Variations in Dust Weather Days and Their Influencing Factors in the Tarim Basin (Postprint)

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Date: 2023-12-16T00:00:00+00:00

Abstract

Based on observational data from 32 meteorological stations in the Tarim Basin from 1964 to 2022, and employing Sen+M-K trend analysis, gravity center movement model, standardized regression coefficients, and spatial clustering methods, this study focuses on analyzing from a spatial characteristics perspective the changes, trends, and movement patterns of annual days of different dust event types in the Tarim Basin, as well as the contribution rates of influencing factors. The results show that: (1) The basin is dominated by floating dust, followed by blowing sand and dust storms, exhibiting an overall spatial distribution pattern of more in the south and less in the north, with a significant decreasing trend. (2) The gravity centers of annual days of different dust event types in the basin show a trend of moving toward the southeast, with the dust storm gravity center showing the largest movement magnitude. (3) Rising temperatures, decreasing wind speeds, and reduced days of strong winds are the main influencing factors for the decrease in dust event days in the Tarim Basin, while precipitation has the smallest impact. (4) High contribution rates of precipitation to dust changes are concentrated in the western part of the basin, those of mean temperature and mean maximum temperature are in the southern and western parts respectively, while those of strong wind days and mean wind speed are in the northwestern and southeastern parts respectively. The research results can provide a scientific basis for the targeted formulation of regionally applicable windbreak and sand fixation measures in the Tarim Basin.

Full Text

Arid Zone Research, Vol. 40, No. 11, November 2023

Variations in Dust Weather Days and Influencing Factors in the Tarim Basin

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Abstract: Based on observational data from 32 meteorological stations in the Tarim Basin from 1964 to 2022, this study employed Sen+M-K trend analysis, gravity center movement model, standardized regression coefficients, and spatial clustering methods to analyze the changes, trends, and movement patterns of annual dust days of different types, as well as the contribution rates of influencing factors from a spatial perspective. The results indicate: (1) Floating dust dominates in the Tarim Basin, followed by blowing sand and sandstorms, showing an overall spatial distribution pattern of more in the south and less in the north, with significant decreasing trends. (2) The gravity centers of different types of dust days in the basin show a trend of moving toward the southeast, with the sandstorm gravity center moving the most. (3) Rising temperatures, decreasing wind speeds, and fewer gale days are the main factors contributing to the reduction of dust days in the Tarim Basin, while precipitation has the least influence. (4) High contribution rates of precipitation to dust variation are clustered in the western part of the basin, mean temperature and mean maximum temperature in the southern and western parts respectively, while gale days and mean wind speed are in the northwestern and southeastern parts respectively. The research results can provide a scientific basis for developing regionally applicable windbreak and sand fixation measures in the Tarim Basin.

Keywords: dust days; gravity center movement model; influencing factors; contribution rate; spatial clustering; Tarim Basin

Dust weather refers to weather phenomena where sand particles and dust are suspended in the air, causing turbidity and reduced visibility. It is classified into three types: floating dust, blowing sand, and sandstorms []. Dust weather can pollute the natural environment, damage crop growth, and significantly impact climate processes, ecosystems, and human health. It is a unique hazardous weather phenomenon in arid regions []. As an important component of the Earth system, dust aerosols also play crucial roles in radiation, ice clouds, and carbon cycles, serving as an indicator of climate and environmental changes. With the continuous intensification of global warming, the Tarim Basin, as one of the high-incidence areas for dust weather, has attracted significant social and governmental attention due to its notable impacts [].

Currently, many scholars have analyzed dust weather in the Tarim Basin from different methods and research perspectives, focusing primarily on climatological characteristics, geographical features, temporal variation patterns, influencing factors, as well as dust source areas and transport pathways. These studies have identified that changes in meteorological elements are the main driving factors for dust generation processes []. Additionally, some scholars have used dust occurrence processes and day counts as factors for cluster analysis to examine regional characteristics of dust weather []. However, previous research has mainly focused on statistical relationships between dust weather and its related elements, and there remain some issues in studying the spatial distribution and temporal variation of dust weather. The spatial distribution characteristics of dust weather are closely related to meteorological elements, but these relationships vary across different regions []. Since existing analyses of dust variation and its influencing factors start from station data and only consider model analysis between sample attributes, they ignore the regional and zonal characteristics of geographical phenomena themselves. For example, if only dust days or influencing factors are considered as the sole criterion, and stations of similar magnitude are grouped together, the resulting station groups become relatively dispersed, making it difficult to apply the analysis results to practical management. This creates certain difficulties for synoptic analysis and the formulation of regional disaster prevention policies. Therefore, further research on dust variation and its influencing factors is needed from a spatial characteristics perspective.

To comprehensively understand the spatial variation of dust weather over time and the distribution pattern of influencing factor contribution rates, it is necessary to quantify and analyze the distribution characteristics of dust variation and its influencing factor contribution rates in space. Therefore, based on observational data from 32 meteorological stations in the Tarim Basin, this study uses Sen+M-K trend analysis and gravity center movement model to analyze the spatiotemporal characteristics of annual variation in different types of dust days in the Tarim Basin from 1964 to 2022, and employs standardized regression coefficients and spatial clustering methods to evaluate the contribution rates of influencing factors. By analyzing dust variation and its influencing factors from a spatial perspective and identifying the important influencing factors for different types of dust weather in different locations of the Tarim Basin, this study aims to comprehensively understand the spatial distribution characteristics of influencing factors, help relevant departments adopt effective regional sand prevention and reduction strategies for different areas, and provide guidance for regional ecological construction and desertification control.

Received date: ; Revised date:
Funding projects: Xinjiang Uygur Autonomous Region Key R&D Special Project (YD202215); Xinjiang Uygur Autonomous Region Natural Science Foundation Youth Science Fund Project (2022D01B09); Xinjiang Meteorological Bureau Guidance Plan Project ( ); National Natural Science Foundation Project ( )
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pp. 1707-1717 http://azr.xjegi.com

1.1 Study Area Overview

The study area is located in southern Xinjiang, China, between the Tianshan and Kunlun Mountains. It is the largest inland basin in China, covering more than X% of southern Xinjiang. The basin has a ring-shaped geomorphological distribution and is a large closed intermountain basin containing the Taklimakan Desert, the second-largest shifting sand desert on Earth. The terrain is higher in the west and lower in the east, with a slight northward tilt. The basin belongs to a warm temperate climate, dominated by northeasterly and northwesterly winds, with frequent wind-blown sand and floating dust weather. It is a region with high frequency of dust weather in China and also an important contributor to the Central Asian dust storm region []. The study area and station distribution are shown in Figure 1 [Figure 1: see original paper].

1.2 Data Sources and Processing

Dust weather is a general term for floating dust, blowing sand, and sandstorms. According to the 'Specifications for Surface Meteorological Observation—Weather Phenomenon (GB/T 35224-2017)' [], dust weather is classified into floating dust, blowing sand, and sandstorms based on visibility when dust weather occurs, with floating dust and blowing sand considered weak dust weather and sandstorms considered strong dust weather. According to the 'Classification of Sand and Dust Weather (GB/T 20480-2017)' [], if dust weather across a date line occurs at a meteorological station in the study area, it is counted as two dust weather days; if two or more types of dust weather (sandstorm, blowing sand, floating dust) occur on the same day, each type is counted separately. Therefore, the total dust weather days may be less than or equal to the sum of floating dust, blowing sand, and sandstorm days [].

Data for floating dust days, blowing sand days, sandstorm days, and total dust weather days at 32 meteorological observation stations in the Tarim Basin from 1964 to 2022 were obtained from the National Meteorological Information Center of China Meteorological Administration. Based on the representativeness of influencing factors and data availability [], mean temperature, mean maximum temperature, mean minimum temperature, precipitation, annual precipitation days, gale days, and mean wind speed were selected as influencing factors for dust weather days analysis.

1.3 Methods

1.3.1 Spatiotemporal Variation Analysis Methods

Theil-Sen Median trend analysis and Mann-Kendall test: Theil-Sen Median trend analysis is a robust non-parametric statistical trend calculation method with high computational efficiency. It is insensitive to measurement errors and outlier data and is often used for trend analysis of long time series data, typically combined with the Mann-Kendall non-parametric test for significance. This paper uses this method to identify stations with statistically significant changes in dust days.

The Theil-Sen Median trend analysis formula is as follows:

$$\text{Slope} = \text{Median}\left(\frac{y_j - y_i}{j - i}\right), \quad 1 \leq i < j \leq n$$

where Slope is the trend value; Median represents taking the median; y_i and y_j are the annual dust weather day values for year i and year j, respectively. If Slope < 0, it indicates a decreasing trend in dust weather days. The larger the absolute value of Slope, the greater the rate of increase or decrease in dust weather days.

The Mann-Kendall test is a non-parametric test method. Compared with other parametric tests, it does not require the sample to follow a normal distribution, is not disturbed by missing values and outliers, and is more suitable for ordinal variables. It is used to analyze continuous increasing or decreasing trends (monotonic trends) in time series data. The calculation formula is:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(y_j - y_i)$$

where n is the number of data points in the time series; sgn is the sign function; y_i and y_j have the same meaning as above; $\text{Var}(S)$ is the variance of S; and Z is the test statistic. A two-sided trend test is adopted. At a given significance level α, when $|Z| < Z_{1-\alpha/2}$, the null hypothesis is accepted, indicating no significant trend; if $|Z| \geq Z_{1-\alpha/2}$, the null hypothesis is rejected, indicating a significant trend. This paper uses this method to test the significance of trends in dust day time series at the 0.05 confidence level [].

1.3.2 Gravity Center Movement Model

The gravity center movement model can intuitively describe the evolution of the distribution pattern of annual dust days of different types in the Tarim Basin from a spatial perspective. To compare different types, the same geographic spatial view is selected to display the gravity center trajectories. The gravity center and its offset in the time series are connected to analyze the trajectory, direction, and speed of annual changes. The formula is as follows:

$$X_j = \frac{\sum_{i=1}^{n} w_{ij} x_i}{\sum_{i=1}^{n} w_{ij}}, \quad Y_j = \frac{\sum_{i=1}^{n} w_{ij} y_i}{\sum_{i=1}^{n} w_{ij}}$$

where n is the total number of meteorological stations in the Tarim Basin; x_i and y_i are the coordinates of meteorological station i; w_{ij} is the annual day count of a certain type of dust at station i in year j; (X_j, Y_j) are the coordinates of the gravity center of the annual day count of a certain type of dust in year j []. For example, if w_{ij} is the annual floating dust day count at station i in year j, then (X_j, Y_j) represents the gravity center coordinates of the annual floating dust day count in year j.

1.3.3 Standardized Regression Coefficients

Standardized regression coefficients refer to regression coefficients after removing the scale effects of dependent and independent variables. The absolute value of the regression coefficient directly reflects the influence degree of the independent variable on the dependent variable—the larger the absolute value, the greater the influence, and vice versa. The relative contribution rate of an independent variable to the dependent variable is defined as the ratio of the absolute value of its coefficient to the sum of absolute values of all regression coefficients. Here, this paper uses the standardized regression coefficient method to discuss the relative contribution rates of various meteorological factors to dust days in the Tarim Basin at the annual scale. The formula is as follows:

$$Y = \sum_{n=1}^{7} a_n x_n + b$$

$$CR_i = \frac{|a_i|}{\sum_{n=1}^{7} |a_n|} \times 100\%$$

where Y is the standardized value of annual dust weather days; a_n is the standardized regression coefficient between the nth meteorological factor and Y; x_n is the standardized value of the nth meteorological factor; b is a constant; and CR_i represents the relative contribution rate of the ith meteorological factor to Y [].

1.3.4 Spatial Clustering

Spatial clustering is a method where both spatial location and thematic attribute information work together to characterize the distribution patterns and features of spatial unit attribute values, particularly analyzing where clustering occurs []. The Getis-Ord G_i^* hotspot analysis method is a common approach for spatial clustering. By performing spatial clustering on the contribution rates of each meteorological factor, it identifies high-value spatial clusters (hotspot areas) of meteorological factor contribution rates. The calculation formula is as follows:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_j}{\sum_{j=1}^{n} x_j}$$

where G_i^* is the hotspot statistic; $Z(G_i^*)$ is the standardized value of G_i^*; $E(G_i^*)$ and $\mathrm{Var}(G_i^*)$ are the expected value and variance coefficient of G_i^*, respectively; x_j is the attribute value of feature j; w_{ij} is the spatial weight between features i

and j; and n is the total number of features. When the $Z(G_i^*)$ value is positive and significant, it indicates that feature i is a hotspot area with high-value clustering [].

2 Results and Analysis

2.1 Spatial Distribution Characteristics of Dust Days

2.1.1 Spatial Distribution of Annual Mean Values Based on the multi-year average dust days from 32 meteorological stations, the spatial distribution characteristics of annual mean floating dust, blowing sand, sandstorm, and total dust weather days in the Tarim Basin were obtained (Figure 2 [Figure 2: see original paper]). From 1964 to 2022, dust weather in the Tarim Basin was dominated by floating dust, followed by blowing sand, with relatively few sandstorm days. The overall spatial distribution showed a pattern of more in the south and less in the north. The spatial distribution of annual mean days differed among dust types. Floating dust had the highest annual mean days, averaging 135.62 days, with a minimum of 20.3 days at Baicheng on the northern edge of the basin and a maximum of 187.4 days at Hotan on the southern edge. Spatially, floating dust was concentrated in the southern Tarim Basin, with annual mean days exceeding 100 days in most areas. Blowing sand had an annual mean of 32.54 days, with a minimum of 1.1 days at Wuqia on the western edge and a maximum of 78.6 days at Pishan in the southwestern part, also showing a pattern of more in the south and less in the north. Sandstorm annual mean days ranged from 0.3 to 15.6 days, with low values (below 3 days) in the northern basin except for relatively high values at Keping, while the southern basin was a high-value area, especially at Minfeng on the southern edge with the maximum annual mean of 15.6 days. Total dust weather days had an annual mean of 168.17 days, with a minimum of 26.4 days at Baicheng and a maximum of 244.7 days at Hotan, showing a spatial distribution very similar to floating dust. In summary, dust weather was generally less frequent on the northern edge of the basin, and the farther from the desert center, the fewer dust days. For example, Baicheng had consistently low dust weather days, while the southern edge centered on Hotan, from Shache to Qiemo from west to east, formed a high-value zone for dust weather, particularly in Hotan and Minfeng where dust weather occurred for more than half the year. This may be related to the region's proximity to the desert, low vegetation coverage, and fragile ecological environment, as well as the combined effects of weather systems and topography in the Tarim Basin that exacerbate dust weather occurrence []. Therefore, these high-incidence areas require heightened attention to dust weather management and prevention of adverse impacts.

2.1.2 Spatial Distribution of Change Trends Trend values and M-K tests were used to analyze the magnitude (increase or decrease) and nature (significant increase or significant decrease, statistically significant at $p < 0.05$) of dust weather changes. Figure 3 [Figure 3: see original paper] shows that from 1964 to 2022, the annual trends of floating dust days, blowing sand days, sandstorm days, and total dust weather days in the Tarim Basin all showed decreasing trends, with trend slopes ranging from -0.84 to $0.01\ d \cdot a^{-1}$, -2.57 to $0.72\ d \cdot a^{-1}$, -2.62 to $0.53\ d \cdot a^{-1}$, and -1.44 to $0.53\ d \cdot a^{-1}$, respectively, all showing significant decreasing trends. Floating dust days showed the most obvious trend, with all stations except Luntai on the northern edge (showing a significant increasing trend) and Makit in the southwest (showing a non-significant increasing trend) showing decreasing trends, with 87.5% of stations showing significant decreases (all percentages calculated from the total number of meteorological stations). For blowing sand days, all stations except Luntai on the northern edge and Ruoqiang on the southeastern edge (showing significant increasing trends) showed decreasing trends, with 84.38% of stations showing significant decreases. For sandstorm days, all stations except Luntai on the northern edge (showing a slight increasing trend) showed decreasing trends, with 87.5% of stations showing significant decreases. For total dust weather days, all stations except Luntai on the northern edge (showing a significant increasing trend) showed decreasing trends, with 90.63% of stations showing significant decreases. The above analysis indicates that dust days in the Tarim Basin showed an overall significant decreasing trend from 1964 to 2022, with far more stations showing decreasing trends than increasing trends.

The reduction in dust days has several causes. In terms of climatic factors, with global warming, the frequency of cold air and strong winds has decreased, weakening the dynamic conditions that trigger dust weather and leading to fewer dust days. In terms of human factors, the implementation of ecological civilization construction and environmental protection measures has been effective. For example, Qiemo County's sand prevention and afforestation project has planted nearly 10,000 hectares of windbreak and sand-fixation forests at the junction of oases and desert to block drifting sand, reduce strong winds from the northeast, effectively curb desert expansion, improve the local microclimate environment, and significantly reduce annual dust days, showing gradual ecological improvement.

Further analysis of dust day trends reveals that the magnitude of dust weather change in southern Tarim Basin is greater than in northern Tarim Basin. The most significant trend changes occur in the southern basin, where both floating dust and blowing sand days show large decreases, with floating dust trend slopes around $-0.57\ d \cdot a^{-1}$ and blowing sand around $-0.57\ d \cdot a^{-1}$, making this the region with the most significant decreasing trends. However, some areas still show increasing trends, such as Luntai on the northern edge and Ruoqiang on the southeastern edge. For example, Luntai shows significant increasing trends in floating dust, blowing sand, and total dust weather days at rates of $0.53\ d \cdot a^{-1}$, $0.72\ d \cdot a^{-1}$, and $0.20\ d \cdot a^{-1}$, respectively. Ruoqiang shows a significant increasing trend in blowing sand days at $0.72\ d \cdot a^{-1}$. These regions should accelerate and strengthen the implementation of ecological restoration and sand control policies to achieve overall improvement.

2.2 Gravity Center Trajectory of Dust Days

The gravity center movement trajectory can visually describe the evolution of the distribution pattern of annual dust days of different types in the Tarim Basin. For comparison, the same geographic spatial view is used to display the gravity center trajectories of different types of annual dust days. Figure 4 [Figure 4: see original paper] shows that from 1964 to 2022, the gravity centers of different types of annual dust days were located in the central-western part of the basin, with all except floating dust moving toward the southeast, showing large differences in movement magnitude. The sandstorm annual day gravity center moved the most, showing large regional differences and the lowest spatial clustering, followed by blowing sand days. The gravity centers of total dust weather days and floating dust days were relatively concentrated with smaller movement magnitudes and more stable interannual variations. The movement of dust day gravity centers results from multiple factors: on one hand, climate change has led to decreasing dust weather in most basin areas, but with smaller decreasing trends in the northern basin where annual dust days were already low, while the southern and southeastern basins had the highest dust days and largest decreasing trends; on the other hand, underlying surface and topographic features affect dust weather, which mainly occurs through “eastward intrusion” and “westward 翻越” patterns. The eastern edge of the Taklimakan Desert is the only low-altitude outlet for dust to flow out of the basin, and the southeastern basin is mostly desert with low vegetation coverage and poor surface stability. For example, Ruoqiang in the southeastern basin is surrounded by three major deserts (Taklimakan, Kumtag, and Kumkuli), with annual mean dust days exceeding 100 days, and its blowing sand days show an increasing trend against the background of overall dust weather reduction in the basin. Consequently, the overall gravity center of annual dust days in the basin moves toward the southeast.

2.3 Contribution Rates of Influencing Factors

2.3.1 Spatial Distribution Characteristics of Influencing Factor Contribution Rates To study the influence of different meteorological factors on changes in different types of dust days in the Tarim Basin, the contribution rates of seven meteorological factors were calculated for each station using the formulas above. Figure 5 [Figure 5: see original paper] shows the contribution rates of meteorological factors at each station to different types of dust days. Table 2 provides the mean contribution rate of each meteorological factor in the basin.

Temperature affects the surface environment and climate change, thereby altering dust sources and thermal conditions, and has the greatest impact on dust weather in the Tarim Basin. The main temperature-related indicators are mean temperature, mean maximum temperature, and mean minimum temperature, with trends of $0.02°C \cdot a^{-1}$, $0.02°C \cdot a^{-1}$, and $0.03°C \cdot a^{-1}$, respectively, all showing increasing trends. Rising temperatures lead to changes in atmospheric temperature-pressure field structure, weakening cold air activity, and making dynamic conditions for dust-raising activities weaker, thus showing reduced dust days []. From the contribution rate perspective, mean temperature shows a larger contribution rate than mean maximum and mean minimum temperatures, with a mean value above 22.55%, mainly contributing significantly to the reduction of floating dust, blowing sand, and dust weather in the southern and western parts of the basin.

Wind-related influencing factors are gale days and mean wind speed, with interannual trends of $-0.23\ \mathrm{d \cdot a^{-1}}$ and $-0.01\ \mathrm{m \cdot s^{-1} \cdot a^{-1}}$, respectively. The decrease in gale days and mean wind speed weakens the dynamic conditions for dust raising in the basin, leading to significantly reduced dust weather, and can be considered the main meteorological factor affecting the overall decline in basin dust days. From the perspective of different dust types, the influence degree of these two meteorological factors varies considerably. For example, mean wind speed has an obvious influence on floating dust, blowing sand, sandstorms, and total dust weather, with mean contribution rates of 12%-18%, mainly distributed in the northern and southwestern parts of the basin. Gale days show higher contribution rates to sandstorms, with a contribution rate of 22.55%, and contribution rates of 11%-17% to floating dust, blowing sand, and total dust weather, mainly distributed in the western part of the basin.

It is worth noting that precipitation shows the smallest contribution rate to basin dust weather, mainly distributed in the western and northern parts of the basin. This is mainly because the Tarim Basin is deep inland, surrounded by mountains that block water vapor from reaching the basin interior, resulting in an arid climate with annual mean precipitation and precipitation days of 73.86 mm and 23.6 days, respectively, indicating scarce precipitation. Increased precipitation can change the surface environment and suppress dust events. Although affected by global warming and humidification, the Tarim Basin has seen some increase in precipitation and precipitation days, the absolute increase is very small due to the low precipitation base, with trend rates of only $0.64\ \mathrm{mm \cdot a^{-1}}$ and $0.11\ \mathrm{d \cdot a^{-1}}$, respectively. The slow increase rate means precipitation remains at a very low level, so its effect on dust days is relatively weak.

Overall, thermal factors (temperature) and dynamic factors (wind) are the main factors affecting dust day changes in the Tarim Basin, while moisture factors (precipitation) have weaker effects. Temperature and wind speed provide dynamic conditions for the occurrence and development of dust weather, show high contribution rates to dust weather, and are the main reasons affecting dust weather changes. Precipitation shows the lowest contribution rate among all meteorological factors, with a mean contribution rate of about 5%.

2.3.2 Spatial Clustering of Influencing Factor Contribution Rates

Spatial differences in meteorological factors create spatiotemporal variations in dust events across different regions. Spatial clustering characteristics can reveal the regional distribution of meteorological factors' influence on dust events, thereby facilitating targeted regional measures to suppress dust events. The hotspot analysis method was used to calculate high-value clustering areas (hotspots) of meteorological factor contribution rates. The hotspot distribution after significance testing is shown in Figure 6 [Figure 6: see original paper].

The hotspots of influencing factor contribution rates for different types of dust days are mainly distributed in the western and southern parts of the basin, with fewer hotspots in the northeastern and eastern parts. From the spatial distribution of high-value clustering areas (hotspots) of contribution rates for different dust types: for floating dust, the southern basin shows hotspots for mean temperature and mean minimum temperature, the southwestern part for mean maximum temperature, the western part for mean maximum temperature, annual precipitation days, and precipitation, the northern part for precipitation, and the southeastern part for mean wind speed. For blowing sand, the northwestern basin shows hotspots for gale days and mean wind speed, while the southern and western parts show hotspots for precipitation and annual precipitation days. For sandstorms, the western basin shows hotspots for annual precipitation days and gale days, the northern part for precipitation, and Qiemo in the southeast for mean wind speed. For total dust weather, Kuche in the northern basin shows hotspots for mean wind speed, the southern part for mean temperature, the southwestern part for mean maximum temperature, and the western part for mean maximum temperature, precipitation, and annual precipitation days.

From the perspective of spatial clustering areas of influencing factor contribution rates, precipitation shows the most hotspots with high spatial clustering, mainly distributed in the western part of the basin, followed by temperature, while gale days and mean wind speed show lower clustering. This is mainly because global warming intensifies the water cycle process, increasing the water vapor content carried by atmospheric circulation. Affected by weather system paths, water vapor conditions, atmospheric circulation, and topography, precipitation increases are concentrated in the western basin, while areas with significant temperature increases are concentrated in the western and southern parts, making these regions high-contribution clustering areas for dust day reduction. Meanwhile, areas with frequent and stable gale weather in the Tarim Basin are mainly in the northwestern part affected by mountain-crossing winds and the eastern part affected by eastward-intrusion winds [], resulting in high-contribution areas for gale and wind speed being mainly concentrated in the northwestern and eastern parts. Overall, dust day changes are affected by multiple factors, and different types of dust days show different spatial relationships in influencing factor contribution rates across different regions.

3 Discussion

This study used spatiotemporal statistical analysis methods to analyze the variation characteristics, trends, and influencing factors of different types of dust days in the Tarim Basin, providing more intuitive spatiotemporal characteristics of dust weather and its influencing factors. This not only helps us further understand the spatiotemporal variation trends of dust weather in the Tarim Basin but also identifies key distribution areas of influencing factors.

From 1964 to 2022, floating dust days > blowing sand days > sandstorm days in the Tarim Basin, showing a significant decreasing trend and a spatial distribution pattern of more in the south and less in the north, with high-value areas mainly in the southern basin. These results are basically consistent with findings from Yang Jie, Ma Yu, Wang Sen, and others []. As an important component of China's ecological security strategic pattern "Two Barriers and Three Belts" (the "Northern Sand Prevention Belt") and the ecological civilization corridor, the reduction of dust weather in the Tarim Basin mainly benefits from years of windbreak and sand-fixation ecological construction projects implemented around the basin [], such as the integrated protection and restoration project of mountains, waters, forests, farmlands, lakes, grasslands, and deserts in the important source area of the Tarim River (Aksu River Basin), the Kekeya desert greening shelterbelt project, the Qiemo sand prevention and afforestation project, and the ecological water conveyance project in the lower reaches of the Tarim River. These projects have significantly improved surface vegetation coverage, effectively curbed the frequency of dust weather in the basin, and strengthened ecological stability and the ability to resist dust.

However, through further study of the spatial characteristics of dust day changes, some local areas still show increasing trends, such as Luntai on the northern edge and Ruoqiang on the southeastern edge of the Tarim Basin. Moreover, the gravity center of dust days in the basin tends to move toward the southeast, particularly the sandstorm day gravity center showing the most complex movement route and largest amplitude, which requires focused attention from relevant departments. Meanwhile, attribution studies are important content in dust day change research. According to spatial analysis of influencing factor contribution rates for dust day changes, rising temperature, decreasing mean wind speed, and fewer gale days are the main reasons for reduced dust days in the basin, but contribution rates of influencing factors for different dust types show significant spatial differences. In the current context of frequent extreme disaster weather globally, dust remains an important hazardous weather in the Tarim Basin. Policy decision-makers should not only focus on station-level changes in dust weather and its influencing factors but also pay attention to spatiotemporal changes across the entire Tarim Basin, fully considering both local and global distribution characteristics to build a more targeted regionally applicable windbreak and sand-fixation system, which has important theoretical value and practical significance for effectively reducing dust hazards in the Tarim Basin.

Additionally, the Tarim Basin is vast and sparsely populated, with long time series dust weather observation stations concentrated in the peripheral areas of the basin. Since the Tazhong station in the basin center began dust weather observations in 2006, the analysis of dust weather in the central basin was not considered in this study. The Tazhong station (39°00 N, 83°38 E, altitude

1103 m) is an atmospheric environment observation station located more than 200 km deep in the flowing desert hinterland, less affected by human activities and extremely sensitive to climate change. From 2006 to 2022, dust days at Tazhong station showed a significant increasing trend, with annual mean floating dust days of 146 days (trend slope of 3.54 $d \cdot a^{-1}$), blowing sand days of 125 days (trend slope of 1.21 $d \cdot a^{-1}$), sandstorm days of 19 days (trend slope of 0.38 $d \cdot a^{-1}$), and total dust weather days of 170 days (trend slope of 3.35 $d \cdot a^{-1}$). Compared with other stations in the basin during the same period, Tazhong station's annual mean floating dust days are only lower than Minfeng and Hotan, its blowing sand days rank first in the basin, and its sandstorm and total dust weather days are only lower than Minfeng. This shows that Tazhong station in the Tarim Basin hinterland is another high-value area for dust days besides Minfeng in the southern basin. Future research should select appropriate study periods to include Tazhong station dust weather observation data to comprehensively and meticulously explore the variation characteristics of dust weather in the Tarim Basin.

4 Conclusions

Through spatial characteristic analysis of dust day changes and influencing factor contribution rates in the Tarim Basin, the following conclusions are drawn:

1) From 1964 to 2022, dust weather in the Tarim Basin was dominated by floating dust, showing a spatial distribution pattern of more in the south and less in the north, with an overall significant decreasing trend. The decreasing rates of floating dust days, blowing sand days, sandstorm days, and total dust weather days were $-0.98\ d \cdot a^{-1}$, $-0.57\ d \cdot a^{-1}$, $-0.22\ d \cdot a^{-1}$, and $-1.16\ d \cdot a^{-1}$, respectively. Stations with decreasing trends outnumbered those with increasing trends, with significantly decreasing stations accounting for 84.38%, 87.5%, 87.5%, and 90.63%, respectively, mainly distributed in the southern basin.

2) From 1964 to 2022, the gravity center of dust weather in the Tarim Basin generally moved toward the southeast. The gravity center trajectory of sandstorm days was relatively complex with the largest movement amplitude, followed by blowing sand days. The gravity center trajectories of total dust weather days and floating dust days were relatively concentrated with smaller movement amplitudes.

3) Temperature increase and wind weakening played dominant roles in reducing different types of dust days in the Tarim Basin, while precipitation showed the smallest contribution rate. Mean temperature had the highest contribution rate to dust day reduction, mainly distributed in the southern and western parts of the basin. Mean wind speed had higher contribution rates to floating dust and total dust weather, mainly distributed in the northern and southwestern parts. Gale days had higher contribution rates to blowing sand and sandstorms, mainly distributed in the northern and

southeastern parts.

4) High-value contribution rates of meteorological factors to dust changes showed obvious clustering in space. Spatial clustering results indicated that precipitation and annual precipitation days had the largest high-value clustering areas for contribution rates to dust changes, mainly in the western basin. Temperature showed high-value clustering for floating dust and total dust weather day changes in the southern and western parts, while gale days showed high-value clustering for blowing sand day changes in the northwestern part, and mean wind speed showed high-value clustering for floating dust and sandstorm day changes in the southeastern part.

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