meteorological observations, environmental monitoring records, and in-situ field investigations. Meteorological data (e.g., wind speed, air temperature, precipitation, atmospheric visibility, air humidity, and barometric pressure) are regularly observed by the China Meteorological Administration (CMA). The 13 meteorological stations in the Tarim Basin for this study are illustrated in Fig. 1c and summarized in the Supplementary Material Table S1. The dust weather is primarily classified into four types according to the criteria of atmospheric visibility and surface wind speed as listed in the Supplementary Material Table S2. Those four types of dust weather are dust in suspension (visibility ≤ 10 km), blowing dust ($1 \text{ km} \leq \text{visibility} < 10 \text{ km}$), dust storm ($0.2 \text{ km} \leq \text{visibility} < 1 \text{ km}$), and severe dust storm (visibility $< 0.2 \text{ km}$)^{16,17}.

Environmental monitoring data for ambient PM₁₀ and PM_{2.5} concentrations, and atmospheric dust deposition at four environmental monitoring cities (Korla, Aksu, Kashgar and Hotan) in the Tarim Basin were obtained from the Ministry of Ecology and Environment (MEE) of the People's Republic of China. Meanwhile, we observed the atmospheric dust deposition in Tazhong, the centre of the Taklimakan (Fig. 1). Ambient PM₁₀ and PM_{2.5} concentration were measured by β -ray absorption method⁴⁷. The sampling time for PM concentration measurement is 1 h and the detection limit is 10,000 $\mu\text{g}/\text{m}^3\cdot\text{h}$. For statistical analysis, the PM₁₀ concentration was considered to be 10,000 $\mu\text{g}/\text{m}^3\cdot\text{h}$ if it exceeded the maximum limit of the instrument. Dust deposition is collected by means of glass cylinders using the gravimetric method⁴⁸. The cylinder is filled with a solution of ethylene glycol (C₂H₆O₂) and water before the sampling experiment. This allows dust particles to be effectively trapped and evaporation to be reduced. The glass cylinder is installed on a 10 m high tower. The deposited dust particles were gravimetrically weighed following collection from glass cylinders, which involved rinsing their contents and oven-drying at 105 °C to remove moisture prior to measurement⁴⁸.

Satellite data

We used the dust AOD and AE data from MISR satellite instrument⁴⁹. The satellite instruments were launched on December 18, 1999 and observed at wavelength of 550 nm. MISR can distinguish different types of atmospheric particles, which contribute to study cloud formation and the various coverings on the Earth's surface⁵⁰. Vertical distribution data of dust AOD were derived from the CALIPSO satellite product of Vertical Feature Mask (VFM) level 2 version 4.10 at 532 nm (https://eosweb.larc.nasa.gov/project/calipso/cal_lid_l2_vfm-standard-v4-10). The CALIPSO satellite can detect the vertical structure and properties of global aerosols using active lidar, providing a three-dimensional view of cloud and aerosol formation and evolution⁵¹.

Results and discussion

Windblown dust in the Tarim basin

Wind erosion and sand dust weather occur frequently in the Tarim Basin^{15,52}. Figure 2 shows the monthly variation of aeolian dust frequency in the Tarim Basin in 2015, including dust in suspension, blowing dust, dust storm and severe dust storm. Dust in suspension accounted for 77.5% of the total dust days, followed by blowing dust (19.1%), dust storm (2.3%) and severe dust storm (1.1%). Aeolian dust events frequently occurred between March and August as depicted in Fig. 2. Spring (March–April–May) is the windblown dust active season of the year, followed by summer (June–July–August), autumn (September–October–November) and winter (December–January–February). Table 1 lists the main windblown dust events in the Tarim Basin during spring dust active season in 2015. These dust episodes were accompanied by strong winds, low visibility, dense

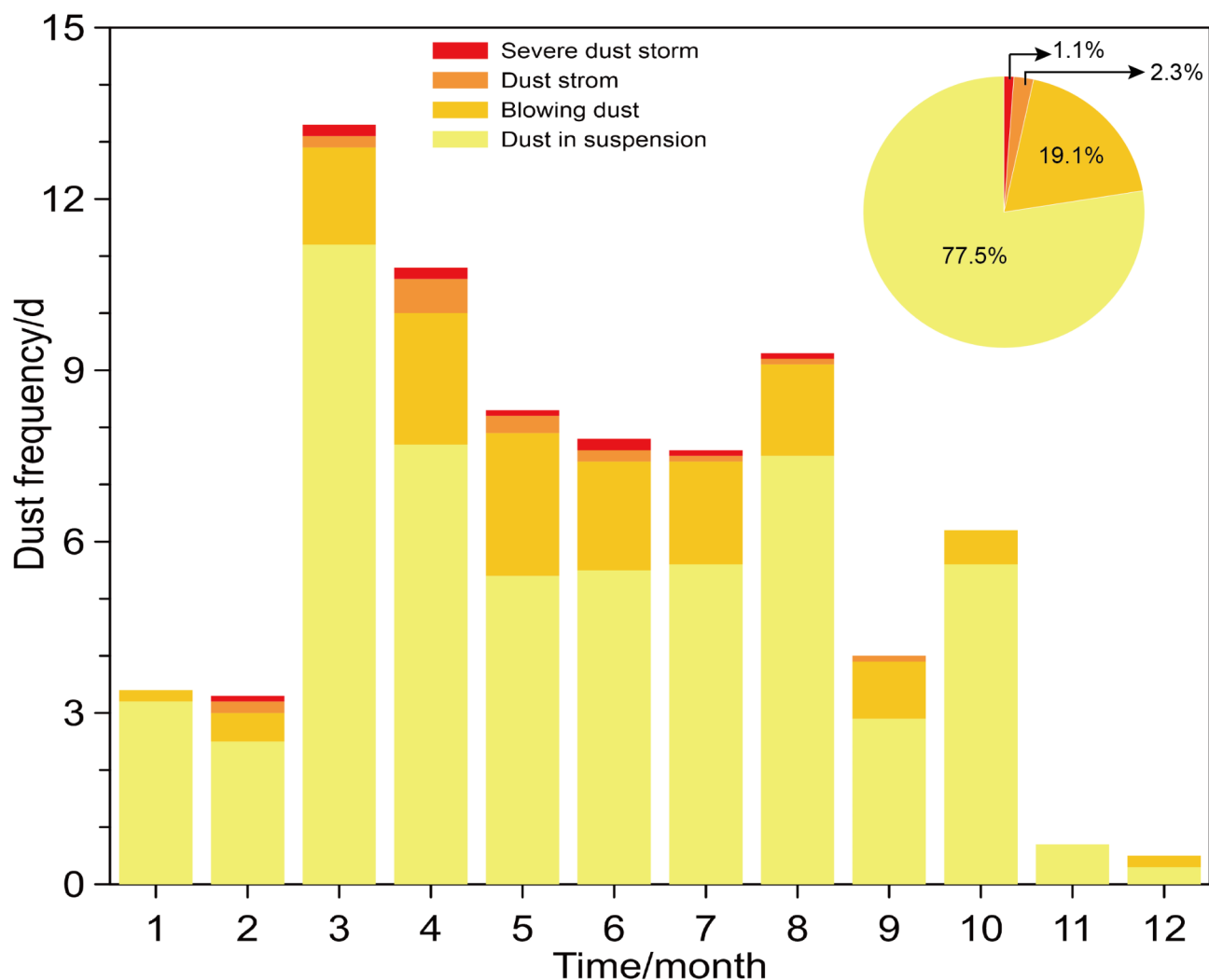


Fig. 2. Monthly mean of the number of days of windblown dust occurrence at 13 meteorological stations over the Tarim Basin in 2015. The pie chart in the right upside represents the proportion of each type of dust event over the total number of dust events.

No.	Dust episodes	Visibility (m)	Wind speed (m/s)†	PM ₁₀ concentration (µg/m ³ ·h)‡
1	March 15–19	90	13.8–16.4	4871
2	March 26–27	10	12.2–17.3	2217
3	March 31–April 6	10	15.2–20.9	7308
4	April 17–20	100	12.0–18.4	8309
5	April 27–May 1	10	16.0–26.2	> 10,000
6	May 10–14	10	13.7–17.8	> 10,000
7	May 18–21	40	10.8–14.0	3000
8	May 23–25	80	13.2–14.7	4206
9	May 29–31	20	16.0–16.6	5018

Table 1. Major strong windblown dust events observed in the Tarim basin in spring 2015. †The maximum wind speed was measured at 10 m above the ground. ‡The detection limit of the environmental monitoring instrument for the maximum PM₁₀ concentration is 10,000 µg/m³·h.

dust clouds, and harmful air pollution⁵³. The maximum observed surface wind speed was 26.2 m/s, while the atmospheric visibility was extremely low (less than 10 m). At the same time, the strong winds blew up large amount of dust particles, which seriously deteriorated the local air quality. Robust dust signals were detected during the windblown episodes, where ambient PM₁₀ concentrations were correspondingly higher than 10,000 µg/m³·h

as observed in late April and mid-May, respectively. This high concentration of PM_{10} in the air greatly exceeds the Air Quality Guideline (AQG, $45 \mu\text{g}/\text{m}^3$ averaged over 24 h) suggested by the World Health Organization (WHO). MODIS Terra satellite images captured clearly several strong sand and dust storms over the Tarim Basin in spring 2015, as shown in Fig. 3. Desert dust swept the entire basin, and were uplifted, suspended, and blown toward the east. It should be noted that in May 2015, severe dust storm blew soil particles into the atmosphere, producing dense yellow dust clouds that looked like the “eye of the Dust Devil” (Fig. 3c). Those satellite images and dust records reveal the Tarim Basin is seriously affected by frequent aeolian dust events.

Surface observation

Figure 4 presents the distribution of spatial occurrence of windblown dust at 13 meteorological stations in the Tarim Basin in 2015, using the spatial analysis tool of ArcGIS. Dust events primarily occurred in Tazhong with 156 d, followed by Pishan, Ruoqiang, Bachu, and Hotan. The yearly mean of dust incidence is 75 d in Tarim Basin. The outbreak occurrence for dust in suspension, blowing dust, dust storm, and severe dust storm are shown in Fig. 4b,e. Significant high incident of dust in suspension was recorded in Pishan (southern Taklimakan Desert) over 119 d. Blowing dust mainly occurs in Tazhong and Tiegankli, while dust storm appears in Tazhong and Alar, and severe dust storm takes place in Ruoqiang and Tazhong. The distribution of spatial occurrence of windblown dust as displayed in Fig. 4 suggests that there is a high incidence of aeolian dust activities within the basin, which in turn may affect the atmospheric environment in the surrounding areas.

The Tarim Basin is in the northern hemisphere's mid-latitudes and is strongly influenced by the westerly circulations, the Asian jet streams, and Mongolian cyclones^{40,51,54}. Erosive soil dust is easily blown into the atmosphere by wind turbulence³⁸. Figure 5a showed the spatial pattern of surface wind speed and direction in the Tarim Basin in 2015. The surface wind directions prevail in NNE in the northeastern and the middle of the basin, WSW in the northwestern basin, and WNW in the southwestern basin. The average surface wind speeds in the Tarim Basin range from 1.1 to 2.9 m/s, which is agreement with Yang et al.³⁷ regarding the low wind energy environment in this area. It showed that surface wind speed has a correlation coefficient of 0.15 with the frequency of windblown dust events (Supplementary Material Figure S1). Wind patterns in the Tarim Basin are closely related to its regional landform structures and the surrounding alpine terrain^{1,55}. Basin topography may have a significant impact on regional wind directions and dust emissions^{14,18,38,41}, which results in geostrophic current and local vortex. Wind thresholds and wind directions are, therefore, differed at regional scale in specific sites³⁷. Mountain ranges that are transverse to wind current usually generate wave motion in the atmosphere⁶. On the edges of the Tarim Basin, Fohn and valley winds could be somehow responsible for generating dust devil

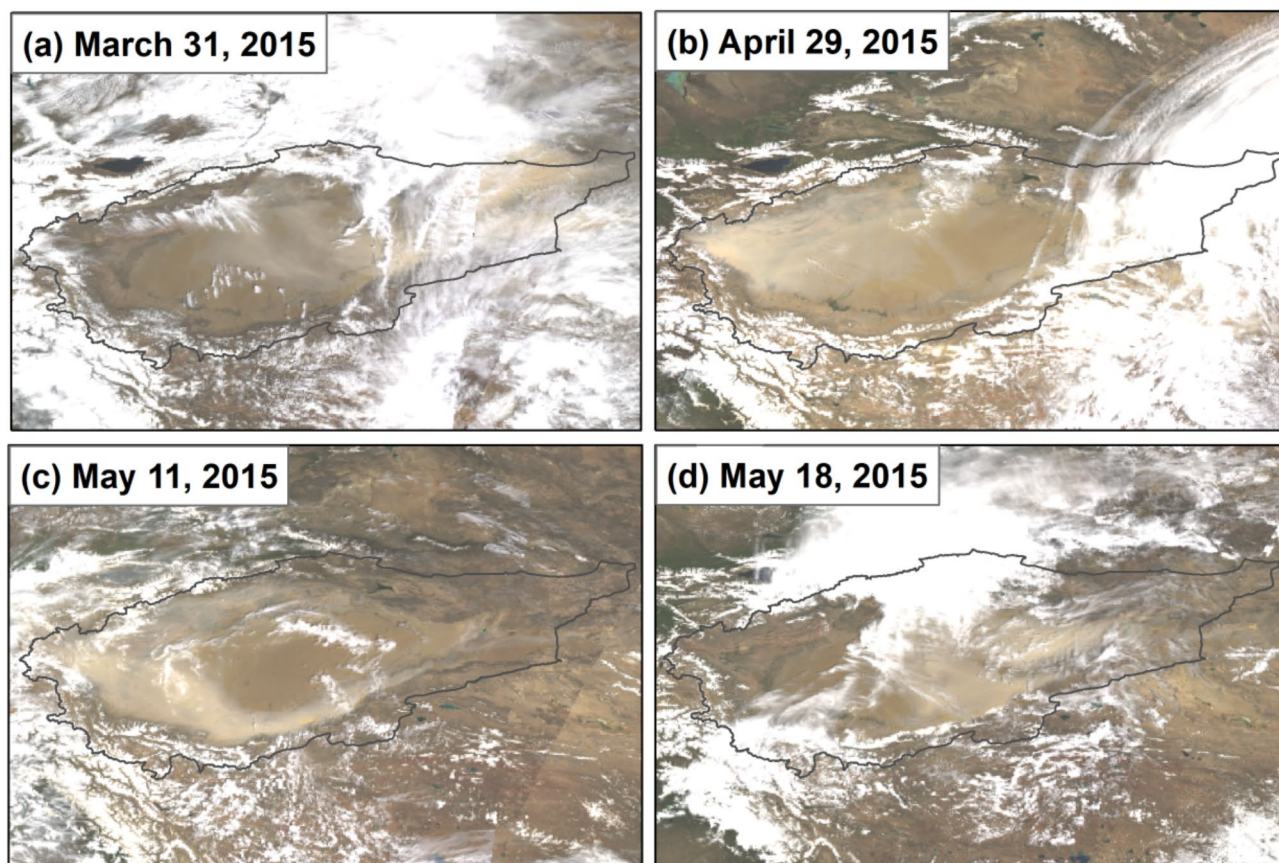


Fig. 3. True-colour images of several strong sand and dust storms over the Tarim Basin in 2015 as observed from the MODIS Terra satellite.

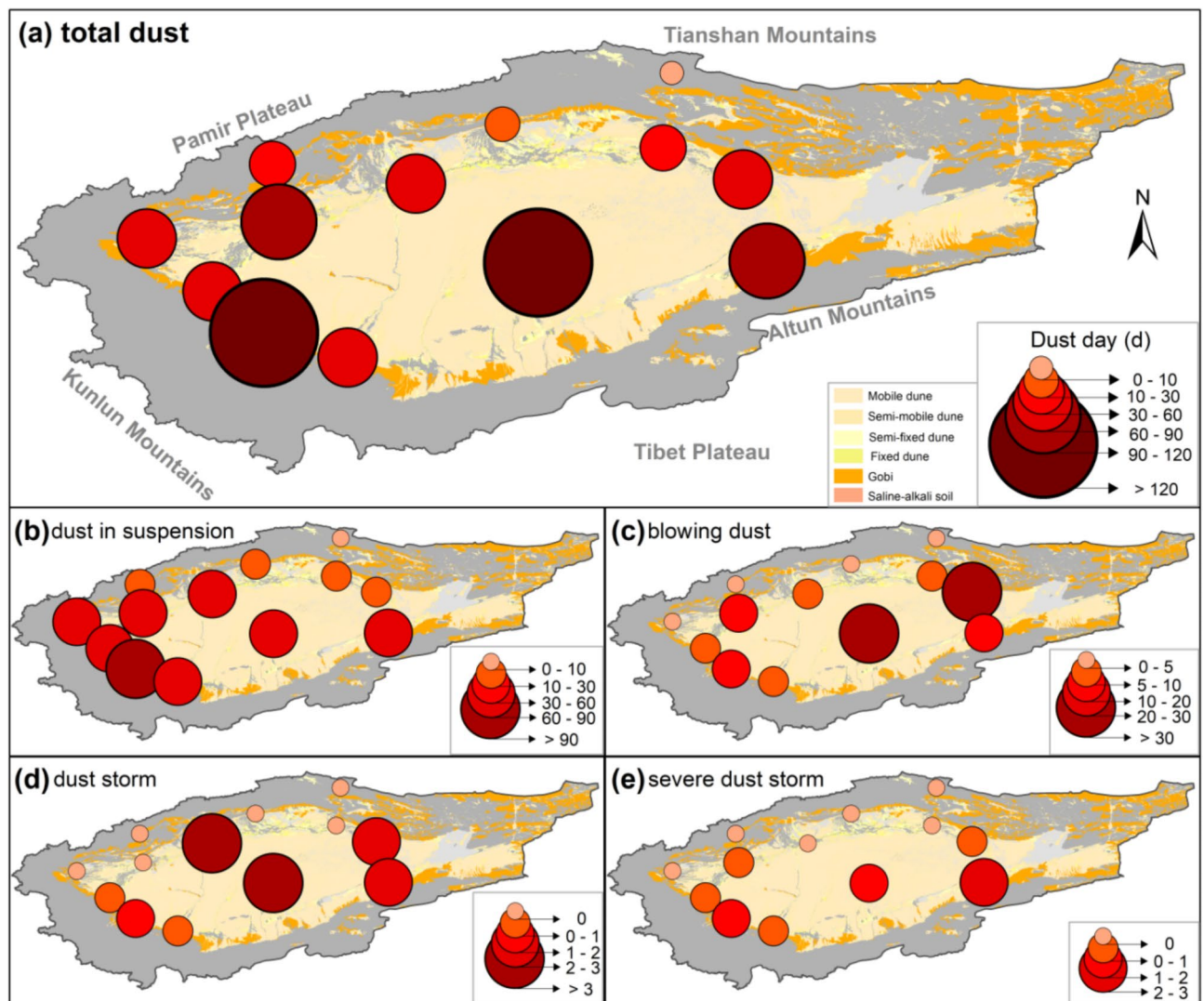


Fig. 4. Spatial distribution of total dust events (a), dust in suspension (b), blowing dust (c), dust storm (d), and severe dust storm (e) over the Tarim Basin in 2015. The map was created using ArcGIS 10.6 (<https://www.esri.com/en-us/arcgis/geospatial-platform/overview>).

or dust storms over the fluvio-lacustrine sedimentary areas. The environment of the Tarim Basin is dominated by desert climate due to the scarcity of precipitation. In 2015, the annual average precipitation in the arid region of Tarim Basin was 132.5 mm (excluding the alpine stations Baluntai and Aheqi), with the lowest observed records being 54.1 mm in Ruqiang and 63.4 mm in Tazhong (Fig. 5b). Precipitation peaks in summer, followed by spring, autumn, and winter. The lack of rainfall severely restricts the growth of local plants, fungi, and algae, resulting in sparse vegetation throughout the basin. Biological soil crusts are, therefore, fragile and the surface aeolian sandy soils are easily to emitted into the atmosphere⁵⁶.

Figure 6 shows the time series changes of hourly ambient particulate matter (PM) concentrations at four major environmental monitoring cities over the Tarim Basin in 2015. PM concentrations were highest in spring and lowest in winter, while they varied from Korla to the other cities in summer and autumn. The maximum PM concentrations were detected in Kashgar in early May, exceeding 10,000 $\mu\text{g}/\text{m}^3$. Consistently elevated dust concentrations were monitored from March to August in Hotan at the south margin of the basin. The high PM concentrations in the Tarim Basin are associated with extreme arid environment caused by intense wind erosion and prolonged periods of scarce precipitation³⁸.

High concentrations of PM detected in the Tarim Basin lead to large dust depositions and ecological effects^{1,16}. Figure 7 depicted the intra-annual variability of atmospheric deposition in Tarim Basin in 2015. Monthly dust deposition fluxes in the Tarim Basin, northwest China, vary between three orders of magnitude (1 to 1000 $\text{g}/\text{m}^2\text{-mon}$). Korla and Aksu have the lowest records with average deposition of less than 22 $\text{g}/\text{m}^2\text{-mon}$, while Kashgar, Hotan, and Tazhong have a relatively high values of 91, 147 and 317 $\text{g}/\text{m}^2\text{-mon}$, respectively. Dust deposition was highest in the summer (June-July-August), followed by spring (March-April-May), autumn (September-October-November) and winter (December-January-February). It should be noted that anthropogenic

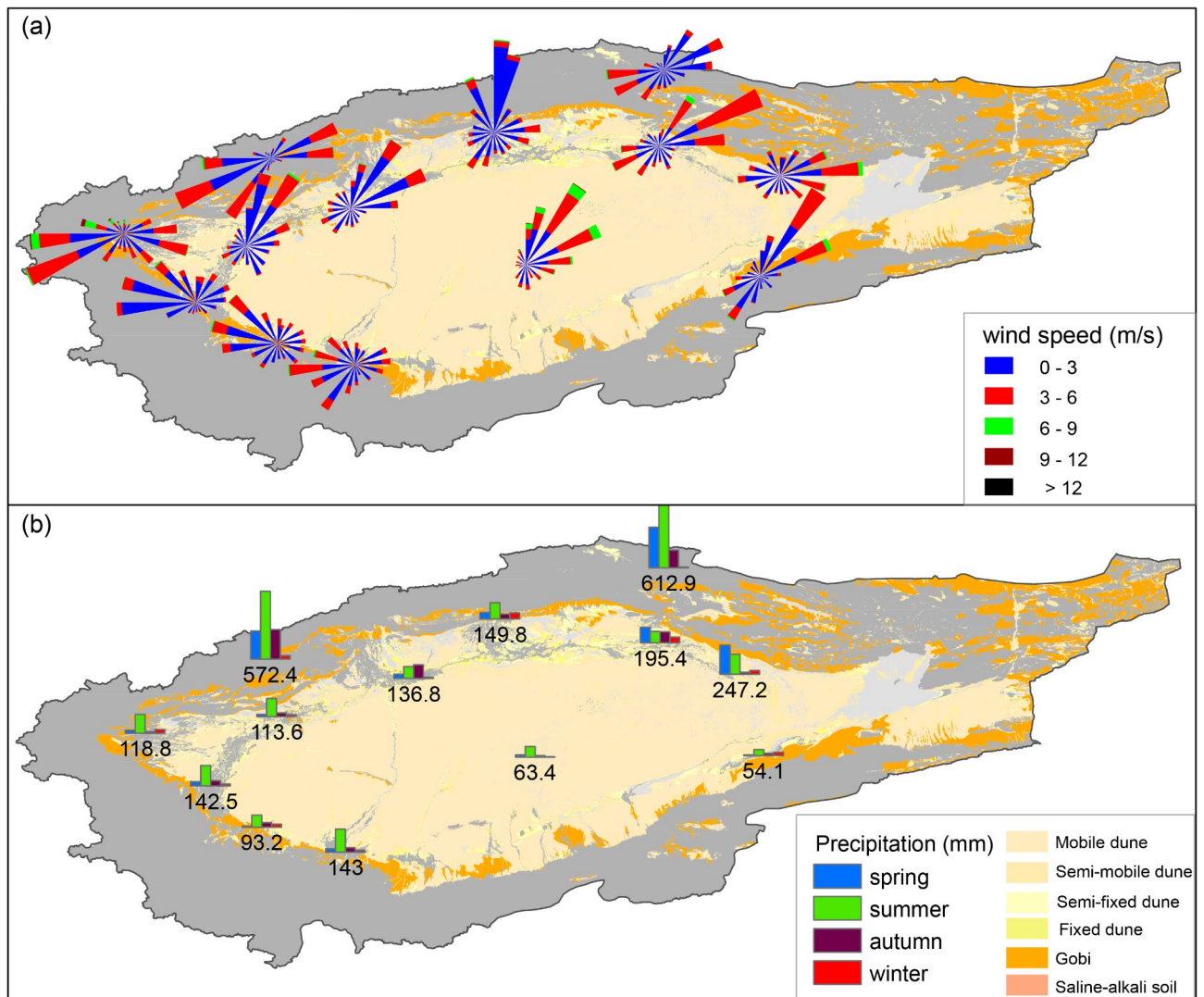


Fig. 5. Spatial distribution of average wind speed and wind direction (a) and precipitation (b) over the Tarim Basin in 2015. The amount of total precipitation at each meteorological station has been labelled. The map was created using ArcGIS 10.6 (<https://www.esri.com/en-us/arcgis/geospatial-platform/overview>).

pollution in populated oasis cities around the basin (e.g., Korla and Kashgar) may contribute to atmospheric deposition. The monthly maximum dust deposition was recorded in Tazhong of the central Taklimakan Desert with 976.5 g/m^2 and 778.2 g/m^2 in July and May, respectively. Among these five environmental monitoring sites, Hotan has the second largest deposition rate in the basin, with 435.5 g/m^2 and 358.8 g/m^2 in June and July, respectively. This high dust depositions are closely associated with ambient PM concentrations as depicted in Fig. 8. Statistical analysis reveals that the higher the concentration of ambient PM, the greater the atmospheric dust deposition. An equation describing the potential relationship between PM concentration and deposition rate is presented in Eq. (1) according to these observational data. Overall, atmospheric dust deposition rates in the basin present a pattern of high levels during May–June–July. This deposition rate may have close linkage with the dry and hot climate in the basin. Specifically, consecutive dust in suspension can contribute to significant dry deposition rates in the basin¹⁵. The maximum ambient PM concentration and dust deposition in the Tarim Basin exceeded $10,000 \mu\text{g/m}^3$ per hour, and 3800 g/m^2 per year, respectively. Compared with global observations of atmospheric deposition for the major arid desert areas^{46,57–61}, the above records suggest relatively high dust fluxes in the Tarim Basin. It is noteworthy that the deposition rates in the Tarim Basin are at a similar order of magnitude level to the largest recorded surface observations in Central Asia as reported by Groll et al.⁵⁹.

$$Q_d = \begin{cases} 11.79e^{0.00046c} & (50 < c \leq 400) \\ 8.14e^{-9}c^{3.83}, & (400 < c < 600) \end{cases} \quad (1)$$

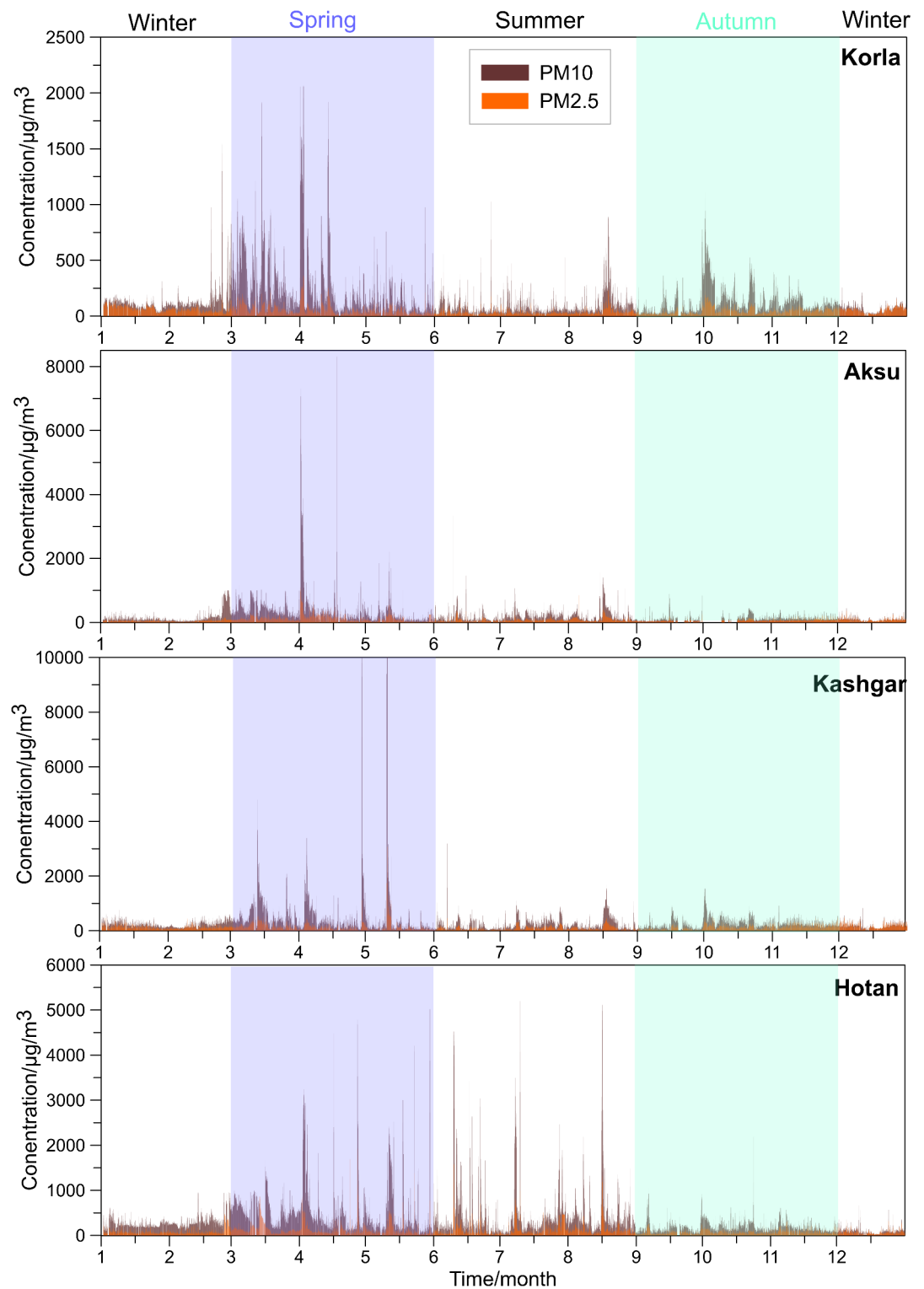


Fig. 6. Time series variation of hourly ambient particulate matter concentration (unit: $\mu\text{g}/\text{m}^3\cdot\text{h}$) in four environmental monitoring cities in the Tarim Basin in 2015.

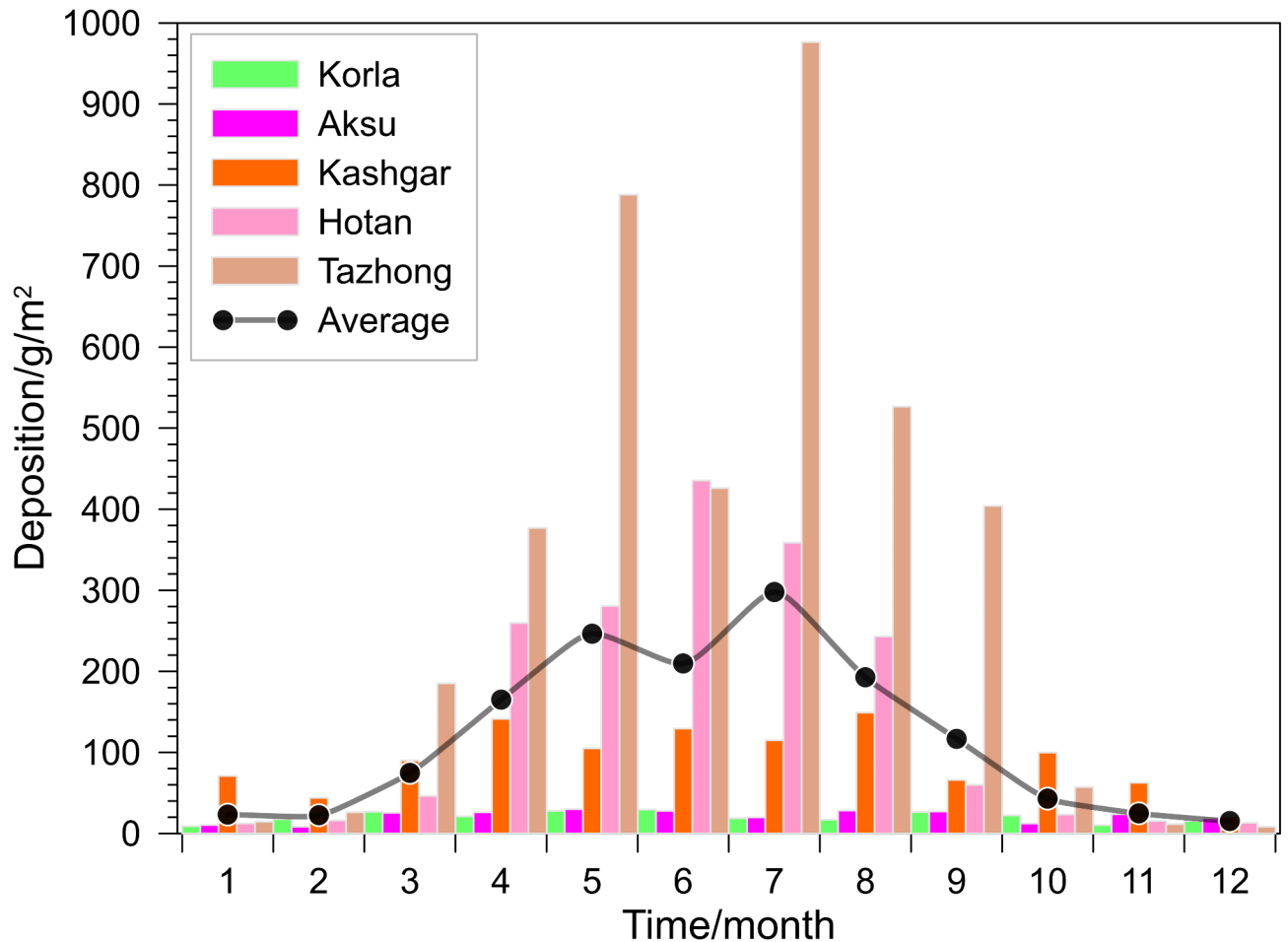


Fig. 7. Monthly atmospheric dust deposition over the Tarim Basin in 2015.

Where Q_d is the monthly dust deposition flux (unit: g/m^2), c is the monthly average ambient PM_{10} concentration (unit: $\mu\text{g/m}^3$).

Satellite measurement

Remote monitoring by satellite instruments is fundamental to understand spatio-temporal change of dust aerosols^{43,51}. Figure 9 illustrates the seasonal AOD spatial pattern obtained from the MISR satellite product over the Tarim Basin, west China in 2015. Dense dust aerosols were evident in Tarim Basin in spring and summer seasons. In autumn and winter, the areas with high AOD values are primarily in the western and eastern periphery of the basin, respectively. This intra-annual AOD variation shows that spatial patterns of windblown dust in the basin, which reflected seasonal dynamic distribution and changes. The Ångström exponent derived from the satellite product is associated with aerosol particle size, and is usually utilized as a qualitative index of atmospheric aerosol particle size⁶². Figure 10 presents the spatial pattern of seasonal Ångström exponent over the Tarim Basin in western China in 2015. It reflected that large particles were measured over most of the basin in the period of spring, autumn and winter, while relative fine particles were measured during summer. This anomaly may be related to the prolonged suspension of fine dust particles in the summer air of the basin, as well as the high temperatures and low winds season (Fig. 2). During the hot summer month, daytime surface temperature in the arid regions of the Tarim Basin can reach over 45 degrees Celsius³⁷. Convective dust emission may produce the suspended dust aerosols due to the regional thermodynamic environment. Particularly, frequent dust whirls (dust vortices) can lead to increased amounts of entrained and uplifted desert dust as reported by Yang et al.¹⁴.

Figure 11 illustrated the vertical profiles of windblown dust in the Tarim Basin as observed by CALIPSO satellite instruments. It revealed that dust particles were blown into the atmosphere and suspended over the basin. Windblown dust particulate matter can even rise as high as an altitude of 12 km. Previous studies reported that variable vertical wind may result to strong atmospheric turbulence, and affect the up-welling and transport of stratospheric aerosols⁶³. The vertical distribution and variation of windblown dust observed in the Tarim Basin indicated that widespread mineral dust dispersion and mixed air pollution (Fig. 11). The satellite measurement provides solid evidence of persistent dust suspension occurring in Tarim Basin, which may result in high dry deposition rates as illustrated in Fig. 7. In addition, windblown dust over the Tarim Basin may

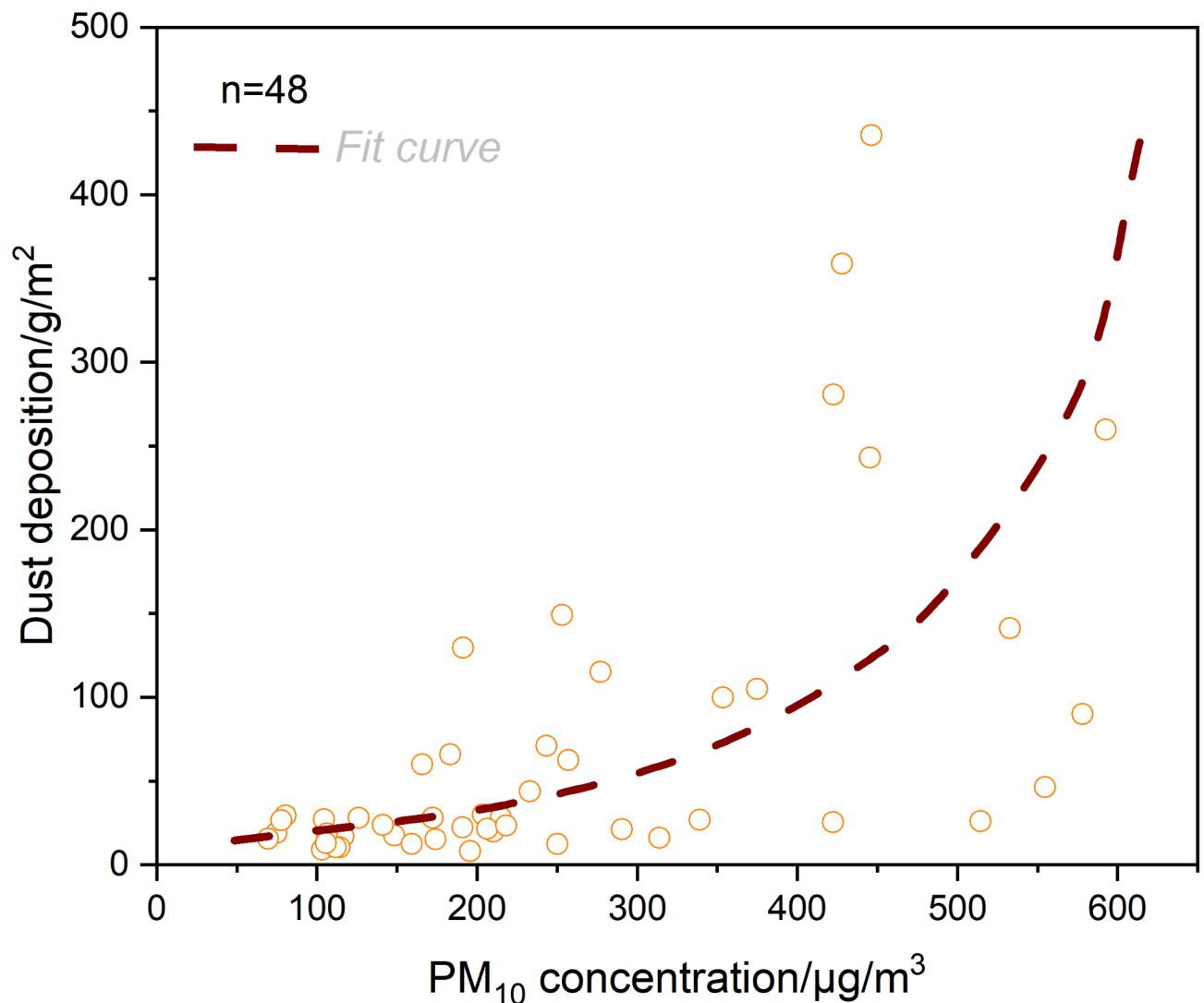


Fig. 8. Relationship between monthly dust deposition and ambient PM concentration in Tarim Basin.

be further transported eastwards across the high-rolling mountains of the Qinghai-Tibet Plateau, affecting the atmospheric environment of East China, Korea Peninsular, Japan and far oceans^{64,65}.

Conclusions

This study presents a continuous full-year observation in Tarim Basin, which help us to gain insight into the dust background in the source region. Both ground-based observations and remote satellite measurements show high dust emissions, ambient PM concentrations and dust depositions in the Tarim Basin. The atmospheric environment of the Tarim Basin in western China is strongly influenced by windblown dust. The most active times of the year for windblown dust are spring and summer, followed by autumn and winter. It shows that frequency of aeolian dust event is higher in Tazhong (center of the basin) and Pishan (southern edge of the basin). Significant deposition of atmospheric dust occurs mainly during the period from April to August. Vertically, dust aerosols have been detected suspended in the atmosphere at altitudes of 3–12 km. During the study period, we observed high dust frequency (> 100 d per year), ambient PM concentrations (> 10,000 µg/m³ per hour) and dust deposition (> 3000 g/m² per year) in the Tarim Basin, northwest China. This notable flux level of dust deposition in the Tarim Basin is of the same order of magnitude as the largest known global surface observations in the arid regions (Central Asia), and higher than in the sub-Sahara, the Middle East and Australia.

Currently, in-situ observations are still limited to a few sites in the Tarim Basin. Therefore, additional multi-source observations from the ground to high altitude need to be initiated in this hyper dry inland region. More details of the formation processes and thermodynamic mechanisms of aeolian dust weather as well as its regional and global impact are required to further study. The convective dust emission, persistent dust in suspension, remote transport of fine dust particles, mixed physicochemical pollution, and dry/wet dynamic deposition process in the Tarim Basin need to be deeply investigated. Furthermore, the continuous spatiotemporal

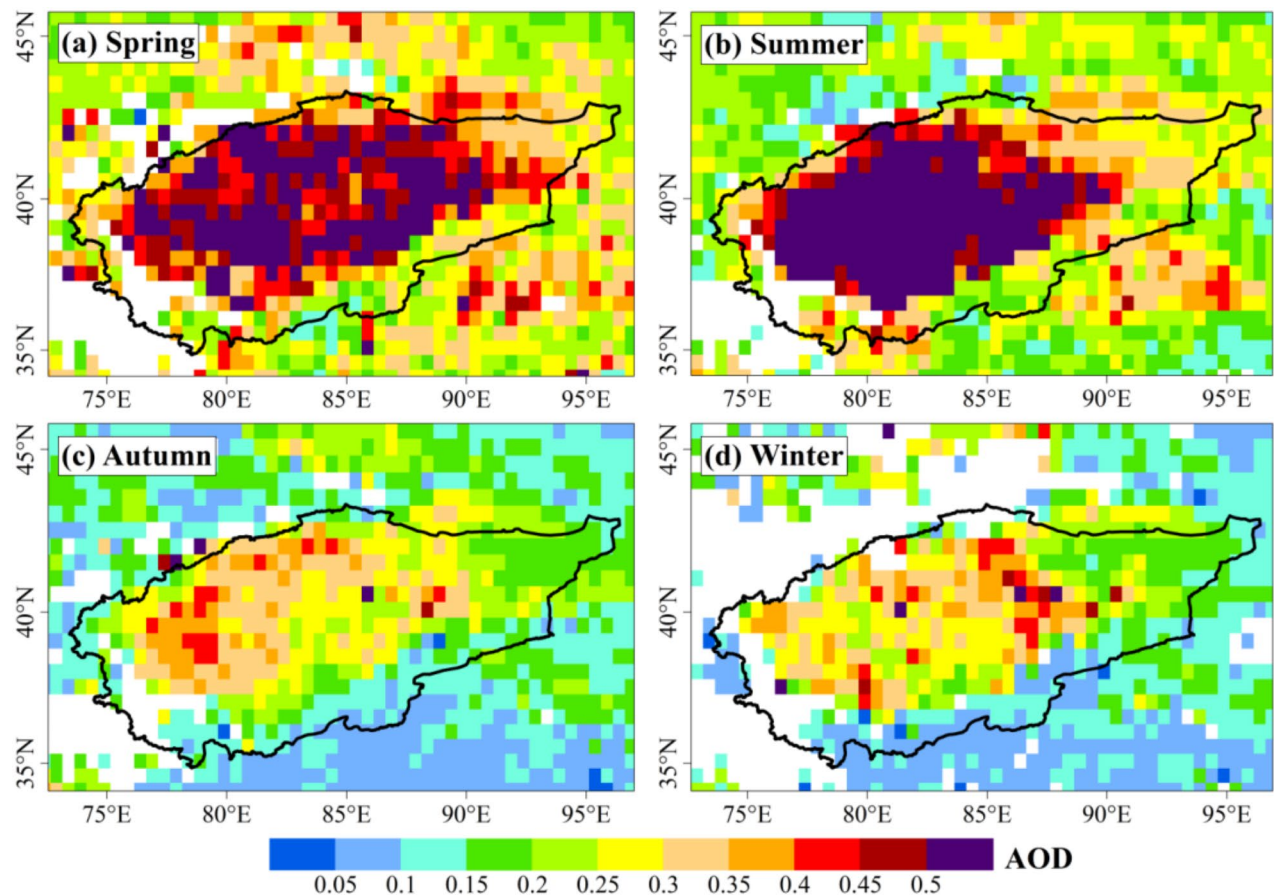


Fig. 9. Spatial distribution of AOD derived from the MISR satellite product over the Tarim Basin in west China in 2015.

observations of the data-sparse desert region provided by this work would contribute to the validation of aeolian dust model and parameter adjustment on numerical scheme in a basin-like terrain.

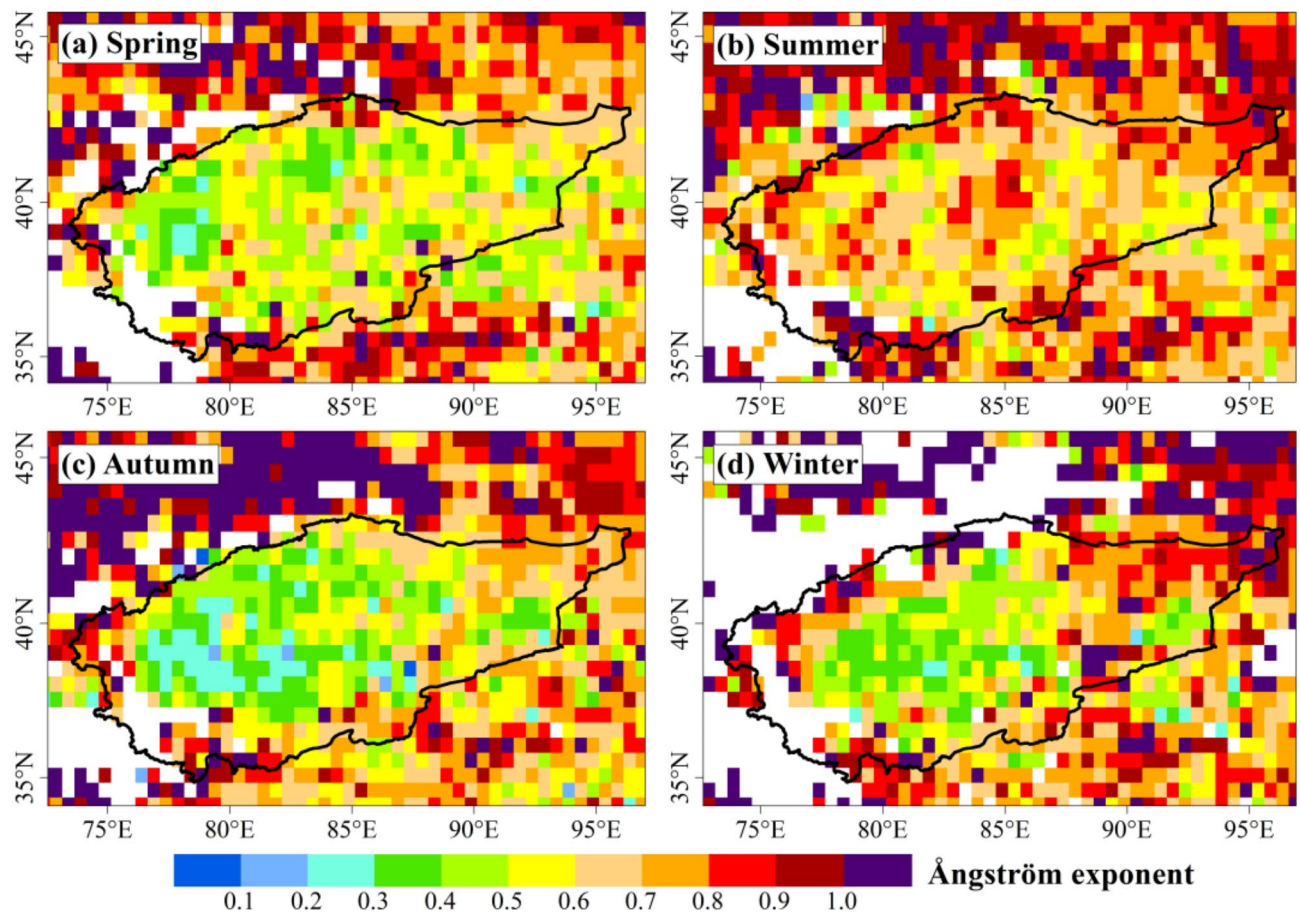


Fig. 10. Spatial distribution of Ångström exponent derived from MISR satellite product over the Tarim Basin in 2015.

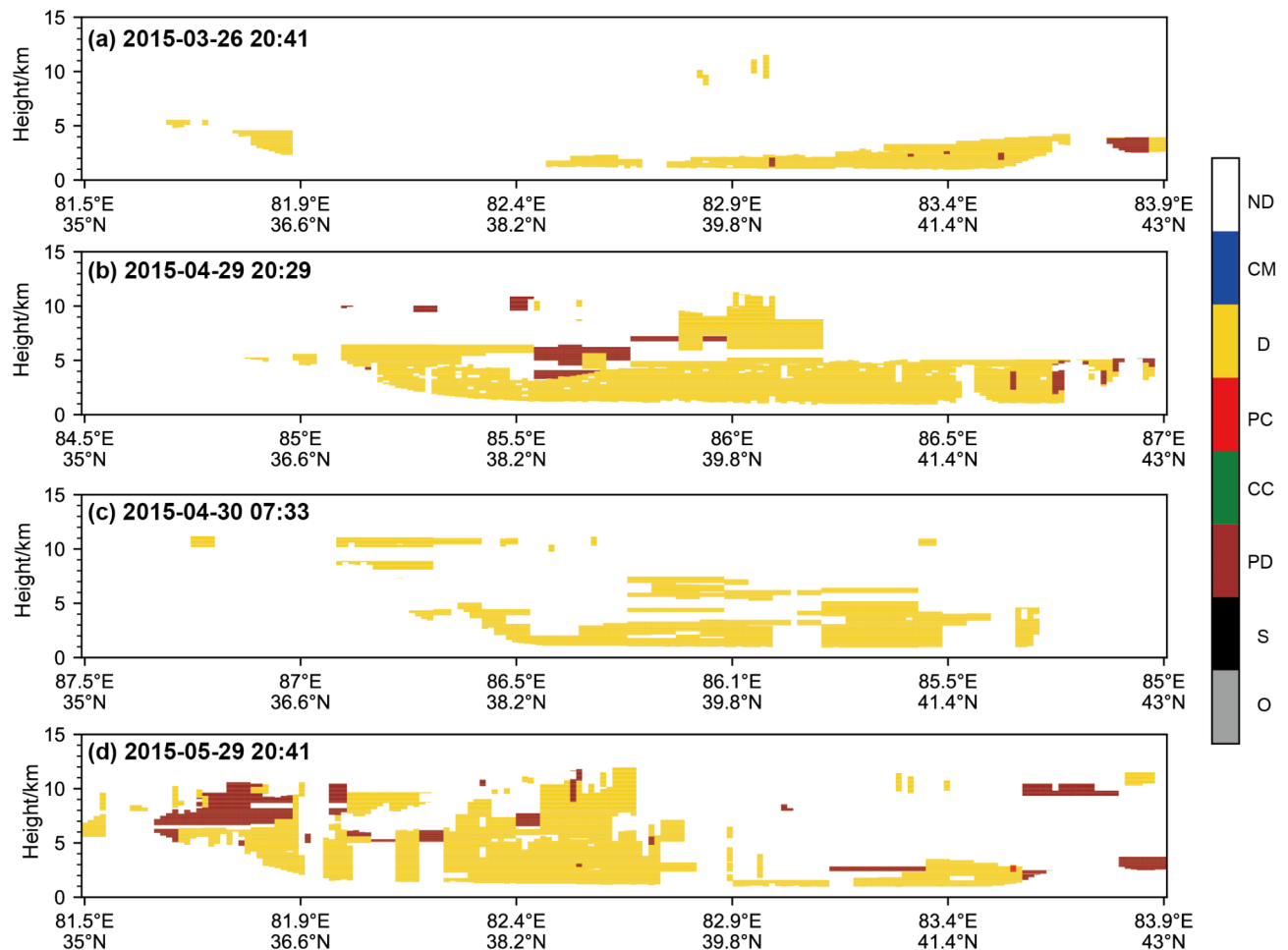


Fig. 11. Vertical profiles of atmospheric features measured by CALIPSO satellite over the Tarim Basin during spring dust active season in 2015. (ND: not determined, CM: clean marine, D: dust, PC: polluted continental, CC: clean continental, PD: polluted dust, S: smoke, O: other).

Data availability

Correspondence and requests for materials should be addressed to Dr. Zhang Xiao-Xiao.

Received: 18 August 2024; Accepted: 25 March 2025

Published online: 02 April 2025

References

- Huang, J. et al. Dryland climate change: Recent progress and challenges. *Rev. Geophys.* **55**, 719–778. <https://doi.org/10.1002/2016RG000550> (2017).
- Yuan, T. et al. Influence of dynamic and thermal forcing on the meridional transport of Taklimakan desert dust in spring and summer. *J. Clim.* **32**, 749–767. <https://doi.org/10.1175/JCLI-D-18-0361.1> (2019).
- IPCC (Intergovernmental Panel on Climate Change). *Climate Change. 2021-The Physical Science Basis* 33–278 (Cambridge University Press, 2021).
- Carslaw, K. S. et al. Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature* **503**, 67–71. <https://doi.org/10.1038/nature12674> (2013).
- Chen, Y. et al. A super dust storm enhanced by radiative feedback. *Npj Clim. Atmos. Sci.* **6**, 90. <https://doi.org/10.1038/s41612-023-00418-y> (2023).
- Pye, K. *Aeolian Dust and Dust Deposits* 5–63 (Academic, 1987).
- Mahowald, N. M. et al. Atmospheric iron deposition: Global distribution, variability, and human perturbations. *Annual Rev. Mar. Sci.* **1**, 245–278. <https://doi.org/10.1146/annurev.marine.010908.163727> (2009).
- Ginoux, P., Prospero, J. M., Gill, T. E., Hsu, N. C. & Zhao, M. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS deep blue aerosol products. *Rev. Geophys.* **50** <https://doi.org/10.1029/2012RG000388> (2012).
- Zhang, T. et al. Environmental impacts of three Asian dust events in the Northern China and the Northwestern Pacific in spring 2021. *Sci. Total Environ.* **859**, 160230. <https://doi.org/10.1016/j.scitotenv.2022.160230> (2023).
- Zhang, X. Y., Arimoto, R. & An, Z. S. Dust emission from Chinese desert sources linked to variations in atmospheric circulation. *J. Geophys. Res. Atmos.* **102**, 28041–28047. <https://doi.org/10.1029/97JD02300> (1997).
- Ginoux, P. et al. Sources and distributions of dust aerosols simulated with the GOCART model. *J. Geophys. Res. Atmos.* **106**, 20255–20273. <https://doi.org/10.1029/2000JD000053> (2001).

12. Shao, Y. et al. Dust cycle: An emerging core theme in Earth system science. *Aeolian Res.* **2**, 181–204. <https://doi.org/10.1016/j.aeolia.2011.02.001> (2011).
13. Klose, M. & Shao, Y. Stochastic parameterization of dust emission and application to convective atmospheric conditions. *Atmos. Chem. Phys.* **12**, 7309–7320. <https://doi.org/10.5194/acp-12-7309-2012> (2012).
14. Zhang, X. X. et al. Parameterization schemes on dust deposition in Northwest China: Model validation and implications for the global dust cycle. *Atmos. Environ.* **209**, 1–13. <https://doi.org/10.1016/j.atmosenv.2019.04.017> (2019).
15. Yang, X. et al. Spatial and temporal variations of blowing dust events in the Taklimakan desert. *Theoret. Appl. Climatol.* **125**, 669–677. <https://doi.org/10.1007/s00704-015-1537-4> (2016).
16. Zhang, X. X. et al. Spatiotemporal evolution of aeolian dust in China: An insight into the synoptic records of 1984–2020 and nationwide practices to combat desertification. *Land. Degrad. Dev.* **34**, 2005–2023. <https://doi.org/10.1002/ldr.4585> (2023).
17. Shao, Y. & Dong, C. H. A review on East Asian dust storm climate, modelling and monitoring. *Glob. Planet. Change.* **52**, 1–22. <https://doi.org/10.1016/j.gloplacha.2006.02.011> (2006).
18. Chen, S. et al. Emission, transport and radiative effects of mineral dust from the Taklimakan and gobi deserts: Comparison of measurements and model results. *Atmos. Chem. Phys.* **17**, 2401–2421. <https://doi.org/10.5194/acp-17-2401-2017> (2017).
19. Uno, I., Eguchi, K. & Yumimoto, K. Asian dust transported one full circuit around the Globe. *Nat. Geosci.* **2**, 557–560. <https://doi.org/10.1038/ngeo583> (2009).
20. Cottle, P., Strawbridge, K., McKendry, I., O'Neill, N. & Saha, A. A pervasive and persistent Asian dust event over North America during spring 2010: Lidar and sunphotometer observations. *Atmos. Chem. Phys.* **13**, 4515–4527. <https://doi.org/10.5194/acp-13-4515-2013> (2013).
21. Richthofen, B. F. On the mode of origin of the loess. *Geol. Mag.* **9**, 293–305. <https://doi.org/10.1017/S001675680017164X> (1882).
22. Huneus, N. et al. Global dust model intercomparison in AeroCom phase I. *Atmos. Chem. Phys.* **11**, 7781–7816. <https://doi.org/10.5194/acp-11-7781-2011> (2011).
23. Marticorena, B. & Bergametti, G. Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme. *J. Geophys. Res. Atmos.* **100**(D8), 16415–16430. <https://doi.org/10.1029/95JD00690> (1995).
24. Zhang, L., Gong, S., Padro, J. & Barrie, L. A size-segregated particle dry deposition scheme for an atmospheric aerosol module. *Atmos. Environ.* **35**, 549–560. [https://doi.org/10.1016/S1352-2310\(00\)00326-5](https://doi.org/10.1016/S1352-2310(00)00326-5) (2001).
25. Shao, Y. A model for mineral dust emission. *J. Geophys. Res. Atmos.* **106**, 20239–20254. <https://doi.org/10.1029/2001JD900171> (2001).
26. Shao, Y. Simplification of a dust emission scheme and comparison with data. *J. Geophys. Res. Atmos.* <https://doi.org/10.1029/2003JD004372> (2004).
27. Shao, Y., Ishizuka, M., Mikami, M. & Leys, J. F. Parameterization of size-resolved dust emission and validation with measurements. *J. Geophys. Res. Atmos.* <https://doi.org/10.1029/2010JD014527> (2011).
28. Tegen, I. Modeling the mineral dust aerosol cycle in the climate system. *Q. Sci. Rev.* **22**, 1821–1834. [https://doi.org/10.1016/S0277-3791\(03\)00163-X](https://doi.org/10.1016/S0277-3791(03)00163-X) (2003).
29. Zender, C. S., Bian, H. S. & Newman, D. Mineral dust entrainment and deposition (DEAD) model: Description and 1990s dust climatology. *J. Geophys. Res. Atmos.* <https://doi.org/10.1029/2002JD002775> (2003).
30. Laurent, B., Marticorena, B., Bergametti, G. & Mei, F. Modeling mineral dust emissions from Chinese and Mongolian deserts. *Glob. Planet. Change.* **52** (1–4), 121–141. <https://doi.org/10.1016/j.gloplacha.2006.02.012> (2006).
31. Jung, E. & Shao, Y. P. An intercomparison of four wet deposition schemes used in dust transport modeling. *Glob. Planet. Change.* **52**, 248–260. <https://doi.org/10.1016/j.gloplacha.2006.02.008> (2006).
32. Lasserre, F. et al. A model tool for assessing real-time mixing of mineral and anthropogenic pollutants in East Asia: A case study of April 2005. *Atmos. Chem. Phys.* **8**, 3603–3622. <https://doi.org/10.5194/acp-8-3603-2008> (2008).
33. Zhang, J. & Shao, Y. A new parameterization of particle dry deposition over rough surfaces. *Atmos. Chem. Phys.* **14**, 12429–12440. <https://doi.org/10.5194/acp-14-12429-2014> (2014).
34. Zhang, L., He, Z., Technical & Note: An empirical algorithm estimating dry deposition velocity of fine, coarse and giant particles. *Atmos. Chem. Phys.* **14**, 3729–3737. <https://doi.org/10.5194/acp-14-3729-2014> (2014).
35. Kok, J. F. et al. An improved dust emission model - Part I: Model description and comparison against measurements. *Atmos. Chem. Phys.* **14**, 13023–13041. <https://doi.org/10.5194/acp-14-13023-2014> (2014).
36. Laurent, B. et al. Simulation of the mineral dust emission frequencies from desert areas of China and Mongolia using an aerodynamic roughness length map derived from the POLDER/ADEOS 1 surface products. *J. Geophys. Res. Atmos.* **110**, D18S04. <https://doi.org/10.1029/2004JD005013> (2005).
37. Yang, X. H. et al. A study on the effects of soil moisture, air humidity, and air temperature on wind speed threshold for dust emissions in the Taklimakan desert. *Nat. Hazards.* **97**, 1069–1081. <https://doi.org/10.1007/s11069-019-03686-1> (2019).
38. Yang, X. H. et al. Saltation activity on non-dust days in the Taklimakan Desert, China. *Remote Sensing* **14**, 2099. <https://doi.org/10.3390/rs14092099> (2022).
39. Li, H., Zhang, H., Mamtimin, A., Fan, S. & Ju, C. A new land-use dataset for the weather research and forecasting (WRF) model. *Atmosphere* **11**, 350. <https://doi.org/10.3390/atmos11040350> (2020).
40. Li, H. et al. A new dataset of erodibility in dust source for WRF-Chem model based on remote sensing and soil texture - Application and validation. *Atmos. Environ.* **315**, 120156. <https://doi.org/10.1016/j.atmosenv.2023.120156> (2023).
41. Meng, L. et al. Modeling study on three-dimensional distribution of dust aerosols during a dust storm over the Tarim basin, Northwest China. *Atmos. Res.* **218**, 285–295. <https://doi.org/10.1016/j.atmosres.2018.12.006> (2019).
42. Tang, Y., Han, Y., Ma, X. & Liu, Z. Elevated heat pump effects of dust aerosol over Northwestern China during summer. *Atmos. Res.* **203**, 95–104. <https://doi.org/10.1016/j.atmosres.2017.12.004> (2018).
43. Zhang, X. X. et al. Aeolian dust in central Asia: Spatial distribution and Temporal variability. *Atmos. Environ.* **238**, 117734. <https://doi.org/10.1016/j.atmosenv.2020.117734> (2020).
44. Helin, A. et al. Variation of absorption Ångström exponent in aerosols from different emission sources. *J. Geophys. Res. Atmos.* **126**. <https://doi.org/10.1029/2020JD034094> (2021).
45. Wang, J., Wang, Y., Yan, C. & Qi, Y. 1:100,000 desert (sand) distribution dataset in China. *Big Earth Data Platf. Three Poles.* <https://doi.org/10.3972/westdc.006.2013.db> (2013).
46. Zhang, X. X. et al. Dust deposition and ambient PM₁₀ concentration in Northwest China: Spatial and Temporal variability. *Atmos. Chem. Phys.* **17**, 1699–1711. <https://doi.org/10.5194/acp-17-1699-2017> (2017).
47. MEE (Ministry of Ecology and Environment, China). *Determination of atmospheric particles PM₁₀ and PM_{2.5} in ambient air by gravimetric method (HJ 618–2011)* (Environmental Science Press of China, 2011).
48. MEE (Ministry of Ecology and Environment, China). *Ambient Air Determination of Dustfall Gravimetric Method (HJ 1221–2021)* (Environmental Science Press of China, 2022).
49. Hsu, N. C., Tsay, S. C., King, M. D. & Herman, J. R. Deep blue retrievals of Asian aerosol properties during ACE-Asia. *IEEE Trans. Geosci. Remote Sens.* **44**, 3180–3195. <https://doi.org/10.1109/TGRS.2006.879540> (2006).
50. Gui, K. et al. A global-scale analysis of the MISR Level-3 aerosol optical depth (AOD) product: Comparison with multi-platform AOD data sources. *Atmos. Pollut. Res.* **12**, 101238. <https://doi.org/10.1016/j.apr.2021.101238> (2021).
51. Pan, H., Huang, J., Kumar, K. R., An, L. & Zhang, J. The CALIPSO retrieved Spatiotemporal and vertical distributions of AOD and extinction coefficient for different aerosol types during 2007–2019: A recent perspective over global and regional scales. *Atmos. Environ.* **274**, 118986. <https://doi.org/10.1016/j.atmosenv.2022.118986> (2022).

52. Zu, R. P. et al. Characteristics of near-surface wind regimes in the Taklimakan desert, China. *Geomorphology* **96**, 39–47. <https://doi.org/10.1016/j.geomorph.2007.07.008> (2008).
53. World Health Organization. WHO global air quality guidelines. Particulate matter (PM_{2.5} and PM₁₀), Ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. *Geneva*, 74–97. (2021). <https://apps.who.int/iris>
54. Mao, R. et al. Increasing spring dust storms in the future over the Taklimakan desert, Northwest China: Implications from changes in circulation pattern frequency in CMIP6. *Environ. Res. Commun.* **3**, 111002. <https://doi.org/10.1088/2515-7620/ac37ee> (2021).
55. Chen, S. et al. Modeling the transport and radiative forcing of Taklimakan dust over the Tibetan plateau: A case study in the summer of 2006. *J. Geophys. Res. Atmos.* **118**, 797–812. <https://doi.org/10.1002/jgrd.50122> (2013).
56. Rodriguez-Caballero, E. et al. Global cycling and climate effects of aeolian dust controlled by biological soil crusts. *Nat. Geosci.* **15**, 458–463. <https://doi.org/10.1038/s41561-022-00942-1> (2022).
57. Kathleen, W. B., Walid, B., Denise, P. L., John, S. E. & Petros, K. Characterization of particulate matter for three sites in Kuwait. *J. Air Waste Manag. Assoc.* **58**, 994–1003. <https://doi.org/10.3155/1047-3289.58.8.994> (2008).
58. Cattle, S. R., Hemi, K., Pearson, G. L. & Sanderson, T. Distinguishing and characterising point-source mining dust and diffuse-source dust deposits in a semi-arid district of Eastern Australia. *Aeolian Res.* **6**, 21–29. <https://doi.org/10.1016/j.aeolia.2012.07.001> (2012).
59. Groll, M., Opp, C. & Aslanov, I. Spatial and Temporal distribution of the dust deposition in central Asia - results from a long term monitoring program. *Aeolian Res.* **9**, 49–62. <https://doi.org/10.1016/j.aeolia.2012.08.002> (2013).
60. Marticorena, B. et al. Mineral dust over West and central Sahel: Seasonal patterns of dry and wet deposition fluxes from a pluriannual sampling (2006–2012). *J. Geophys. Res. Atmos.* **122**, 1338–1364. <https://doi.org/10.1002/2016JD025995> (2017).
61. Froushani, M. A., Opp, C. & Groll, M. Investigation of aeolian dust deposition rates in different climate zones of Southwestern Iran. *Atmosphere* **12**, 229. <https://doi.org/10.3390/atmos12020229> (2021).
62. Schuster, G. L., Dubovik, O. & Holben, B. N. Angstrom exponent and bimodal aerosol size distributions. *J. Geophys. Res. Atmos.* **111** (D7). <https://doi.org/10.1029/2005JD006328> (2006).
63. Junge, C. E. & Manson, J. E. Stratospheric aerosol studies. *J. Phys. Res.* **66**, 2163–2182. <https://doi.org/10.1029/JZ066i007p02163> (1961).
64. Zhang, X. X. et al. East Asian dust storm in May 2017: Observations, modelling, and its influence on the Asia-Pacific region. *Atmos. Chem. Phys.* **18**, 8353–8371. <https://doi.org/10.5194/acp-18-8353-2018> (2018).
65. Zhou, C. et al. Terrain effects of the Tibetan plateau on dust aerosol distribution over the Tarim basin, China. *Atmos. Res.* **298**, 107143. <https://doi.org/10.1016/j.atmosres.2023.107143> (2024).

Acknowledgements

The authors would like to thank anonymous reviewers and editors for their useful comments that contributed to improving the manuscript.

Author contributions

Xiao-Xiao Zhang: Writing - original draft, Data curation, Methodology, Software, Investigation. Xing-Hua Yang: Writing - review & editing, Supervision. Fan Yang: Writing - review & editing, Supervision. Jia-Qiang Lei: Investigation, Supervision. Ali Mamtimin: Investigation, Supervision. Sheng-Yu Li: Investigation, Supervision. Li-an-You Liu: Writing - review & editing, Methodology, Investigation, Supervision. Yi-Bo Xue: Writing - review & editing, Data curation, Methodology, Investigation. Zi-Fa Wang: Investigation, Supervision. Wen-Jun Tian: Data curation, Methodology. Yong-Dong Wang: Investigation, Supervision. Xiao Tang: Investigation, Supervision.

Funding

This work was supported by the Cultivation Plan for Tianshan Talent Scholar, China (No. 2022TSYCCX0012), the Second Tibetan Plateau Scientific Expedition and Research Program, China (STEP, No. 2019QZKK0606), the National Natural Science Foundation of China (No. 41730639, No. 42177088), the West Light Foundation of the Chinese Academy of Sciences (No. 2020-XBQNXZ-015), and the Ministry of Science and Technology, China (No. 2021xjkk0305).

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-95974-z>.

Correspondence and requests for materials should be addressed to X.-X.Z.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025