Transport and Persistent Characteristics of a Rare Severe Dust Weather Event in the Hexi Corridor (Postprint)

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Abstract

From March 15 to 19, 2021, the Hexi Corridor experienced a rare severe sand and dust weather process with the widest coverage and longest duration in nearly 10 years. Using conventional meteorological observation data and physical quantity field data from MICAPS, this study analyzes the transport and persistence characteristics of this severe sand and dust weather event from the perspectives of synoptic-climatic causes, evolution of circulation patterns, and physical quantity diagnosis. The results show that: (1) On March 14, 2021, under the influence of a strongly developed Mongolian low-pressure trough, a severe sandstorm broke out in southern Mongolia and central-western Inner Mongolia. The anomalous warming in Mongolia and northern China in the early stage was one of the inducing factors for the sandstorm outbreak. (2) Under the combined influence of the northwest airflow behind the deep low-pressure trough over Lake Baikal in the upper atmosphere guiding cold air eastward and southward, momentum transfer from the upper-level jet stream, and the passage of a surface cold front, sand and dust particles from the middle and upper levels of central-western Mongolia were transported to the Hexi Corridor, causing local severe sandstorms and blowing sand weather in the Hexi Corridor from the early morning to morning of March 15. (3) After the severe sandstorm occurred, the prevailing easterly winds at 700 hPa, 850 hPa, and near the surface over Inner Mongolia, North China, Ningxia, and Shaanxi transported sand and dust from Mongolia and Inner Mongolia to the Hexi Corridor, resulting in floating dust weather in the Hexi Corridor from the afternoon of March 15 to March 19. (4) During the maintenance period of the sand and dust weather, the surface cold high pressure moved slowly, the Hexi Corridor was located behind the surface cold high pressure, and the surface wind speed and humidity were relatively low, which was unfavorable for the settling and horizontal diffusion of sand and dust; over the Hexi Corridor, the prevailing downdrafts, deep inversion layer,

dry atmosphere, and stable stratification were unfavorable for the vertical diffusion and settling of low-level sand and dust, which contributed to the sustained maintenance of the sand and dust.

Full Text

Preamble

Transmission and Process Persistence Characteristics of Rare Strong Dust Weather in the Hexi Corridor

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Abstract: From March 15 to 19, 2021, a rare strong floating dust weather process with the widest range and longest duration in recent 10 years occurred in the Hexi Corridor. Using conventional meteorological observation data and physical quantity field data from the Meteorological Information Comprehensive Analysis and Process System (MICAPS), this study analyzed the transmission and persistence characteristics of this strong dust weather from the perspectives of synoptic-climatic causes, circulation pattern evolution, and physical quantity diagnosis. The results show: (1) Under the influence of a strongly developed Mongolian low-pressure trough, a strong sandstorm erupted in southern Mongolia and central-western Inner Mongolia. Abnormal warming in Mongolia and northern China in the early stage was one of the inducing factors for the sandstorm outbreak. (2) Guided by the northwest airflow behind the deep low-pressure trough over Lake Baikal, cold air moved eastward and southward, with momentum transfer from the upper-level jet stream and passage of a surface cold front. These factors collectively transported dust particles from high and low altitudes in central-western Mongolia to the Hexi Corridor, causing local strong sandstorms and blowing sand from early morning to morning on March 15. (3) During the dust weather maintenance period, the surface cold high pressure moved slowly, with the Hexi Corridor located behind the high-pressure system. Low surface wind speed and humidity were unfavorable for dust settling and horizontal diffusion. Prevailing downdrafts, a deep inversion layer, dry atmosphere, and stable stratification over the Hexi Corridor inhibited vertical diffusion and settlement of low-level dust, promoting the persistent maintenance of dust.

Keywords: dust; transmission; persistence; temperature inversion; Hexi Corridor

Dust storms are disastrous weather phenomena that frequently occur in northern China during spring, often causing significant losses. In recent years, Chinese scholars have made substantial progress in dust storm research [?]. Yang et al. [?] analyzed a dust storm event in Wuwei City and pointed out that strong cold air intrusion intensified the Siberian cold trough, providing dynamic conditions for dust storm development, while the vertical structure of the Siberian cold trough facilitated momentum transfer, and strong winds behind the surface cold front created basic conditions for dust storm formation. Xiao et al. [?] diagnosed an extremely strong dust storm in March 2002, finding that it was triggered by northwesterly winds generated along a cold front behind a Mongolian cyclone. Increased vertical wind shear near the surface and enhanced surface heat flux strengthened boundary layer turbulence, lifting surface dust. Strong horizontal wind shear near the surface front, frontal vertical circulation, and post-frontal baroclinic conversion transported dust to high altitudes, triggering the strong dust storm. Wang et al. [?] used model output data to analyze a strong dust storm and found that the upper-level jet stream played a crucial role in energy conversion. Jiang [?] analyzed an extremely large sandstorm in Ningxia using satellite imagery, noting that it was mainly caused by a squall line activity ahead of the cold front. Liu et al. [?] compared two regional strong dust storms in Lanzhou, summarizing their characteristics.

In early March 2021, most areas of Northwest China, central-western Inner Mongolia, and southwestern Mongolia experienced temperatures $4 \sim 6^{\circ}$C higher than normal, with precipitation $42\% \sim 58\%$ below average. These conditions were highly favorable for dust weather. Additionally, according to Duan et al. [?], vegetation coverage in Mongolia in March was only 15%, indicating high-intensity desertified land, while vegetation coverage in northern China was 30%, indicating moderate desertification. The soil thawing period provided favorable underlying surface conditions for dust weather. In early March 2021, temperatures in the Hexi Corridor were also abnormally high, 3.7°C above the historical average, reaching the highest since meteorological records began, with precipitation continuously below normal. The pre-existing climatic conditions of high temperature and low rainfall, along with a dry atmospheric environment, were unfavorable for the settling of floating dust and fine sand, representing one of the reasons for the long-duration dust weather in the Hexi Corridor.

3.2.1 High-Altitude Circulation Pattern

At 08:00 on March 14, the 500 hPa pattern showed a "two ridges and one trough" configuration across the Eurasian continent, with a deep low-pressure trough near Lake Baikal. The trough front had a strong frontal zone, accompanied by a cold vortex center with intensity reaching -40°C and maximum wind speeds of $40\,\mathrm{m \cdot s^{-1}}$. The isotherms were dense, with strong cold advection. The intersection angle between isotherms and isobars approached 90°, indicating strong baroclinicity and baroclinic instability. Both high and low altitudes over the Hexi Corridor were controlled by northwesterly airflow. As the cold vortex moved eastward and southward, the Mongolian low-pressure trough at 500 hPa moved to Northeast China and developed into a low vortex with intensity of 516 gpm. At 700 hPa, the low-pressure trough also developed into a low vortex with intensity of 268 gpm, and the height of the cold air mass decreased. The low-level airflow over the Hexi Corridor shifted from northwesterly to easterly (Fig. [Figure 2: see original paper]).

During the day on March 15, sandstorms occurred in central-western Inner Mongolia, and large-scale dust weather affected central-western Gansu, northern Ningxia, northern Shaanxi, and North China. Over the Hexi Corridor, the 500 hPa airflow was easterly, with a warm tongue extending from the high plateau to the Hexi Corridor, manifesting as warm advection and indicating downdrafts over the region. At 700 hPa, the airflow was northwesterly. The circulation pattern changed little, remaining basically easterly at 500 hPa with wind speeds of $8 \sim 10\,\mathrm{m \cdot s^{-1}}$. The Hexi Corridor had temperature ridges at both high and low levels, with relatively stable stratification. This circulation pattern was maintained continuously.

3.2.2 Low-Level Abnormal Northeasterly Airflow

During the dust weather maintenance period, an exceptionally significant northeasterly airflow was established from Mongolia through North China, Ningxia, and Shaanxi (Fig. [Figure 3: see original paper]). At 08:00 on March 15, the area from Xinjiang to the Hexi Corridor was under northwesterly airflow, while Mongolia to Inner Mongolia was under northerly airflow, and the Hexi Corridor had shifted to easterly airflow. Influenced by this northerly-to-easterly airflow transport belt, dust from low-level Mongolia and along the path was transported to the Hexi Corridor, causing dust weather in the early morning of March 16. This northerly-to-easterly airflow was maintained on March 17, continuously transporting slowly settling dust from high altitudes and dust from low-level areas along the path to the Hexi Corridor, representing the dust source for the long-duration floating dust weather in the region. Due to the low wind speed in the Hexi Corridor, there was no significant local dust lifting.

At 08:00 on March 18, the Hexi Corridor was under northwesterly airflow, cutting off the dust transport pathway, but floating dust weather persisted until nighttime. This may be because dust diffusion and settlement require time, causing the floating dust weather to end slightly later than the weather system.

3.2.3 Ground System

At 14:00 on March 14, a strong cold high pressure dominated the area from Siberia to Lake Baikal, with central intensity reaching 1040.0 hPa. A strong thermal low pressure was located ahead of it in Mongolia, with central intensity of 885.0 hPa. The dense isobars created a large pressure gradient. A strong cold front existed ahead of the area with large differences between high and low pressure centers. At this time, strong winds and sandstorms appeared behind the front (Fig. [Figure 4: see original paper]). Under the influence of the eastward and southward movement of the cold high pressure, most areas of Mongolia and Inner Mongolia experienced sandstorms from evening to night on March 15. The cold high pressure expanded further, with its bottom entering western Hexi Corridor at 02:00 on March 16. The cold high pressure occupied most of Mongolia and Inner Mongolia, with central intensity increasing to 1042.5 hPa.

The slow movement of the surface cold high pressure meant the Hexi Corridor remained behind the high-pressure system. The ground wind speed and humidity were low, unfavorable for dust settling and horizontal diffusion. The surface front passed through the Hexi Corridor from west to east between 02:00-08:00 on March 15, which was one reason for the strong winds, local sandstorms, and blowing sand from early morning to morning.

At 08:00 on March 17, the isobars over the Hexi Corridor became denser, with southeasterly airflow maintained. At 20:00, the high pressure moved slowly, with southeasterly airflow over the Hexi Corridor maintained continuously and both wind speed and humidity remaining low, which was unfavorable for horizontal and vertical dust diffusion, allowing the floating dust weather to persist for an extended period.

3.3.1 Vertical Velocity Field

In the vertical velocity field, Xinjiang was located in the center of strong upward airflow, with central values reaching $-1.0 \times 10^{-1}\,\mathrm{hPa \cdot s^{-1}}$. The Hexi Corridor was situated in the weak upward airflow area to its southeast, with values of $-0.6 \times 10^{-1}\,\mathrm{hPa \cdot s^{-1}}$ (Fig. [Figure 5: see original paper]), indicating stronger upward airflow in the upper layer than in the lower layer. At 20:00 on March 14, there was also a corresponding upward airflow center over Xinjiang, with central values of $-0.8 \times 10^{-1}\,\mathrm{hPa \cdot s^{-1}}$. The Hexi Corridor was also located in the weak upward airflow area to its southeast, with values of $-0.4 \times 10^{-1}\,\mathrm{hPa \cdot s^{-1}}$. This shows that the upper layer had a pumping effect on the lower layer, with unstable atmospheric stratification.

At 08:00 on March 15, southern Mongolia, western Inner Mongolia, and the Hexi Corridor formed an obvious downdraft center, with central values reaching $0.4 \times 10^{-1}\,\mathrm{hPa \cdot s^{-1}}$. At 700 hPa, there was also a corresponding downdraft center, with central values of $0.3 \times 10^{-1}\,\mathrm{hPa \cdot s^{-1}}$ (Fig. [Figure 5: see original paper]). The vertical velocity over the Hexi Corridor was consistent at 500 hPa and 700 hPa, with central values reaching $0.3 \times 10^{-1}\,\mathrm{hPa \cdot s^{-1}}$ and $0.1 \times 10^{-1}\,\mathrm{hPa \cdot s^{-1}}$, respectively. The Hexi Corridor was located in the divergence center. The downdraft center moved slowly eastward on March 16, with intensity weakening, but the Hexi Corridor remained within the downdraft range. The upper-level downdraft was slightly stronger than the lower-level downdraft, indicating relatively stable atmospheric stratification.

The above analysis shows that at 20:00 on March 14, the Hexi Corridor had obvious upward airflow and unstable atmospheric stratification, which easily triggered convection between high and low layers, increased wind speed, and provided dynamic conditions for dust lifting. From March 15 to 16, the opposite condition occurred, with prevailing downdrafts in both upper and lower layers, a deep inversion layer, dry lower-level atmosphere, and relatively stable atmospheric conditions, which inhibited vertical diffusion and settlement of low-level dust and promoted the maintenance of floating dust weather.

3.3.2 Vorticity Field

In the vorticity field, at 20:00 on March 14, eastern Mongolia to the Qinghai-Tibet Plateau showed an obvious divergence zone, with vorticity center intensity of $-3 \times 10^{-5}\,s^{-1}$. The Hexi Corridor was located at the bottom of the divergence center (Fig. [Figure 6: see original paper]), showing upper-level divergence and lower-level convergence, indicating unstable atmospheric stratification. At 08:00 on March 15, the Hexi Corridor, western Inner Mongolia to Mongolia showed an obvious convergence zone, with vorticity center intensity of $10 \times 10^{-5}\,s^{-1}$. The Hexi Corridor was located behind the convergence center (Fig. [Figure 6: see original paper]), showing upper-level convergence and lower-level divergence, indicating stable atmospheric stratification.

At 08:00 on March 16, the vorticity center moved slowly eastward with weakened intensity, but the Hexi Corridor remained within the range of upper-level convergence and lower-level divergence, i.e., showing downdraft motion, consistent with the vertical velocity field. At 08:00 on March 17, the Hexi Corridor to Inner Mongolia was a divergence zone with weakened intensity, and the vorticity center intensity was $-5 \times 10^{-5}\,s^{-1}$. The Hexi Corridor was located at the bottom of the divergence center (Fig. [Figure 6: see original paper]), consistent with the situation at 500 hPa and 700 hPa. The vorticity center further moved eastward and weakened on March 18, but the Hexi Corridor remained within the negative value range. This negative K-index configuration indicated very stable atmospheric stratification over the Hexi Corridor.

3.4.1 Sounding Data (T-logP)

From the perspective of stability, analyzing the atmospheric stratification characteristics during the floating dust weather maintenance in the Hexi Corridor using the Minqin station sounding curve revealed that at 20:00 on March 14, the atmosphere below 500 hPa was in a dry and warm state, with almost no inversion layer. The atmosphere was very dry, especially below 500 hPa, which could easily trigger dry convection and provide thermal instability conditions for strong winds and dust.

At 08:00 on March 15, the Minqin station sounding showed a clear inversion layer from the surface to 850 hPa, with the inversion top height reaching nearly 2000 m, forming a deep inversion layer (Fig. [Figure 7: see original paper]). At 08:00 on March 16, a double inversion layer appeared, with the lower inversion at 700 hPa and the upper inversion at 850 hPa. The double inversion layer still existed at 08:00 on March 17, with reduced height. The atmosphere below 500 hPa was dry, especially in the near-surface layer, which was not conducive to the settlement of low-level floating dust. In general, during the floating dust weather maintenance period, the atmospheric stratification over the Hexi Corridor was extremely stable, consistent with the vertical structures of floating dust weather studied by Bai et al. [**?**] and Yang et al. [**?**].

The persistent deep inversion layer acted like a lid, suppressing vertical diffusion of dust and promoting dust maintenance. Additionally, from March 15 to 18, the pseudo-equivalent potential temperature at Minqin showed a basically linear downward trend from the surface to the upper layer, indicating no unstable energy and relatively stable atmospheric stratification. The local dust lifting capacity was weak.

3.4.2 K-Index

In the K-index field, western Hexi Corridor was a weak negative K-index zone, while eastern Hexi Corridor was a weak positive K-index zone (figure omitted), indicating relatively unstable stratification. At 20:00 on March 14, there was a K-index negative center of $\leq -60°$C from eastern Xinjiang to Inner Mongolia and Gansu, with the Hexi Corridor located behind the dense isopleth area of the negative center (figure omitted). At 08:00 on March 15, the K-index negative center moved slightly eastward with weakened intensity, and the Hexi Corridor was in the negative value range (figure omitted). At 08:00 on March 17, the K-index negative center split into two, one moving into the sea and the other remaining over Inner Mongolia to Gansu, with a center value of $-45°$C. The Hexi Corridor was in the negative value zone (Fig. [Figure 8: see original paper]). At 08:00 on March 18, the K-index negative center further moved eastward and weakened, but the Hexi Corridor remained within the negative value range (figure omitted). This negative K-index configuration indicated very stable atmospheric stratification over the Hexi Corridor.

4 Conclusions

Using MICAPS conventional meteorological observation data and physical quantity field data, this study analyzed the transmission and long-duration characteristics of the rare strong dust weather in the Hexi Corridor, yielding the following conclusions:

(1) From afternoon to night on March 14, 2021, under the influence of a strongly developed Mongolian low-pressure trough, a strong sandstorm erupted in southern Mongolia and central-western Inner Mongolia. The pre-existing drought and low rainfall, along with abnormally high temperatures in Mongolia and northern China, were important causes of this strong sandstorm. Low vegetation coverage provided favorable sand sources for the strong dust weather.

(2) From early morning to morning on March 15, guided by the northwest airflow behind the deep low-pressure trough over Lake Baikal, cold air moved eastward and southward, with momentum transfer from the upper-level jet stream and passage of a surface cold front. These factors collectively caused strong winds, local sandstorms, and blowing sand in the Hexi Corridor. After the strong sandstorm occurred, abnormal northeasterly airflow at middle and low levels (700 hPa and 850 hPa) and near the surface continuously transported dust from Mongolia, Inner Mongolia, and along the path to the Hexi Corridor, causing the strong floating dust weather from March 15 to 18 in the Hexi Corridor. This is consistent with Yang et al.' s [?] simulation results showing that dust particle backward trajectories originated from eastern Mongolia.

(3) During the floating dust weather maintenance period, wind speeds at high and low levels were low, which was unfavorable for vertical dust transport. The surface cold high pressure moved slowly, with the Hexi Corridor located behind the high-pressure system. Low surface wind speed and humidity were unfavorable for dust settling and horizontal diffusion, promoting dust persistence. Additionally, after dust transport to the Hexi Corridor, blocking and accumulation by the Qilian Mountains may have intensified and maintained the floating dust, which requires further investigation.

(4) Analysis of vertical velocity, vorticity, sounding curves, and K-index showed that prevailing upward airflow at high and low levels, absence of inversion layers, warm and dry atmosphere, and relatively unstable atmospheric conditions favored the generation of strong winds and dust weather at 20:00 on March 14. From March 15 to 16, the opposite conditions occurred: prevailing downdrafts at high and low levels, a deep inversion layer, dry lower-level atmosphere, and relatively stable atmospheric conditions inhibited vertical diffusion and settlement of low-level dust, promoting the long-term maintenance of floating dust weather.

This study analyzed the causes of occurrence, transmission, and long-duration persistence of the dust weather in the Hexi Corridor from perspectives of climatic causes, circulation evolution, and physical quantity diagnosis, but remains at a preliminary diagnostic level. The physical mechanisms of dust formation are extremely complex, including the specific impacts of boundary layer thermal instability, triggered low-level dry convection, mixed layer height variations, the relationship between inversion layer height/thickness and dust intensity [?], and the role of continuous dust weather [?]. The relationship between dust transport and topography, as well as other special meteorological factors, requires in-depth discussion and research in future work. Additionally, this study concluded that "during the floating dust weather maintenance period, the atmospheric stratification over the Hexi Corridor was extremely stable," which may be a necessary condition for floating dust maintenance and warrants further verification in operational applications and scientific research.

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