Variation Characteristics of Spring Dust Storms in the Central-Eastern Hexi Corridor and Typical Case Analysis (Postprint)

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Abstract

The central-eastern Hexi Corridor is a high-incidence and severely affected area for spring sandstorms in China, having caused economic losses exceeding 15$×$10^8 yuan and nearly a hundred deaths over the past 40 years. Spring sandstorms in this region exhibit significant diurnal variation. To deeply analyze their temporal variation patterns and improve forecasting and early warning capabilities, this study utilizes ground observation data of sandstorms from three representative stations in the region from 1961–2019 and meteorological data from two sandstorm events in May 2019, employing a combined synoptic, dynamic, and statistical approach to derive the diurnal variation characteristics and forecast focal points of spring sandstorms in this region. The results show that: (1) The number of spring sandstorm days in the central-eastern Hexi Corridor has shown a decreasing trend over the past 60 years, with a significant reduction in the 1980s; diurnal variations of sandstorms with different intensities are evident across stations: they occur more frequently during daytime with higher wind speeds, and after the 1980s, moderate sandstorms have outnumbered severe sandstorms, with high-incidence areas all located in Minqin. (2) When sandstorms pass through, the prevailing wind direction is consistent between day and night across stations, concentrated between northwesterly and northerly winds; severe sandstorms are strongest at 00:00–01:00 and 18:00–19:00, while moderate sandstorms are strongest at 08:00–09:00. (3) Further comparative analysis of two sandstorm processes occurring in the afternoon and at night in May 2019 reveals: the afternoon process featured strong winds and caused disaster conditions; the nighttime process was intense and long-lasting. Although the low-to-mid-level patterns were basically the same for both processes, with sandstorms occurring downstream of the negative horizontal helicity center and during periods of large ground-air temperature differences, the 500 hPa upper-level patterns differed: the afternoon process featured a transverse trough turning vertical, large diurnal temperature range and wind speed variation, unstable stratification, downward momentum transfer from upper-level winds, and low height of maximum wind speed in the near-surface layer; the nighttime process was mainly influenced by the development of an unstable low trough and a cold front at the base of a Mongolian cyclone, accompanied by strong vertical upward motion but with small vertical wind shear. (4) Spring sandstorms in the central-eastern Hexi Corridor are not only related to large-scale circulation patterns, but also associated with physical quantities such as vertical velocity, horizontal helicity, and total wind speed, as well as diurnal variations of surface temperature, humidity, and wind, unstable parameters, and boundary layer elements.

Full Text

Variation Characteristics of Spring Sandstorms and Analysis of Typical Cases in the Middle East of Hexi Corridor

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Abstract: The middle east of the Hexi Corridor represents a high-incidence and severely affected region for spring sandstorms in China. Over the past 40 years, economic losses have exceeded 1.5$×10^{9}$ Yuan, with nearly 100 fatalities. Spring sandstorms in this region exhibit pronounced diurnal variation. To analyze their temporal variation patterns and improve forecasting and early warning capabilities, this study employs ground observation data of sandstorms from 1961–2019 and meteorological data from two sandstorm processes in May 2019, using integrated synoptic, dynamic, and statistical methods to characterize diurnal variation features and forecast indicators. Results show that: (1) Spring sandstorm days in the middle east of Hexi Corridor have decreased over the past 60 years, particularly after the 1980s. General sandstorms peaked during 00:00–01:00 and in the afternoon and nighttime, showing significant reduction. Obvious diurnal variations occurred across stations: daytime events were more frequent with higher wind speeds, and since the 1980s general sandstorms have outnumbered strong sandstorms. (2) During sandstorm passage, prevailing wind directions remained consistent day and night, concentrated between northwest and north winds; strong sandstorms peaked at 18:00–19:00. (3) Comparative analysis of two May 2019 processes reveals that the afternoon event featured strong winds and caused disasters, while the nighttime event was more intense and longer-lasting. Although mid-low level patterns were similar, with sandstorms occurring downstream of negative horizontal helicity centers and large ground-air temperature differences, the 500 hPa patterns differed: the afternoon process involved a transverse trough turning vertical, with large diurnal temperature and wind speed variations, unstable stratification, upper-level momentum transfer, and low-level maximum wind speeds; the nighttime process was dominated by unstable trough development and a cold front at the base of a Mongolian cyclone, with strong vertical ascent but weak vertical wind shear. (4) Spring sandstorms in this region relate not only to large-scale circulation but also to physical parameters including vertical velocity, horizontal helicity, total wind speed, and boundary layer elements such as daily variations of surface temperature, humidity, wind, and instability parameters.

Keywords: spring sandstorms; variation characteristics; forecast indicators; middle east of Hexi Corridor

Introduction

Sandstorms severely impact local living environments, industrial and agricultural production, and the dust emitted affects downstream air quality, ecological environments, and climate change through long-range transport. Strengthening sandstorm analysis has become a national priority for disaster prevention and mitigation. Numerous scholars have investigated sandstorm spatiotemporal distribution, source regions, movement paths, and meteorological causes. Previous research identified positive correlations between sandstorms and wind speed/evaporation, and negative correlations with water vapor pressure, relative humidity, and minimum temperature. Northern China' s arid and semi-arid regions, particularly the Hexi Corridor, are prone to sandstorms that occur mainly in spring with obvious diurnal variation, peaking during 13:00–14:00. East Asian sandstorms exhibit approximately decadal oscillation periods, and recent decades show decreasing trends across Central Asia with identified dust-active zones.

Studies have examined relationships between sandstorm frequency and surface wind speed, evolution trends of sandstorm days and meteorological elements in northern China, and the weakening frequency but intensifying strength of sandstorms in this region. The Hexi Corridor's boundary layer height correlates with wind-sand intensity, and oasis areas have increased while desert areas decreased, though rapid population growth exacerbates desertification. With 94.5% of the region comprising deserts and Gobi, abundant dust sources provide material for sandstorms. The continental arid climate features frequent spring cold air activity, dramatic temperature fluctuations, high drought frequency, and strong winds. The corridor' s "tube effect" significantly enhances wind speeds when cold air moves southeastward, providing favorable dynamic conditions for sandstorm formation.

The middle east of Hexi Corridor suffers the most frequent sandstorms with severe casualties and economic losses—for example, the Zhangye black wind on [date] caused [number] deaths, and the Wuwei black wind on [date] caused direct economic losses of 1.36$×10^{8}$ Yuan and [number] deaths. Spring sandstorms show more pronounced diurnal variation than other seasons, yet research on temporal characteristics and causes of diurnal changes for different intensity sandstorms remains limited. This study analyzes 60 years of spring sandstorm data and two typical cases to understand diurnal variation patterns and improve forecasting capabilities.

1 Study Area Overview

The middle east of Hexi Corridor lies at the junction of the Tibetan, Inner Mongolian, and Loess plateaus, adjacent to the Taklamakan Desert and Gobi to the west, bordered by the Badain Jaran and Tengger deserts to the north, backed by the Tibetan Plateau to the southwest, and interlaced with the Loess Plateau to the east. Geographically located at approximately 97°–104°E, 36°–40°N, the terrain forms a narrow northwest-southeast oriented corridor. The region' s unique geography features low soil moisture rates and severe land desertification—Minqin alone has extensive desertified land. The area serves as both a source and high-frequency zone for sandstorms.

[Figure 1: see original paper] Distribution of meteorological stations and average annual days of spring sandstorms during 1961–2019 in the middle east of Hexi Corridor

2 Data and Methods

2.1 Data

This study uses spring ground observation data of sandstorms from 1961–2019 at three representative stations (Zhangye, Liangzhou, and Minqin) in the middle east of Hexi Corridor, obtained from 14 meteorological stations in the region. As shown in [Figure 1: see original paper], Zhangye, Liangzhou, and Minqin are the most affected areas. Additionally, we use upper-air and surface meteorological observation data from two sandstorm processes in May 2019, which represent the most frequent and intense sandstorm events in the region over the past decade.

2.2 Methods

Strong sandstorms are defined by visibility of 0–499 m, while general sandstorms have visibility of 500–1000 m. Sandstorm onset times are rounded to whole hours, with event times recorded as start times; when visibility is unclear, 999 m is used as the calculation value. Linear trend regression analyzes annual variation trends, with significance tested using correlation coefficients between time and spring sandstorm days. Anomaly statistics examine decadal variations.

Horizontal helicity represents the intensity of cold advection invading the boundary layer and the degree of wind reversal with height. Its negative center correlates with downstream sandstorm intensity—the stronger the negative center, the stronger the surface winds and sandstorms. The calculation formula is:

$$he = \int_0^h (V - C) \cdot \zeta \, dz$$

where he is horizontal helicity ($\mathrm{m}^2 \cdot \mathrm{s}^{-2}$), h is layer thickness (m), V and C are environmental wind field and storm movement speed ($\mathrm{m} \cdot \mathrm{s}^{-1}$), and ζ is horizontal vorticity vector (s^{-1}).

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3 Variation Characteristics

3.1 Decadal Variation of Sandstorms

The decadal average sandstorm days at Zhangye, Liangzhou, and Minqin stations ([Figure 2: see original paper]) show that Zhangye had more sandstorms in the 1960s–1970s, while Minqin and Liangzhou peaked in the 1970s (Minqin reached 14.7 days). All stations show decreasing trends, with the 1970s being the high-incidence period for spring sandstorms.

3.2 Interannual Variation of Sandstorms

Linear equations for interannual variation of spring sandstorm days during 1961–2019 show trend rates of [values] and correlation coefficients of [values], passing the 99% significance level, indicating an obvious oscillating decreasing trend ([Figure 3: see original paper]). A mutation from more to fewer sandstorms occurred around 1988 at Liangzhou station. Zhangye showed fluctuating decreases after the 1970s, significant reduction in the 1980s, and days dropping below [threshold] with increased vegetation. Liangzhou decreased from the 1970s, surged in the late 1970s, decreased again in the 1980s, and rapidly reduced in the mid-1990s and early 21st century. Minqin fluctuated decreasingly, with slight increases in the early 21st century. However, all three stations show increasing trends in recent 5 years.

Strong sandstorms at Zhangye show continuous decrease from [value] to 0.2 days, while general sandstorms show unimodal diurnal variation peaking in the 1970s at 0–0.6 days. Liangzhou shows consistent diurnal variation across intensities with continuous decline—no strong sandstorms occurred at night in the early 21st century, while 2019 had [value] strong sandstorm days. Minqin shows consistent diurnal variation with fluctuating decline—strong sandstorms reduced below [threshold] by 2019, while general sandstorms show unimodal variation similar to Zhangye, peaking in the 1970s at 0.3 days and reducing to 0.2–0.6 days by 2019.

3.3 Diurnal and Decadal Variation of Sandstorms

Diurnal variations of different intensity sandstorms show clear patterns: overall annual average sandstorm days are decreasing, with more daytime than nighttime events. General sandstorms exceed strong sandstorms after the 1980s. High-incidence areas remain in Minqin. During the 1970s–1980s, Zhangye and Liangzhou had no strong sandstorms during daytime, while nighttime events increased. By the 2010s, Minqin had fewer than [threshold] annual sandstorm days.

3.4 Diurnal Wind Direction Variation Rose Diagram

Analysis of wind direction frequency during spring sandstorms ([Figure 5: see original paper]) shows that prevailing wind directions at Zhangye, Liangzhou, and Minqin remain consistent day and night, concentrated between northwest and north winds. Station-specific patterns show Zhangye dominated by north-northwest winds (north by day, northwest by night); Liangzhou by north winds (north-northwest by day, north-northeast by night); and Minqin by northwest winds (north-northwest second). Maximum wind speeds show obvious diurnal variation, with daytime speeds 1.0 $m \cdot s^{-1}$ greater than nighttime, ranging 12.0–14.0 $m \cdot s^{-1}$ (largest in Minqin, smallest in Liangzhou).

3.5 Diurnal Visibility Variation of Sandstorms

Diurnal visibility variations ([Figure 6: see original paper]) reveal opposite patterns between strong and general sandstorms. Strong sandstorms peaked at 00:00–01:00 and 18:00–19:00 (visibility 200–267 m), weakest at 10:00–11:00 (visibility 500–630 m). General sandstorms peaked at 08:00–09:00 (visibility 350–400 m), weakest at 00:00–01:00 and 18:00–19:00 (visibility 700–800 m). Zhangye's strong sandstorms were relatively stronger due to its upstream northwest location and proximity to Mongolian cyclones that generate strong ascent.

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4 Characteristics of Two Typical Sandstorm Cases

4.1 Pre-event Climate and Weather Conditions

Spring 2019 featured persistently high temperatures and exceptionally low precipitation in early March, causing the most severe early spring drought since 2000. This dry, warm climate provided the main background for frequent March sandstorms. On May 11 and 14, regional strong wind and sand weather occurred, with local sandstorms ().

The afternoon event (May 11) brought strong winds and sandstorms to Zhangye and Liangzhou with minimum visibility of 600–800 m, damaging greenhouses and crops but lasting only 1–2 hours with maximum winds of [level]. The nighttime event (May 14) produced strong sandstorms with maximum winds of [level], longer duration (1-2 hours), and affected more stations.

4.2 Synoptic Patterns

4.2.1 Upper-level Circulation at 500 hPa Both processes featured strong northerly jets ahead of ridges continuously guiding polar dry-cold air southward, strengthening frontal zones, increasing pressure and temperature gradients, and enhancing vertical ascent. The first event involved a transverse trough turning vertical—on May 10, a transverse trough from Lake Baikal to northern Xinjiang deepened and moved southward to western Hexi Corridor, with northerly jet center winds reaching 44 $m \cdot s^{-1}$. The second event featured an unstable low trough developing eastward and southward—on May 14, a meridional trough over central-eastern Xinjiang intensified, with a southern trough rapidly moving to western Hexi Corridor and northwest jet center winds reaching 52 $m \cdot s^{-1}$, causing strong sandstorms at night.

4.2.2 Surface Patterns Cold fronts caused both sandstorm events. The first occurred behind a cold front, with a surface cold high over southwestern Lake Baikal and northern Xinjiang, and a thermal low developing strongly over Hexi Corridor, creating a steep pressure gradient. The front entered western Hexi Corridor at 20:00 on May 11, with maximum 3-hour pressure change of 7.7 hPa, causing strong winds and sandstorms in Zhangye. The second occurred behind a cold front at the base of a Mongolian cyclone. A blocking high near 110°E prevented the cold high from moving, steepening the pressure gradient. The Mongolian cyclone moved eastward and southward, with the front reaching central areas at 23:00 on May 14, causing strong sandstorms in Zhangye and later in Liangzhou and Minqin.

4.2.3 Comparison of Meteorological Elements Both processes occurred during severe early spring drought with obvious diurnal variation. Although both had unstable stratification and large ground-air temperature differences, the second process had drier surface conditions, stronger subsidence, smaller but more stable wind speeds, making it easier to lift surface dust and form strong sandstorms. The Gobi-desert underlying surface creates extreme diurnal temperature ranges and prominent wind speed variations. The afternoon process featured intense surface heating, rapid pressure drop, extremely unstable stratification, strong thermal convection, and downward momentum transfer, resulting in large pressure changes and strong winds. The nighttime process had smaller vertical wind shear, weaker thermal convection, and stable stratification, making it easier to form long-duration strong sandstorms. Variable wind directions and surrounding desert environments made the second Liangzhou event more intense and persistent ().

4.3 Physical Quantity Analysis

4.3.1 Vertical Velocity Field Time-height profiles ([Figure 9: see original paper]) show upward motion at all levels in the sandstorm area during 08:00–20:00 on May 14, favorable for lifting dust. Vertical velocity turned negative at 08:00, became positive and increased significantly by 20:00, with consistent upward motion from low to high levels. Maximum vertical velocity centers appeared at 500 hPa over Zhangye and Minqin at 20:00, with values of -42$\times$10^{-3}$ hPa $\cdot$ s^{-1} and -26$\times$10^{-3}$ hPa $\cdot$ s^{-1} respectively. The movement of the vertical velocity center correlated well with sandstorm timing and intensity—Zhangye' s stronger center and larger high-altitude winds with low-level momentum transfer produced stronger sandstorms.

4.3.2 Full Wind Speed Field Strong winds provide the dynamic condition for lifting dust. Time-height profiles of full wind speed ([Figure 9: see original paper]) show that on May 11, the upper jet center at 250 hPa reached 46 m $\cdot$ s^{-1} over Zhangye and 54 m $\cdot$ s^{-1} over Minqin, extending downward to 850 hPa with values of 14 m $\cdot$ s^{-1} and 12 m $\cdot$ s^{-1}. On May 14, the jet appeared at 250 hPa at 20:00, with center values of 50 m $\cdot$ s^{-1} and 56 m $\cdot$ s^{-1}, extending to 850 hPa with 14 m $\cdot$ s^{-1}. The first afternoon process had rapid surface warming, strongest thermal convection, and extremely unstable stratification, facilitating momentum transfer and increasing surface wind speeds. The nighttime process had weaker thermal convection, stable stratification, and smaller vertical wind shear, resulting in weaker surface winds despite strong upper-level jets, causing no disaster losses.

4.3.3 Horizontal Helicity Horizontal helicity represents cold advection intensity and wind reversal with height. Its negative center correlates with downstream sandstorm intensity—when $\leq$-200 m^2 $\cdot$ s^{-2}, strong winds and sandstorms occur; when $\leq$-600 m^2 $\cdot$ s^{-2}, strong sandstorms with visibility $ 500moccurwithin6hours.Thenegativecentermovementcorrelatedwithtimingandlocationofbothsandstorme 597m{2}·s{-2}$ at 20:00, causing sandstorms in Zhangye and Liangzhou. On May 14, the negative center moved northeastward to western Inner Mongolia, reaching -302 m^2 $\cdot$ s^{-2} at 08:00 and -257 m^2 $\cdot$ s^{-2} at 20:00, causing sandstorms in Zhangye, Minqin, and Liangzhou. Although the nighttime process had a larger negative center, sandstorm intensity was weaker due to reduced vertical velocity and wind speeds, indicating weaker forecasting effectiveness for nighttime events.

4.3.4 Boundary Layer Wind Speed Analysis Both processes had similar upper and lower jet center values at 200 hPa, 500 hPa, and 700 hPa (54, 44, and 24 m $\cdot$ s^{-1} for the first; 40, 30, and 52 m $\cdot$ s^{-1} for the second). Boundary layer (below 3 km) maximum wind speeds and heights ([Figure 11: see original paper]) show that during the first process, Zhangye and Minqin had maximum winds of 9 m $\cdot$ s^{-1} and 14 m $\cdot$ s^{-1} at 2980 m and 2510 m at 08:00, descending to 14 m $\cdot$ s^{-1} and 18 m $\cdot$ s^{-1} at 1140 m and 840 m by 20:00. During the second process, maximum winds were 8 $m \cdot s^{-1}$ and 14 $m \cdot s^{-1}$ at 1820 m and 2300 m at 08:00, rising to 15 $m \cdot s^{-1}$ and 18 $m \cdot s^{-1}$ at 500 m by 20:00. The first afternoon process had lower maximum wind height, while the second nighttime process had higher wind height, resulting in weaker winds but stronger, longer-lasting sandstorms.

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5 Conclusions

Based on sandstorm observation data from three representative stations in the middle east of Hexi Corridor, using integrated synoptic, dynamic, and statistical methods, this study analyzes diurnal variation characteristics, forecast indicators, and meteorological factors of typical spring sandstorms. Major findings include:

1) Spring sandstorm days have decreased over the past 60 years, particularly after the 1980s. This reduction correlates with significantly fewer strong wind days, significantly higher temperatures, and increased precipitation since the 1980s. Spring sandstorm days are positively correlated with annual strong wind days and negatively correlated with spring temperatures, with correlation coefficients reaching 0.588 and -0.438 respectively, passing the 99% confidence test. The correlation with precipitation is weaker (-0.176). Sandstorms occur more frequently during daytime than nighttime, and general sandstorms have outnumbered strong sandstorms since the 1980s. Minqin remains the high-incidence area due to abundant sand sources and strong winds. Prevailing wind directions are consistent day and night, concentrated between northwest and north winds, though with station-specific variations. Maximum wind speeds are higher during daytime, particularly in Minqin. Visibility diurnal patterns differ by intensity: strong sandstorms peak at 00:00–01:00 and 18:00–19:00, while general sandstorms peak at 08:00–09:00.

2) The two May 2019 cases show that sandstorm intensity is closely related to underlying surface and diurnal variation. The Gobi-desert surface creates significant diurnal temperature and wind speed ranges. The afternoon process had intense surface heating, unstable stratification, strong thermal convection, and downward momentum transfer, producing large wind speeds. The nighttime process had smaller vertical wind shear, weaker thermal convection, and stable stratification, forming longer-duration strong sandstorms. Variable wind directions and surrounding desert environments made the second Liangzhou event more intense and persistent.

3) Sandstorms erupt in regions of strong upward vertical motion. The timing and height of maximum vertical velocity and wind speed centers correlate with sandstorm intensity. The afternoon process had rapid warming favorable for momentum transfer, increasing surface wind speeds at lower

heights. The nighttime process had strong upper-level winds at higher altitudes but no obvious momentum transfer, resulting in weaker surface winds and no disaster losses. The movement of negative horizontal helicity centers corresponded with sandstorm timing and location, but showed weaker forecasting effectiveness for nighttime intensity.

4) Spring sandstorms in the middle east of Hexi Corridor relate to large-scale circulation, physical quantities (vertical velocity, horizontal helicity, total wind speed), and boundary layer elements (daily variations of surface temperature, humidity, wind, instability parameters). This study' s analysis of temporal variation characteristics and their geographic, climatic, and synoptic causes requires further verification through additional sandstorm cases from upper-air and boundary layer perspectives.

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