Analysis of the Causes and Transport Characteristics of Two Severe Dust Storm Events in Summer and Autumn over the Hexi Corridor (Post-Print)

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Abstract

In the summer of 2023, the Hexi Corridor experienced the strongest regional high-temperature and drought event in nearly 60 years, with frequent strong wind and sand-dust weather. On September 6-7, Minqin County witnessed the strongest sandstorm in September in nearly 40 years. Two strong sandstorm processes in the summer and autumn of 2023 in the Hexi Corridor were selected to analyze changes in pre-event meteorological elements, synoptic conditions, and boundary layer characteristics. Using HYSPLIT model backward trajectories, Himawari-8 satellite dust monitoring, and other methods, the source and transport pathways of dust in this region were determined. The results show that: (1) The regional high-temperature and drought event in the Hexi Corridor in summer 2023 provided abundant dust conditions for sandstorm occurrence. (2) A low-pressure trough existed over West Siberia at 65°-85°E, 50°-58°N, a stepped trough pattern was present over eastern Xinjiang-Hexi Corridor, and a mesoscale shear existed in the Hexi Corridor. The 500 hPa cold center was ≤-20 ℃, the 700 hPa cold center was $ $0 ℃, the mid-level jet was $ $20 m·s-1, the low-level jet was $ $14 m·s-1, and the K index was $ $21 ℃. The convergence zone was located below 700 hPa with divergence ≤-0.75$×$10-5 s-1; the divergence zone was located at 700-650 hPa with divergence $ 0.75×$10-5 s-1; the ascending motion layer was located at 800-600 hPa with vertical velocity ≤-0.6 hPa·s-1; and below 700 hPa was a positive vorticity zone with intensity $ 0.75×$10-5 s-1. (3) When local dust is the primary source, near-surface air humidity is the main influencing factor on sandstorm intensity. (4) Compared with spring sandstorms, the formation of summer and autumn sandstorms requires stronger ascending motion, larger near-surface wind speeds, and a 3-hour surface pressure difference.

Full Text

Preamble

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Analysis of Causes and Transport Characteristics of Two Strong Sandstorms in Summer and Autumn in the Hexi Corridor

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Abstract

In the summer of 2023, the Hexi Corridor experienced its most intense regional high-temperature drought event in nearly 60 years, with frequent wind and sand weather. Two particularly strong sandstorm processes occurred during the summer and autumn of 2023 in the Hexi Corridor, with Minqin County recording its strongest sandstorm in nearly 40 years on September 7. This study analyzes the evolution of meteorological elements, synoptic conditions, and boundary layer characteristics preceding these events. Using HYSPLIT backward trajectory modeling and Himawari-8 satellite dust monitoring, we determined the sources and transport pathways of dust in the region. The results show: (1) The regional high-temperature drought event provided abundant material conditions for sandstorm development. (2) Synoptic analysis reveals that low-pressure troughs located at 65°–85°E and 50°–58°N, combined with a stepped trough pattern from eastern Xinjiang to the Hexi Corridor and mesoscale shear lines, contributed to the events. At 500 hPa, the cold center intensity reached –24°C; at 700 hPa, it reached –20°C. The mid-level jet exceeded 20 $m \cdot s^{-1}$, the low-level jet exceeded 14 $m \cdot s^{-1}$, and the K index reached \$ \$21°C. Convergence occurred below 700 hPa (divergence ≤–0.75\$×10^{-5}\$ s^{-1}), while divergence occurred between 700–650 hPa (divergence \$ 0.75×10^{-5}\$ s^{-1}). Ascending motion was observed between 800–600 hPa with intensity ≤–0.6 $hPa \cdot s^{-1}$. Below 700 hPa was a region of positive vorticity with intensity \$ 0.75×10^{-5}\$ s^{-1}. (3) When the dust source is primarily local, near-surface air humidity is the main factor influencing sandstorm intensity. (4) Compared to spring sandstorms, summer and autumn sandstorms require stronger ascending motion, higher near-surface wind speeds, and larger surface pressure changes for formation.

Keywords: strong sandstorms from summer to autumn; regional high temperature and drought; remote sensing monitoring; transmission characteristics;

Hexi Corridor

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1. Introduction

Sandstorms predominantly occur in arid and semi-arid regions with severe desertification and represent one of the major disastrous weather events in northern China during spring. They cause rapid increases in atmospheric pollutant concentrations and dramatic reductions in horizontal visibility to below 1000 m within short periods, significantly impacting ecology, public health, transportation, and the social economy, sometimes resulting in casualties. Previous studies using numerical models, remote sensing, and other new data and methods have shown that the primary influencing systems for spring sandstorms are upper-level troughs, Mongolian cold vortices, and cold fronts. In the Hexi Corridor region, spring cold-front-type sandstorms are often accompanied by Mongolian cyclones, with the intensity and position of upper-level troughs, jet streams, and surface cold fronts determining sandstorm intensity and impact range.

Drought exacerbates desertification in the Hexi Corridor, thereby increasing sandstorm frequency and intensity. Therefore, studying sandstorm genesis and transport under drought climate backgrounds is crucial for protecting lives and property, disaster prevention and mitigation, and ecological environmental management. Strong wind, dust sources, and unstable atmospheric stratification are necessary conditions for sandstorm formation. In recent years, many scholars have applied numerical weather prediction models, remote sensing observations, and other new data and methods to study sandstorms, revealing that summer sandstorm influencing systems are mostly short-wave troughs, mesoscale shear lines, and surface thermal lows. Sandstorm outbreaks result from coordinated development of upper- and lower-level circulations, with momentum downward transfer features often increasing surface wind speeds and intensifying sandstorms when atmospheric stratification is unstable.

Since 2000, northwestern China has shown increasing temperatures and decreasing sandstorm frequency. However, the summer of 2023 saw the most intense regional high-temperature drought event in nearly 60 years in the eastern Hexi Corridor, with significantly increased wind and sand events—the highest since 1961. On September 7, Minqin County experienced its strongest sandstorm in nearly 40 years, a historically rare event. Data show that Hexi Corridor sandstorms exhibit significant seasonal differences, with occurrence rates of 86.6% in winter-spring (December–May) versus only 13.4% in summer-autumn (June–November). Due to the rarity of strong summer-autumn sandstorms, limited research exists on their causes and transport mechanisms, making forecasting and early warning challenging. This paper selects two strong sandstorm events from summer-autumn 2023 and compares them with typical spring cases to reveal the genesis, dust sources, and transport pathways of summer-autumn sandstorms under high-temperature drought conditions, clarifying differences in formation mechanisms between spring and summer-autumn events and exploring dynamic and thermodynamic parameter indicators suitable for summer-autumn sandstorm forecasting.

2. Study Area Overview

The Hexi Corridor in Gansu Province is located in arid and semi-arid inland regions, extending from Wushaoling in the east to Xingxingxia at the Gansu-Xinjiang border in the west, with a total length of approximately 1000 km and a width of 40–200 km. The region has a temperate continental arid climate with annual precipitation far less than evaporation and severe water shortages. Desertification affects over 60% of the area, with Minqin County exhibiting typical ring-shaped desert topography (surrounded by desert at a rate of 86%) and abundant sand sources, making it a high-vulnerability zone for natural disasters and a region with frequent sandstorms in China.

3. Data and Methods

This study analyzes two strong sandstorm events in the Hexi Corridor during summer-autumn 2023 using data from 18 ground meteorological observation stations (Figure 1), ERA5 reanalysis data (0.25° × 0.25°), hourly PM_{10} concentration data, Himawari-8 satellite dust monitoring products, and HYSPLIT backward trajectory simulation results. Synoptic diagnostic methods were applied to analyze the two strong sandstorm processes. All times mentioned in the text and figures are Beijing Time.

3.1 Weather Observations

From 06:00–08:00 on August 16, strong sandstorms occurred in Liangzhou District and Minqin County in the eastern Hexi Corridor (Figure 2), with average maximum wind speeds of 9.9 $m \cdot s^{-1}$, instantaneous peak winds of 16.2 $m \cdot s^{-1}$, and minimum visibility of 300 m. From 15:45–22:00 on September 6–7, sandstorms affected Zhangye City and a strong sandstorm hit Minqin County in the eastern Hexi Corridor, with average maximum wind speeds of 13.2 $m \cdot s^{-1}$, instantaneous peak winds of 22.3 $m \cdot s^{-1}$, and minimum visibility of 133 m.

3.2 Pre-event Climate Conditions

Affected by the transition from La Niña to El Niño, the Hexi Corridor experienced extreme climate conditions in 2023, with the highest average temperatures and lowest precipitation on record. In summer 2023, most of the Hexi Corridor experienced its most intense regional high-temperature drought event in nearly 60 years. Precipitation in Minqin County, Jiuquan City, and Jinta County was

50–75% below normal, with most areas receiving less than 50% of average summer precipitation. The Standardized Precipitation Index (SPI) reached severe drought levels, and most stations in the central and eastern regions had temperature anomalies exceeding 2°C. The number of high-temperature days was the highest in nearly 60 years, ending later than any previous record. The high temperatures provided favorable thermal conditions for sandstorms, while the dry climate background thickened the underlying sand layer, providing abundant material basis. This climate background facilitated frequent summer-autumn sandstorms in 2023.

3.3 Upper-level Circulation Characteristics

Both sandstorm events exhibited a stepped trough pattern, a typical configuration for summer-autumn severe convective weather in northwest China. Both processes featured strong atmospheric baroclinicity, northwesterly jet streams, and unstable stratification with cold air aloft and warm air below. The intensities of the western trough cold center, plateau warm center, mid-level jet, low-level jet, and upper-level frontal zone in the September 6–7 event were stronger than in the August 16 event, resulting in more intense, longer-lasting sandstorms with broader impact (the September event affected central-eastern Hexi Corridor, while the August event only impacted eastern Hexi Corridor).

3.4 Surface Frontogenesis Effects

Surface cold fronts were the direct cause of both sandstorm events. During the August 16 event, a thermal low existed over central Inner Mongolia while a cold high pressure system was located in western-central Xinjiang. The cold high was blocked by the thermal low and remained stable, allowing cold air to accumulate in the Hexi Corridor and form a strong pressure gradient zone. The September 6–7 event featured a saddle-shaped pressure field over central-eastern Hexi Corridor, with intense frontogenesis as the cold front entered the region, significantly strengthening the frontal surface.

Both events were post-cold-front northwesterly wind-type sandstorms. The September event had a smaller area of force 8 or greater winds but featured cyclonic convergence between post-cold-front northwesterlies and pre-frontal easterlies. The maintenance of small-scale surface convergence systems prevented dust diffusion, causing visibility in Minqin County to plummet to 133 m. The saddle-shaped pressure field and diurnal temperature variation promoted frontogenesis, increased surface wind speeds, and created small-scale wind field convergence that hindered dust diffusion.

3.5 Surface Meteorological Elements and PM_{10} Variation

3.5.1 Surface Meteorological Elements and PM_{10} Change Characteristics During the August 16 event, from 04:00–05:00, the pressure tendency shifted from negative to positive and wind direction changed from easterly to northwesterly. PM_{10} concentration rapidly increased to 1520 $g \cdot m^{-3}$ while wind speed quickly increased to 9.3 $m \cdot s^{-1}$, with minimum visibility dropping to 300 m. During the September 6–7 event, from 17:00–18:00, the pressure tendency shifted from negative to positive and wind direction changed from northeasterly to northwesterly. PM_{10} concentration increased to 1150 $g \cdot m^{-3}$ while wind speed rose to 13.2 $m \cdot s^{-1}$, with minimum visibility dropping to 100 m. The onset of both sandstorm events synchronized with frontal passage. Before the events, visibility remained at 2000–3000 m. As visibility rapidly decreased, PM_{10} concentration and wind speed increased almost simultaneously, indicating that local dust lifting was the primary source, with external transport playing a secondary role.

3.5.2 Near-surface Intensive Meteorological Element Characteristics Analysis of intensive upper-air data shows that the August 16 event occurred in the early morning (08:00) while the September 6–7 event occurred in the evening (20:00). The inversion layer was thinner and lower in the evening compared to early morning, making the stratification more unstable. Consequently, the frontal passage in the evening produced stronger sandstorms. During the August 16 event, strong winds at 360 m height reached 19.2 $m \cdot s^{-1}$, providing dynamic conditions for sandstorm development. During the September 6–7 event, winds at 630 m height reached 15.9 $m \cdot s^{-1}$. Near-surface air was warm and dry, with temperature-dewpoint differences below 1400 m exceeding 20°C, making the air even warmer and drier. This near-surface warm dryness enhanced thermal convection development, accelerated soil moisture evaporation, rapidly decreased soil moisture content, and made loose surface dust more easily lifted by strong winds.

3.5.3 Atmospheric Stratification Stability Analysis The K index is a physical parameter for assessing atmospheric stratification stability, expressed as: $K = (T_{850} - T_{500}) + Td_{850} - (T - Td)_{700}$, where T_{850} and T_{500} are temperatures at 850 hPa and 500 hPa, Td_{850} is the dewpoint temperature at 850 hPa, and T and Td are temperature and dewpoint temperature at 700 hPa. The greater the temperature difference between lower and upper layers, the more unstable energy accumulates, and the larger the K index, indicating more unstable stratification. K-index charts show that at 08:00 on August 16, the stratification over eastern Hexi Corridor was extremely unstable with K index reaching 37.5°C, while at 20:00 on September 6, it reached 21.3°C. The August 16 event had more unstable stratification, but the September 6–7 event had stronger sandstorm intensity due to drier near-surface air and more abundant dust sources.

3.6 Divergence, Vertical Velocity, and Vorticity

Using ERA5 0.25°$×$0.25° reanalysis data, we diagnosed divergence, vertical velocity, and vorticity. The expressions for divergence and vorticity are given by: D = u/ x + v/ y + w/ z and = w/ y - v/ z + u/ z - w/ x + v/ x -

u/ y, where D is divergence, is vorticity, u, v, w are wind components, and x, y, z are coordinate axes.

During both events, the divergence field over Minqin County showed low-level convergence and upper-level divergence. The August 16 event had maximum convergence at 850 hPa with intensity -0.75×10^{-5} s^{-1} and maximum divergence at 650 hPa with intensity 0.75×10^{-5} s^{-1}. The September 6–7 event had maximum convergence at 800 hPa with intensity -2.4×10^{-5} s^{-1} and maximum divergence at 600 hPa with intensity 2.4×10^{-5} s^{-1}. Ascending motion occurred between 800–550 hPa, with strongest ascent near 700 hPa at -0.6 $hPa \cdot s^{-1}$. Below 700 hPa was consistent positive vorticity, with maximum positive vorticity centers at 800 hPa (0.75×10^{-5} s^{-1} for August 16) and 700 hPa (3.2×10^{-5} s^{-1} for September 6–7). Strong mid-to-lower tropospheric ascent is the primary dynamic mechanism for lifting surface dust. Although the September event had stronger ascent, the August event had drier near-surface air, demonstrating that summer-autumn sandstorm intensity is significantly influenced by near-surface humidity.

3.7 Dust Transport Characteristics

Using the Global Data Assimilation System $1°\times1°$ field data as initial conditions, we simulated backward trajectories starting from Minqin County meteorological station (38.6319°N, 103.0886°E) at 1000 m height. Results show that for the August 16 event, dust originated from the Badain Jaran Desert, transported via easterly and northeasterly paths through central and western Inner Mongolia to the Hexi Corridor. For the September 6–7 event, dust sources were the Gurbantünggüt Desert and Badain Jaran Desert, transported west-to-east by northwesterly flow, with additional dust replenishment from the Badain Jaran Desert. Himawari-8 satellite dust products clearly show dust bands, with remote sensing monitoring paths consistent with HYSPLIT simulation results.

3.8 Comparison Between Summer-Autumn and Spring Sandstorms

Comparing typical cases from summer-autumn 2023 (2 events) and spring (2 events) in the Hexi Corridor reveals that spring sandstorms are primarily influenced by long-wave and transverse troughs at 500 hPa, while summer-autumn events are dominated by short-wave and stepped troughs. Both seasons feature cold fronts at the surface, but spring events often have Mongolian cyclones ahead of the cold front, whereas summer-autumn events have mesoscale shear lines. Analysis of mid-low level jets, vertical velocity, near-surface wind speeds, and pressure differences across cold fronts shows that summer-autumn sandstorms require stronger ascent, higher near-surface wind speeds, and larger pressure differences compared to spring events. Threshold parameters include: 500 hPa stepped/short-wave troughs, surface fronts or shear lines, mid-level jets $20 m \cdot s^{-1}$, low-level jets $14 m \cdot s^{-1}$, vertical velocity ≤ -0.6 $hPa \cdot s^{-1}$, and near-surface wind speeds $9 m \cdot s^{-1}$, with 3-hour pressure differences $6.0 hPa.

4. Conclusions

Through comparative analysis of two strong sandstorm events in summer-autumn 2023 and typical spring cases, we conclude:

1. Both events primarily involved local dust lifting, with external transport playing a secondary role. The preceding drought provided abundant material basis. When dust sources are local, near-surface air humidity is the key factor affecting sandstorm intensity.
2. The physical quantity characteristics of the two strong sandstorms show: convergence zone below 800 hPa with center intensity $\leq -0.75\times10^{-5}$ s^{-1}; divergence zone at 700–650 hPa with intensity 0.75×10^{-5} s^{-1}; ascending motion layer at 800–600 hPa with maximum vertical velocity ≤ -0.6 $hPa \cdot s^{-1}$; positive vorticity zone below 700 hPa with maximum center intensity 0.75×10^{-5} s^{-1}.
3. External dust transport pathways: the August 16 event passed through central and western Inner Mongolia; the September 6–7 event passed through western Mongolia, Xinjiang, and western Inner Mongolia. Both followed northwesterly paths at low levels with slight differences.
4. Compared to spring sandstorms, summer-autumn sandstorms require stronger ascending motion, higher near-surface wind speeds, and larger surface pressure differences. When 500 hPa shows stepped or short-wave troughs with surface fronts or shear lines, mid-level jets $20m \cdot s^{-1}$, low-level jets $14m \cdot s^{-1}$, vertical velocity ≤ -0.6 $hPa \cdot s^{-1}$, and near-surface wind speeds $9m \cdot s^{-1}$, sandstorms may occur in the Hexi Corridor during summer-autumn.

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