

Spatiotemporal patterns and driving forces of dust weather events in Central Asia from 2000 to 2020 postprint

Authors: LIU Yuhan, ZHAO Yuanyuan, GAO Guanglei, DING Guodong, LI Ning, ZHAO Yuanyuan

Date: 2026-02-04T17:33:44+00:00

Abstract

Central Asia is characterized by an arid climate and extensive deserts, and its sustainable development is severely constrained by dust events. Objectively understanding the spatiotemporal patterns and driving mechanisms of dust weather in this region is therefore of great importance. Based on meteorological observations from 2000 to 2020, we investigated the spatiotemporal characteristics of dust weather in the five Central Asian countries (Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan) using Theil-Sen trend analysis and the Geodetector method, and quantitatively assessed the influence of environmental factors such as temperature, precipitation, and vegetation on dust weather frequency. The results show that: (1) dust weather in Central Asia is primarily distributed within a broad “dust belt” extending west-east from the northern Caspian lowland desert, and is concentrated in basins, plains, and other low-elevation areas. Intense dust weather mainly occurs in the northern Aral Sea region and along the southern margin of Central Asia, with a maximum annual frequency of 21.9%; (2) strong dust weather in Central Asia has fluctuated but shown a slight overall decrease since 2001, with the highest seasonal frequency (1.1%) occurring in spring (March to June); (3) from 2000 to 2020, the four major dust source regions in Central Asia (north of the Aral Sea, the Kyzylkum Desert, the Karakum Desert, and the Garabogazköl Bay region) experienced changes such as shifts and contractions in their dust-affected areas, and the northern Caspian lowland desert has become the most important low-emission dust source in Central Asia; and (4) the combined effect of soil moisture and air temperature exerts the strongest influence on dust weather in Central Asia. This study provides a theoretical basis for sand prevention and control in the region. In the future, Central Asia should prioritize the rational utilization of land and water resources and implement human interventions such

as vegetation restoration and optimization of irrigation practices to curb further desertification.

Full Text

Preamble

Journal of Arid Land (2026) 18(1): 1–16

doi: 10.1016/j.jaridl.2026.01.002; CSTR: 32276.14.JAL.20250249

Spatiotemporal Patterns and Driving Forces of Dust Weather Events in Central Asia from 2000 to 2020

LIU Yuhan¹, ZHAO Yuanyuan^{1*}, GAO Guanglei¹, DING Guodong¹, LI Ning²

¹College of Forestry, Beijing Forestry University, Beijing 100083, China

²Guyuan Forestry and Grassland Development Service Center, Ningxia 756000, China

Abstract: Central Asia is characterized by an arid climate and widespread desert distribution, with its sustainable development severely constrained by dust events. An objective understanding of the spatiotemporal patterns and driving forces of dust weather is highly important in this region. Based on meteorological observations from 2000 to 2020, we examined the spatiotemporal characteristics of dust weather in the five Central Asian countries (Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan) via Theil-Sen trend analysis and Geodetector modeling, quantitatively revealing the influence of environmental factors such as temperature, precipitation, and vegetation on dust weather frequency. The results showed that: (1) dust weather in Central Asia was mainly distributed in a large “dust belt” extending west-to-east from the northern Caspian lowland desert, concentrated in basins, plains, and other low-altitude areas. Strong dust weather occurred primarily in northern areas of the Aral Sea and the southern edge of Central Asia, with a maximum annual frequency of 21.9%; (2) strong dust weather in Central Asia has fluctuated and slightly decreased since 2001, with the highest frequency (1.1%) occurring in spring (March–June); (3) from 2000 to 2020, the four main source areas (north of the Aral Sea, Kyzylkum Desert, Karakum Desert, and Garabogazköl Bay region) experienced spot shifting and shrinking, while the northern Caspian lowland desert became the most important low-emission dust source in Central Asia; and (4) the combined effect of soil moisture and air temperature had the most significant influence on dust weather in Central Asia. This study provides a theoretical basis for sand prevention and control in Central Asia. In the future, Central Asia should focus on rational utilization of land and water resources and implement human interventions such as vegetation restoration and optimization of irrigation methods to curb further desertification.

Keywords: Central Asia; dust weather; temporal and spatial distribution; influencing factor; Geodetector

Citation: LIU Yuhan, ZHAO Yuanyuan, GAO Guanglei, DING Guodong, LI Ning. 2026. Spatiotemporal patterns and driving forces of dust weather events in Central Asia from 2000 to 2020. *Journal of Arid Land*, 18(1): 1-16. <https://doi.org/10.1016/j.jaridl.2026.01.002>; <https://cstr.cn/32276.14.JAL.20250249>

1 Introduction

Dust events are common meteorological phenomena in arid and semi-arid areas, where winds sweep loose dust and sand particles from dry ground into the air, making the air turbid [?]. The occurrence of dust weather not only poses a direct threat to human lives and property but also has significant impacts on global climate and the dust cycle [?, ?]. As one of the four major active dust centers in the world, Central Asia experiences dozens of sandstorms annually, with a total desertification area of nearly 4.00×10^6 km², making it an important source of dust aerosols in Asia [?, ?]. In addition to original natural desert areas, new anthropogenically formed deserts (the Aral Sea, Caspian Sea, Lake Balkhash, etc.) are becoming important sources of dust and salt in Central Asia [?]. Reportedly, agricultural economic losses attributed to dust storms account for 2.0%-5.0% of Gross Domestic Product (GDP) in Central Asia. In the Aral Sea region, pediatric pulmonary diseases are severe, and in Turkmenistan, 50.0% of all reported diseases are respiratory diseases [?]. Moreover, the environmental problems of Central Asia, which serves as an essential transportation route between Europe and Asia, threaten the ecological security of the “New Silk Road Economic Belt” [?]. Therefore, the Central Asian sand problem is not only an object of research in natural sciences but also a matter of human well-being and ecological stability.

Early routine observations of dust events relied heavily on surface meteorological observation systems, recording dust frequency (number of sandstorm days), duration, intensity (atmospheric visibility), direction of motion (wind direction), and deposition rate [?]. This information has played an important role in dust studies and other climate research. The dust record in Central Asia has lasted for nearly 100 years, and dust aerosol studies in this sparsely populated region have been based mostly on ground-based stations, which are few in number and unevenly distributed in typical data-deficient areas. For example, [?] reported that the number of sandstorm days reached 25-42 d/a along the Caspian Sea coast from 1936 to 1995. In agricultural areas and the Amu Darya River basin, the number of sandstorm days can reach 40-70 d/a. In addition to regular recording of dust events by meteorological stations, satellite remote sensing provides another effective data source. Geostationary meteorological satellites and Moderate-Resolution Imaging Spectroradiometers (MODIS) are important data sources for remote sensing monitoring of sandstorms. Since the mid-1970s, remote sensing data have been used to track sandstorms and salt dust storms near the Aral Sea in Uzbekistan, Kazakhstan, and Turkmenistan [?]. Each observation method has its advantages: remote sensing can provide timely, long-term,

and large-scale aerosol observations, but data on the frequency, intensity, and duration of sandstorms are still based mainly on ground-based meteorological station observations.

The frequency of global dust events varies significantly across spatial and temporal scales. Dust movement is a complex process controlled by various climatic factors such as precipitation, wind, vegetation, and soil moisture, leading to a close association between dust and climate at annual, interdecadal, and millennial time scales [?]. Currently, methods commonly used to determine the drivers of dust weather include Geodetector, Pearson' s correlation analysis, and standardized regression coefficients. Pearson' s correlation analysis is mainly used to analyze linear relationships between two continuous variables, which is fast and easy to calculate [?]. However, it can only measure linear relationships and has higher requirements for data. Standardized regression coefficients should exclude the effects of scale of dependent and independent variables. The ratio of absolute value of a given independent variable' s coefficient to the sum of absolute values of all regression coefficients is defined as the relative contribution of that independent variable to the dependent variable [?]. However, the results are applicable only to specific environments and have limited utility in practical settings. Geodetector is a statistical model for analyzing spatial data and exploring variable drivers. Compared with other traditional statistical models, Geodetector can determine spatial correlations based on geographic divergence of influencing factors. It can also explore the effects of individual factors as well as interactions between different factors without requiring strict adherence to traditional statistical assumptions or complex parameter-setting processes [?]. For example, [?] used Geodetector to explore the effects of six driving factors on Aerosol Optical Depth (AOD) distribution in Central Asia. [?] investigated the correlation between long-term Dust Aerosol Optical Depth (DAOD) distribution and influencing factors via Geodetector analysis. Although these findings provide insights into the driving mechanisms of dust events in Central Asia, the linkages between different dust weather types and Central Asian climate remain largely uninvestigated. Therefore, in this study, we choose Geodetector to explore the relationships between dust weather and its driving factors.

As an indispensable part of the global dust circulation system, Central Asia exhibits significant spatial variability in topography, climatic conditions, soil types, and vegetation cover, with obvious geographical differences in the frequency and intensity of dust weather [?]. However, most current studies on sandstorms have focused on arid and semi-arid areas of North Africa, the western United States, and Australia [?], and few studies on dust in Central Asia have focused on the origin, formation, transportation, and deposition of aeolian sand [?]. Moreover, to analyze variations in dust events and their influencing factors more accurately, it is necessary to conduct more in-depth research by considering both spatial and temporal characteristics.

Therefore, in this study, five Central Asian countries—Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan—are selected as the research area.

Using the latest ground observations of dust data combined with meteorological, topographic, and vegetation data, we statistically analyzed the spatial and temporal distribution characteristics of weak, strong, and total dust weather over the past 21 years, revealing the key driving factors. The primary objectives of this study are to: (1) characterize the dynamic distribution of long time series of dust weather in Central Asia; (2) reveal the key drivers affecting the distribution of dust weather in Central Asia; and (3) elucidate the underlying mechanisms for the characteristics of dust weather in Central Asia and propose corresponding measures.

2.1 Study Area

The study area covers the five countries of Central Asia (35°06′–55°27′N, 46°30′–87°21′E), including Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan, with a combined area of 5.67×10^6 km² (Fig. 1 [Figure 1: see original paper]). Central Asia is located in the center of Eurasia and serves as an important transportation hub connecting Asia and Europe. A unique climate pattern is formed by its complex landscapes including alpine meadows, forest lands, grasslands, oases, deserts, and mountains [?]. The vegetation is rich but sparse, with grassland and desert vegetation predominating, and is very sensitive to climate change [?, ?]. There are six major deserts in Central Asia: the Caspian lowland desert, Aralkum Desert, Karakum Desert, Kyzylkum Desert, Pre-Balkhash Desert, and the Garabogazköl Bay region [?].

2.2 Data Sources

Dust data were obtained from the Integrated Surface Dataset (ISD) of the National Climatic Data Center (NCDC; <http://ftp.ncdc.noaa.gov/pub/data/noaa/>), observed every 3 or 6 hours. Dust weather was categorized into strong dust weather (sandstorms and strong sandstorms) and weak dust weather (floating dust and blowing dust) [?]. Meteorological data such as annual precipitation, temperature, and average wind speed from 2000 to 2020 were obtained from the NCDC meteorological dataset. We performed this study according to the Northern Hemisphere seasonal classification standard: March–May (spring), June–August (summer), September–November (autumn), and December–February (winter). Normalized Difference Vegetation Index (NDVI) data were derived from the MOD13A2 product with a spatial resolution of 1 km. The images were subsequently processed by Google Earth Engine (GEE) to obtain annual average NDVI. Soil moisture data were obtained using the high-resolution ERA5 (ECMWF Reanalysis v5.0) dataset with a resolution of $0.25^\circ \times 0.25^\circ$. Land use data were obtained from the European Space Agency (ESA) Climate Change Initiative (CCI) Land Cover dataset (<https://maps.elie.ucl.ac.be/CCI/viewer/>) with a spatial resolution of 300 m.

2.3.1 Calculation of Dust Weather Frequency

Dust frequency is an effective indicator of spatiotemporal variability and magnitude of wind and sand, defined as the ratio of the number of dust occurrences to the total number of observation days during a period [?]. We calculated dust data for each meteorological station in the study area. When weak or strong dust weather occurred more than once in one day, it was counted as a single dust weather day [?]. Finally, excluding stations with dust frequency less than 1%, we retained 91 meteorological observation stations.

2.3.2 Analysis of Spatial Distribution of Dust Weather Frequency

The Theil-Sen median method was used to analyze the trend of dust frequency changes in Central Asia from 2000 to 2020, and the results were tested using the Mann-Kendall method for significance testing. Theil-Sen median slope estimation is a robust nonparametric statistical method for trend calculation, suitable for trend analysis of long-time series data. The specific formula is as follows [?]:

$$TS_{\text{slope}} = \text{median} \left(\frac{x_j - x_i}{j - i} \right), \quad \forall i < j$$

where TS_{slope} is the Theil-Sen median slope; x_j and x_i are the dust frequency data in the j th and i th year of the time series, respectively; and i and j are the time series indices. $TS_{\text{slope}} > 0$ indicates an upward trend and vice versa.

The Mann-Kendall trend test was calculated as follows [?, ?]:

$$S = \sum_{k=1}^{n-1} \sum_{l=k+1}^n \text{sign}(x_l - x_k)$$

$$\text{Var}(S) = \frac{n(n-1)(2n+5)}{18}$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases}$$

where S is the test statistic; n is the length of the data; k and l are the time series indices; x_k and x_l are the dust frequency data in the k th and l th year of the time series, respectively; and Z is the standardized test statistic. When $|Z| \geq 1.65$,

1.96, and 2.58, the trend has passed significance tests at 90.0%, 95.0%, and 99.0% confidence levels, respectively, with trend characteristics expressed as minimally significant, significant, and extremely significant change.

2.3.3 Analysis of Factors Affecting Dust Weather Frequency

Geodetector, as a new type of econometric model with geographic characteristics, can be used to investigate the spatial heterogeneity of geographic phenomena, and its mechanisms of divergence and driving factors have been widely analyzed in dust weather studies [?, ?]. The method is based on spatial difference theory and detects discretely categorized independent and dependent variables on the same spatial scale. If the independent variable has a significant effect on the dependent variable, the spatial distributions of the two variables will show a certain degree of similarity [?].

By reviewing the literature [?, ?, ?], we selected six environmental drivers (precipitation, temperature, wind speed, NDVI, soil moisture, and land use type), which were comparatively analyzed using the factor detector and interaction detector of Geodetector. Since Geodetector requires discrete variables, the optimal scale of spatial data discretization was determined via screening discrete data from 91 meteorological stations and cluster analysis using SPSS v24.0 software. The degree of factor influence was expressed as the q -value, and the method with the largest q -value was used as the optimal parameter of Geodetector in this study. The q -value was calculated as follows [?]:

$$q = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2}$$

where h is the classification or partition of factor Y or factor X ; L is the number of sample points; N_h and σ_h^2 are the number and variance of samples (pixels) in layer h ; and σ^2 is the variance of the whole region. The q -value ranges from $[0, 1]$. A high q -value indicates a high degree of correlation between two variables and vice versa.

Interaction detection is used to analyze the combined effects of two factors on the dependent variable Y in terms of explanatory power. These interactions can be categorized into five types, as shown in Table 1 .

3.1 Spatial Distribution of Dust Weather Frequency in Central Asia

As shown in Figure 2a [Figure 2: see original paper]a1-a3, weak dust weather occurred mostly in western and central areas of Kazakhstan from 2000 to 2020,

with average frequency between 3.0% and 8.0%. The Caspian lowland desert had the highest weak dust frequency with an annual average of 4.0%–12.0%, exceeding 12.0% at some stations, followed by northern areas of the Aral Sea. Additionally, frequency ranged from 1.0% to 5.0% in Aktobe State of Kazakhstan, northern areas of the Garabogazköl Bay region, the Karakum Desert, and Issyk-Kul Lake in northeastern Kyrgyzstan.

In contrast to weak dust weather, strong dust weather was concentrated mainly in the central and western parts of Kazakhstan as well as marginal areas of southeastern Uzbekistan (Fig. 2b1–b3). The Aralkum Desert and Termez State of Uzbekistan had the highest frequency of strong dust weather at 3.0%–9.0%. The Caspian Basin region and northern area of the Karakum Desert had frequencies within the range of 1.0%–5.0%.

The spatial distribution of total dust weather in the study area was greater in the west than in the east (Fig. 2c1–c3). Dust activities focused on the area from the Caspian Basin to northern areas of the Aralkum Desert, with frequency greater than 14.0% at some stations, followed by the southeastern part of Uzbekistan where frequency ranged from 5.0% to 10.0%. Dust frequency in the Garabogazköl Bay region, the Karakum Desert, and northern area of the Kyzylkum Desert was 3.0%–7.0%. In the rest of the study area, total dust weather frequency was lower, at less than 1.0%.

Over the past 20 years, the main dust source areas and types in Central Asia have significantly shifted, with blowing dust and sandstorms emerging as the most common dust event types. Weak dust events were dominant and have greatly increased in frequency and extent, whereas strong dust events have decreased. In 2000, Central Asia was characterized by strong dust weather, especially in the northern part of the Aral Sea, which was the main dust source. In 2010, dust events occurred mainly along the Caspian Sea coastal region to the Aral Sea and northern Kyzylkum Desert. The intensity of dust events gradually shifted from strong to weak, and the Caspian Basin became a new dust active area. In 2020, the study area experienced mostly weak dust weather. The northern part of the Aral Sea, a multi-sandstorm area, has experienced a decline in frequency and extent of dust occurrences. Additionally, dust events in the Caspian lowland desert became more active, making it the main dust source in Central Asia.

In summary, areas with high dust frequencies were located mainly in the Caspian lowland desert, Aralkum Desert, Kyzylkum Desert, southeastern Central Asia, and other low-lying areas, whereas areas with low dust frequencies were located in the Kazakhskiy Melkosopochnik (Kazakh Uplands), mountainous areas, and other high-altitude regions. The largest dust source region occurred in the Caspian lowland desert of western Kazakhstan, forming a “belt” shape stretching from west to east. Furthermore, southern edges of Central Asia were characterized mostly by strong dust weather, whereas the Caspian Basin experienced powerful but generally weak dust events.

3.2.1 Monthly Dust Weather Variation

As shown in Figure 3 [Figure 3: see original paper], dust weather frequency in different countries exhibited distinct monthly variation characteristics. Kazakhstan experienced mainly weak dust events concentrated in spring and summer, with two peaks in May and August. Tajikistan experienced mostly weak dust events and few strong dust events, which occurred in summer and autumn with the highest frequency in July. Kyrgyzstan was characterized by weak dust events focused in spring and autumn, with the highest frequency in April. In Uzbekistan, strong dust weather usually occurred, concentrated in spring and summer with the highest frequency in June. Turkmenistan had relatively active dust events throughout the year, with weak dust weather occurring mostly in spring and summer, and the average monthly frequency of strong dust events fluctuated around 1.5%.

Generally speaking, weak dust weather in Central Asia was concentrated in summer, followed by spring. The highest monthly average dust frequency was 1.7% in August, and the lowest was 0.1% in January, occurring primarily in Kazakhstan, Tajikistan, and Kyrgyzstan. Strong dust weather was concentrated in spring, followed by summer. The highest monthly average dust frequency was 1.1% (June) and the lowest was 0.2% (January), mainly in Kazakhstan, Uzbekistan, and Turkmenistan. Total dust weather was concentrated in spring and summer, with a sharp decrease in winter. The highest frequency occurred in June (2.4%), whereas the lowest was in January (0.4%).

3.2.2 Seasonal Dust Weather Variation

Figure 4 [Figure 4: see original paper] shows that dust weather frequency in Central Asia had notable seasonal variations. Multiannual weak dust weather frequency followed this order: summer (2.0%) > spring (1.8%) > autumn (1.2%) > winter (0.3%). Strong dust frequency followed: spring (1.5%) > summer (1.4%) > autumn (0.8%) > winter (0.4%). Total dust events varied similarly to weak dust events: summer (3.2%) > spring (3.0%) > autumn (1.8%) > winter (0.7%).

Dust events in Central Asia were most active in summer, followed by spring, and sharply declined in autumn and winter. In the Caspian Basin, weak dust events were most common in spring, decreasing in number but increasing in extent in summer, while frequency of strong dust events was highest in summer. In the Aralkum Desert, frequency of dust events was relatively high in spring. Weak dust events obviously increased in summer, but strong dust events decreased. Frequency of strong dust events was higher in southern fringes of the study area in spring. The southern edge of Central Asia was dominated by strong dust

weather, with the greatest frequency in spring. In winter, dust occurred at the southern fringe of Central Asia and along the coast of the Caspian Sea.

3.2.3 Inter-Annual Dust Weather Variability Characterization

As shown in Figures 5 and 6 [Figure 5: see original paper][Figure 6: see original paper], average frequency of weak dust weather in the study area over 21 years exhibited an overall increasing trend, especially between 2000 and 2010, after which it fluctuated. In most parts of central and western Kazakhstan (from the Caspian Sea coast to northern Kyzylkum Desert), frequency of weak dust events showed an extremely significant increase, particularly in the Caspian lowland desert. Frequency of weak dust events rose from 0.6% in 2000 to 28.4% in 2022, mainly after 2008. Additionally, there was a notable increase in weak dust events in the Pre-Balkhash Desert and part of northeastern Turkmenistan. In high-altitude mountainous areas of southeastern Central Asia, frequency of weak dust events significantly decreased over 21 years. In general, the increase in weak dust frequency occurred mainly in Kazakhstan and Turkmenistan, whereas the other three countries showed decreasing trends.

Overall, average frequency of strong dust weather in the study area did not change substantially. Frequency was highest in 2001, then decreased markedly and fluctuated around 0.9%. Frequency of strong dust events increased significantly in southern fringes of Central Asia and along the Caspian Sea coast but decreased significantly in northern areas of the Aral Sea and along the Tianshan Mountains. In general, strong dust weather increased mainly in Turkmenistan and Uzbekistan but decreased significantly in Kazakhstan.

Total dust frequency slowly increased with fluctuations, similar to weak dust events. There were two peaks in 2010 and 2014 with a maximum of 2.7%, and two low peaks in 2003 and 2016 with a minimum of 1.4%. Spatially, western Kazakhstan and eastern Turkmenistan showed significant increases in dust event frequency, with increased weak dust weather in the northern Caspian Sea and strong dust weather around the Karakum Desert. Influenced by decreased frequency of strong dust events, total dust weather frequency tended to decrease in some high-elevation areas in central and eastern parts of the study area.

3.3.1 Single-Factor Analysis

Table 2 shows the single-factor analysis results. Influence of each environmental factor on weak dust weather in descending order was: temperature (0.099) > NDVI (0.071) > land use type (0.065) > soil moisture (0.055) > wind speed (0.034) > precipitation (0.026). Influence on strong dust weather was: soil moisture (0.126) > temperature (0.113) > land use type (0.078) > NDVI (0.041)

> wind speed (0.030) > precipitation (0.004). Trend of total dust weather was similar to strong dust weather, with influence in this order: temperature (0.128) > soil moisture (0.091) > land use type (0.079) > NDVI (0.070) > wind speed (0.044) > precipitation (0.009). Except for precipitation, all other factors were significantly correlated ($P < 0.01$). The nonsignificant effect of precipitation may be related to the extremely arid climate characteristics of the study area. Average annual precipitation in Central Asia was less than 200 mm, and spatiotemporal distribution was heterogeneous, leading to its low degree of influence on dust weather. Temperature and soil moisture played dominant roles in influencing dust weather across Central Asia, followed by land use type, which affected dust amount by changing surface roughness and dust erodibility. NDVI also strongly influenced dust weather. Compared with the first four factors in Table 2, wind speed and precipitation had smaller effects on dust frequency.

3.3.2 Two-Factor Analysis

In natural environments, various environmental factors affect spatial and temporal distributions of dust weather. In Table 3, interactions between factors were nonlinearly enhanced. Common explanatory power of these factors for dust weather frequency was greater than individual explanatory power of each factor, indicating that their joint influence on dust weather in Central Asia was more notable and that no factors acted individually. For weak dust weather, the interaction between temperature and soil moisture had the largest q -value, reaching 0.440. For strong dust weather, the interaction between wind speed and temperature had the largest q -value, reaching 0.455, followed by the interaction between temperature and soil moisture with a q -value of 0.422. Overall, the combined effect of temperature and humidity had the strongest influence on the spatial distribution of dust weather ($q = 0.464$).

4.1 Environmental Factors Synergistically Determine Spatial Patterns of Dust Weather Events in Central Asia

Studies have shown that aeolian sand activity has occurred intensively in Central Asia, mainly in Kazakhstan, Uzbekistan, and Turkmenistan, and that its spatial pattern formation has been synergistically controlled by a series of environmental factors. Kazakhstan, the hub of Eurasia, is located between the Siberian taiga in the north and Central Asian deserts in the south [?]. Approximately 50.0% of its land is occupied by deserts and semi-deserts, making it the region of Central Asia with the most frequent dust events [?]. Dust activity was concentrated along the large “dust belt” extending eastward from northern areas of the Caspian Desert, primarily in semi-desert and desert grasslands. These drylands are sparsely vegetated and widely used for agricultural or industrial development, providing large amounts of dust emissions. Most of the Aral Sea

area is covered with sand and light-textured soils conducive to wind erosion. With the shrinking area of the Aral Sea in the past decade, the Aralkum Desert has gradually become a powerful source of sandstorms and salt dust storms, affecting Uzbekistan and Kazakhstan [?, ?]. This trend was also demonstrated by studies of [?] and [?]. Because of depletion and evaporation of river water by irrigation and industry, the water level of the Caspian Sea has decreased, and the number of dust events has increased significantly. Since the beginning of the 21st century, the Caspian lowland desert has become an important dust source in Central Asia.

Uzbekistan, as a typical inland basin, is characterized by deserts and desert oases. In summer, maximum temperatures in desert areas can exceed 45°C, whereas in winter, minimum temperatures in the north can drop below -36°C [?]. Influenced by precipitation, Uzbekistan experiences a high incidence of strong dust events in spring and summer, with a marked decrease in autumn and winter [?]. As the world's leading cotton exporter and the most densely populated country in Central Asia, more than half of Uzbekistan's land is used for cotton cultivation, which consumes a great deal of water and produces low output, leading to excessive water depletion in the Aral Sea and a sharp increase in aeolian sand activity [?, ?]. The Aral Sea is surrounded by three deserts: the newly formed Aral Sea Desert, the Kyzylkum Desert in the east, and the Karakum Desert in the south [?]. Dust and strong winds form a "dust corridor" along the meridian 55°-65°E from the Aralkum and Karakum deserts to the south [?]. Moreover, dust events occurring in the southeastern fringe of Uzbekistan may be influenced by deserts, dry lakes, and abandoned agricultural areas along the Iran-Afghanistan border [?, ?, ?].

Turkmenistan is situated in the temperate desert zone, which can be divided into three desert zones: northern Tertiary plateau, sandy desert subzone, and premontane loess plains [?]. Weak dust events were concentrated in the sandy desert of southern Turkmenistan, and strong dust events were in the southeastern loess desert zone. Frequency of weak and strong dust weather was relatively even throughout the year. The plain topography and unstable climate of Turkmenistan provide favorable conditions for sandstorm formation [?]. In spring, the Siberian high pressure triggers strong northerly winds that blow dust from Central Asian deserts (Caspian lowland, Aralkum, Kyzylkum, and Karakum deserts) to southern Turkmenistan [?]. In summer, intense heating of the underlying ground by local tropical air leads to formation of thermal depressions in southeastern Turkmenistan, resulting in dust events. In winter, intrusion of southern cyclones and sharp changes in temperature and humidity affect dust formation. Additionally, the southern part of Turkmenistan is bordered by Iran, a widely desertified country, and the great temperature difference between local and Iranian air masses also leads to sandstorm occurrence [?].

Dust events in Kyrgyzstan occurred mainly in mountainous areas of the south-east, but their frequency decreased. Tianshan mountainous areas are densely populated and can cause certain dust events due to winter heating and industrial

production emissions [?].

4.2 Temperature, Land Use Type, and Soil Moisture Dominate Temporal Variability of Dust Weather in Central Asia

Ecosystems of Central Asia are very fragile and sensitive to climate change and human activities, and dust weather generation is driven by a combination of influencing factors. [?] reported a significant decrease in sand and dust storm activity in Central Asia over the last three decades and explained that this trend may be due to weakening of anthropogenic activities and increased conservation measures since the 1980s. [?] argued that Central Asia had the same decreasing trend of aeolian sand activity as seen globally, indicating that weakening of dust activity was not due to anthropogenic activities but rather was mainly caused by global changes. According to our results, Central Asia showed a significant increasing trend in weak dust weather frequency and a weak decrease in strong dust weather frequency from 2000 to 2020, with main drivers being temperature, land use type, and soil moisture. Therefore, changes in dust activity over the past two decades may be mainly attributed to temperature increases, shifts in land type caused by anthropogenic activities, and changes in soil moisture due to over-irrigation.

Studies by [?] and [?] both revealed that Central Asia has experienced significant warming over the past few decades, even faster than the global rate of terrestrial warming. [?] reported that spring warming was faster in Central Asia. Sharp temperature increases in spring, melting of snow, loosening of surface sediments, and frequent cold front activities increase the likelihood of sand movement. In summer, heat and dryness with lack of vegetation cover, accompanied by strong hot winds, sharply increase the likelihood of triggering weak dust weather such as floating dust and blowing dust. In contrast, winter aeolian sand activity on the ground surface is weakened, and snow accumulation makes it difficult for surface sand to mobilize, especially in Tianshan mountainous areas [?]. [?] reported that cultivated land and urban land in five Central Asian countries increased, whereas water bodies, forest land, and grassland decreased over the past several decades. This result has partly contributed to increased weak dust activity in Central Asia. Soil moisture reflects surface hydrological processes. [?] reported that vertical wind shear, snow depth, and soil moisture together affected seasonal variation in dust aerosols in Central Asia, with soil moisture being the main factor controlling inter-annual scale variation. In Central Asia, sparse vegetation and low soil moisture on the lower surface provide favorable conditions for land desertification [?]. Additionally, [?] found that in extremely arid deserts, vegetation's role was very weak and dust seasonality was controlled mainly via atmospheric circulation. This may explain NDVI's large effect on weak dust weather but small effect on strong dust weather. In comparison, effects of wind speed and precipitation are small. Wind can increase dust activity near the surface, but dust aerosols may remain suspended at high altitudes,

limiting wind's effect on dust movement [?]. Results revealed that precipitation had a more notable effect on weak dust weather frequency and weaker effect on strong dust weather. Under extremely arid and hot climatic conditions in Central Asia, sandy ground is very dry and sporadic rains have little effect. Even after heavy rain, sandstorms can appear after only a few hours [?].

4.3 Limitations and Prospects

Restricted by the wide geographic range and long study period, the number of meteorological stations available that meet research requirements was relatively limited and their distribution was significantly uneven, leading to potentially inaccurate conclusions about spatial and temporal characteristics of dust weather. Moreover, dust weather occurrence results from complex interactions between natural and anthropogenic factors. This study focused mainly on environmental factors and did not analyze key anthropogenic driving factors. In the future, more continuous observation data are needed to study internal patterns of Central Asia at smaller scales. It is also necessary to consider anthropogenic drivers, improve mechanistic understanding of dust drivers in Central Asia, and further analyze characteristics, causes, and trends of dust weather, especially in the Aral Sea and Caspian Sea regions.

In the future, Central Asia should focus on rational use of land and water resources [?]. Over-irrigation leading to river outflow may be the main cause of anthropogenic desertification. Agricultural irrigation methods should be optimized, especially in cotton planting areas such as Uzbekistan and the Amu Darya River basin, where water resources need to be developed and utilized in the context of climate change. Consideration should be given to forest land and grassland conservation, adjustment of agricultural and livestock structures, and restoration of degraded grasslands in future land use planning to curb further desertification in Central Asia [?]. Sandy land management is an effective means of controlling dust weather frequency and intensity [?]. It is recommended that windbreak and sand fixation work, such as vegetation restoration and use of chemical consolidation agents, be carried out in key dust source areas in Central Asia to restore desert ecosystems and effectively curb sand and dust emissions.

5 Conclusions

Based on daily ground-based dust data from NCDC, we analyzed spatial and temporal variations in different dust weather events in Central Asia from 2000 to 2020 and examined impacts of six driving forces—temperature, precipitation, wind speed, NDVI, soil moisture, and land use type—on dust weather via Geodetector. Results show that recent dust characteristics in Central Asia have under-

gone significant changes due to combined effects of climate change and human activities. Spatially, dust weather in Central Asia was distributed mainly in a large “dust belt” extending west-to-east from the northern Caspian lowland desert, concentrated in basins, plains, and other low-altitude areas. From 2000 to 2020, spot shifting and shrinking occurred in four main source areas (north of the Aral Sea, Kyzylkum Desert, Karakum Desert, and Garabogazköl Bay region), and the northern Caspian lowland desert became the most important low-emission dust source in Central Asia. Temporally, strong dust weather frequency in Central Asia has slightly decreased with a peak in spring, while weak dust weather frequency has increased, peaking in summer. Among influencing factors, the combined effect of soil moisture and air temperature had the most significant influence on dust weather in Central Asia.

This study presents a long-term dust weather dataset and a map of spatial and temporal distribution of dust source areas in Central Asia, providing important basic data support for climate change research in Central Asia and laying the foundation for studying dust emission mechanisms and driving factors in arid areas of Central Asia.

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

Acknowledgements: This research was funded by the National Natural Science Foundation of China (42571311).

Author Contributions: Conceptualization: ZHAO Yuanyuan, LIU Yuhan; Methodology: LIU Yuhan, DING Guodong; Formal analysis: LIU Yuhan, LI Ning; Writing—original draft preparation: LIU Yuhan, ZHAO Yuanyuan; Writing—review and editing: ZHAO Yuanyuan, DING Guodong, GAO Guanglei; Funding acquisition: ZHAO Yuanyuan; Resources: ZHAO Yuanyuan; Supervision: ZHAO Yuanyuan, LIU Yuhan, DING Guodong, GAO Guanglei, LI Ning. All authors approved the manuscript.

References

- Abula T, Jilili A, Ge Y X, et al. 2020. Potential spatiotemporal variability of dust from the playa of the dry lake bed of the Aral Sea in Central Asia. *China Environmental Science*, 40(9): 3756–3766. (in Chinese)
- Bao C L, Yong M, Jin E, et al. 2021. Regional spatial and temporal variation characteristics of dust in East Asia. *Geographical Research*, 40(11): 3002–3015. (in Chinese)
- Bazarbayev R, Zhou B, Allaniyazov A, et al. 2022. Physical and chemical properties of dust in the Pre-Aral region of Uzbekistan. *Environmental Science and*

Pollution Research, 29(27): 40893–40902.

Chen X G, Zhang C J, Dong A X, et al. 2004. Study on intensity standard of regional sandstorm in Gansu Province. *Plateau Meteorology*, 23(3): 374–381. (in Chinese)

Cheng H X, Lin Y J, Chen P, et al. 2023. Spatial characteristics of sand-dust weather days and influencing factors in the Tarim Basin. *Arid Zone Research*, 40(11): 1707–1717. (in Chinese)

De Keersmaecker W, Lhermitte S, Tits L, et al. 2015. A model quantifying global vegetation resistance and resilience to short-term climate anomalies and their relationship with vegetation cover. *Global Ecology and Biogeography*, 24(5): 513–525.

Fan X W, Duan Q Y, Shen C W, et al. 2020. Global surface air temperatures in CMIP6: Historical performance and future changes. *Environmental Research Letters*, 15(10): 104056, doi: 10.1088/1748-9326/abb051.

Groll M, Opp C, Aslanov I. 2013. Spatial and temporal distribution of the dust deposition in Central Asia—results from a long term monitoring program. *Aeolian Research*, 9: 49–62.

Guo Y, He Y, Zhang L F, et al. 2021. Remote sensing monitoring of vegetation change in Central Asia from 2000 to 2017. *Chinese Agricultural Science Bulletin*, 37(8): 123–131. (in Chinese)

Han H Q, Wang X H, Niu L Z, et al. 2020. The land-use and land-cover change characteristics and driving forces of cultivated land in Central Asian countries from 1992 to 2015. *Chinese Journal of Eco-Agriculture*, 29(2): 325–339. (in Chinese)

Howard K W F, Howard K K. 2016. The new “Silk Road Economic Belt” as a threat to the sustainable management of Central Asia’ s transboundary water resources. *Environmental Earth Sciences*, 75: 976, doi: 10.1007/s12665-016-5752-9.

Huang J P, Wang T H, Wang W C, et al. 2014. Climate effects of dust aerosols over East Asian arid and semiarid regions. *Journal of Geophysical Research: Atmospheres*, 119(19): 11398–11416.

Indoitu R, Orlovsky L, Orlovsky N. 2012. Dust storms in Central Asia: Spatial and temporal variations. *Journal of Arid Environments*, 85: 62–70.

Jing Y, Sun Y L, Gao S, et al. 2020. Spatiotemporal variations of AOD and geographical detection of its influence factors in Beijing-Tianjin-Hebei region. *Arid Land Geography*, 43(1): 87–98. (in Chinese)

Kendall M G. 1962. *Rank Correlation Methods*. New York: Hafner Publishing Company.

- Li Y H, Sun G W, Zhang Q, et al. 2006. The analysis of environmental creeping problems in Central Asia and Northwest China. *China Environmental Science*, 26(5): 609-613. (in Chinese)
- Mohammadpour K, Sciortino M, Kaskaoutis D G, et al. 2022. Classification of synoptic weather clusters associated with dust accumulation over southeastern areas of the Caspian Sea (Northeast Iran and Karakum Desert). *Aeolian Research*, 54: 100771, doi: 10.1016/j.aeolia.2022.100771.
- Mohammad A, Wang X H, Xu X T, et al. 2013. Drought and spring cooling induced recent decrease in vegetation growth in Inner Asia. *Agricultural and Forest Meteorology*, 178-179: 21-30.
- Nishonov B E, Kholmatjanov B M, Labzovskii L D, et al. 2023. Study of the strongest dust storm occurred in Uzbekistan in November 2021. *Scientific Reports*, 13: 20042, doi: 10.1038/s41598-023-42256-1.
- Onishi K, Kurosaki Y, Otani S, et al. 2012. Atmospheric transport route determines components of Asian dust and health effects in Japan. *Atmospheric Environment*, 49: 94-102.
- Opp C, Groll M, Aslanov I, et al. 2017. Aeolian dust deposition in the southern Aral Sea region (Uzbekistan): Ground-based monitoring results from the LUCA project. *Quaternary International*, 429: 86-99.
- Orlovsky L, Orlovsky N, Durdyev A. 2005. Dust storms in Turkmenistan. *Journal of Arid Environments*, 60(1): 83-97.
- Rashki A, Rautenbach C J W, Eriksson P G, et al. 2013. Temporal changes of particulate concentration in the ambient air over the city of Zahedan, Iran. *Air Quality, Atmosphere & Health*, 6: 123-135.
- Rezazadeh M, Irannejad P, Shao Y. 2013. Climatology of the Middle East dust events. *Aeolian Research*, 10: 103-109.
- Shao Y P. 2008. *Physics and Modelling of Wind Erosion* (2nd ed.). Dordrecht: Springer.
- Shao Y P, Klose M, Wyrwoll K-H. 2013. Recent global dust trend and connections to climate forcing. *Journal of Geophysical Research: Atmospheres*, 118(19): 11107-11118.
- Shen H, Abuduwaili J, Samat A, et al. 2016. A review on the research of modern aeolian dust in Central Asia. *Arabian Journal of Geosciences*, 9: 625, doi: 10.1007/s12517-016-2646-9.
- Shi L M, Zhang J H, Yao F M, et al. 2020. Temporal variation of dust emissions in dust sources over Central Asia in recent decades and the climate linkages. *Atmospheric Environment*, 222: 117176, doi: 10.1016/j.atmosenv.2019.117176.
- Spivak L, Terechov A, Vitkovskaya I, et al. 2012. Dynamics of dust transfer from the desiccated Aral Sea bottom analysed by remote sensing. In: Breckle S

- W, Wucherer W, Dimeyeva L A. *Aralkum-A Man-Made Desert: The Desiccated Floor of the Aral Sea (Central Asia)*. Dordrecht: Springer, 97-106.
- Sun H, Liu X D, Wang A Q. 2020. Seasonal and interannual variations of atmospheric dust aerosols in mid and low latitudes of Asia—A comparative study. *Atmospheric Research*, 244: 105036, doi: 10.1016/j.atmosres.2020.105036.
- Sun R, Zhang F M, Weng S S, et al. 2023. Spatio-temporal changes of NDVI and its response to climate in China from 2001 to 2021. *China Environmental Science*, 43(10): 5519-5528. (in Chinese)
- UNDP (United Nations Development Programme). 2002. *Human Development Report 2002: Deepening Democracy in a Fragmented World*. New York: UNDP.
- Wang G X, Yuan X L, Jing C Q, et al. 2024a. The decreased cloud cover dominated the rapid spring temperature rise in arid Central Asia over the period 1980-2014. *Geophysical Research Letters*, 51(2): 107523, doi: 10.1029/2023GL107523.
- Wang J F, Xu C D. 2017. Geodetector: Principle and prospective. *Journal of Geographical Sciences*, 72(1): 116-134. (in Chinese)
- Wang N, Zhang Y Y. 2023. Long-term variations of global dust emissions and climate control. *Environmental Pollution*, 340: 122847, doi: 10.1016/j.envpol.2023.122847.
- Wang W, He S F, Guo H, et al. 2024b. Sand and dust storm risk assessment in Arid Central Asia: Implications for the environment, society, and agriculture. *International Journal of Disaster Risk Science*, 15(5): 703-718.
- Wang Y J, Tang J K, Wang W H, et al. 2024c. Long-term spatiotemporal characteristics and influencing factors of dust aerosols in East Asia (2000-2022). *Remote Sensing*, 16(2): 318, doi: 10.3390/rs16020318.
- Wiggs G F, O'Hara S L, Wegerdt J, et al. 2003. The dynamics and characteristics of aeolian dust in dryland Central Asia: Possible impacts on human exposure and respiratory health in the Aral Sea Basin. *Geographical Journal*, 169(2): 142-157.
- Wu J, Kurosaki Y, Shinoda M, et al. 2016. Regional characteristics of recent dust occurrence and its controlling factors in East Asia. *Semantic Scholar*, 12: 187-191.
- Xi X, Irina N S. 2015. Dust interannual variability and trend in Central Asia from 2000 to 2014 and their climatic linkages. *Journal of Geophysical Research: Atmospheres*, 120(23): 12175-12197.
- Xu H J, Wang X P, Yang T B. 2017. Trend shifts in satellite-derived vegetation growth in Central Eurasia in 1982-2013. *Science of the Total Environment*, 579: 1658-1674.

Xu T, Shao H, Zhang C. 2015. Temporal pattern analysis of air temperature change in Central Asia during 1980–2011. *Arid Land Geography*, 38(1): 25–35. (in Chinese)

Xu Y, Lu Y G, Dai Q Y, et al. 2023. Assessment of the relative contribution of climate change and land use change on net primary productivity variation in the middle and lower reaches of the Yangtze River Basin. *China Environmental Science*, 43(9): 4988–5000. (in Chinese)

Yang S C, Qin F C, Wang M F. 2023. Spatial-temporal evolution characteristics and driving factors of sand-dust weather for Inner Mongolia Autonomous region during 1960–2020. *Bulletin of Soil and Water Conservation*, 43(5): 235–243. (in Chinese)

Yang S, Sun L X, He J, et al. 2024. Evolution of the Aral Sea: Crisis and present situation. *Arid Land Geography*, 47(2): 181–191. (in Chinese)

Zhou Y C, Gao X, Meng X Y, et al. 2022. Characteristics of the spatio-temporal dynamics of aerosols in Central Asia and their influencing factors. *Remote Sensing*, 14(11): 2684, doi: 10.3390/rs14112684.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.