Numerical simulation and spatiotemporal tracking of sand and dust storm events in East Asia (Postprint)

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Abstract

Sand and dust storms (SDSs) are natural disasters that frequently occur during spring in arid and semi-arid areas, causing serious impacts on human health, air quality, transportation, and agricultural production. Accurately simulating the occurrence and evolution of SDSs is of great significance for identifying dust sources and formulating effective disaster prevention measures. In this study, numerical simulations were conducted to reveal the dynamic spatiotemporal evolution and transport of dust load across East Asia. Using the Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem) and European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) data, the most severe SDS events in the spring of 2023 in East Asia were numerically simulated. The simulated results were compared and validated using meteorological observations and multisource remote sensing data. The results showed that the simulated dust load in the peak regions showed close agreement with ground-based observations during the events. The primary dust sources in spring 2023 were identified as the western desert of Mongolia, the Gobi Desert, and the Taklimakan Desert in Xinjiang Uygur Autonomous Region of China. Peak dust load and maximum wind speed occurred almost simultaneously, indicating that high wind speed was the primary driver of sand and dust mobilization during individual SDS events. Increased surface vegetation covers partially mitigated wind-driven dust emissions. In April, strong winds over the Gobi Desert on the Mongolian Plateau predominantly drove cross-border SDSs along northwestern and northward transport pathways. Dust originating from Mongolia exerts a substantial influence on particulate dust load in the central and eastern parts of Inner Mongolia Autonomous Region of China. In contrast, their impact on the northwestern regions of China remains relatively limited. These findings contribute to understanding the source areas of SDS events in East Asia by simulating the dynamic evolution of SDSs and elucidating the relationships between

SDS events and local geographical and environmental factors.

Full Text

Preamble

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Numerical simulation and spatiotemporal tracking of sand and dust storm events in East Asia HUANG Shaopu1,2, WANG Juanle2,3*, WANG Lixin1, GUO Yanhong1

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Abstract

Sand and dust storms (SDSs) are natural disasters that frequently occur during spring in arid and semi-arid areas, causing serious impacts on human health, air quality, transportation, and agricultural production. Accurately simulating the occurrence and evolution of SDSs is of great significance for identifying dust sources and formulating effective disaster prevention measures. In this study, numerical simulations were conducted to reveal the dynamic spatiotemporal evolution and transport of dust load across East Asia. Using the Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem) and European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5) data, the most severe SDS events in the spring of 2023 in East Asia were numerically simulated. The simulated results were compared and validated using meteorological observations and multisource remote sensing data. The results showed that the simulated dust load in the peak regions showed close agreement with ground-based observations during the events. The primary dust sources in spring 2023 were identified as the western desert of Mongolia, the Gobi Desert, and the Taklimakan Desert in Xinjiang Uygur Autonomous Region of China. Peak dust load and maximum wind speed occurred almost simultaneously, indicating that high wind speed was the primary driver of sand and dust mobilization during individual SDS events. Increased surface vegetation covers partially mitigated wind-driven dust emissions. In April, strong winds over the Gobi Desert on the Mongolian Plateau predominantly drove cross-border SDSs along northwestern and northward transport pathways. Dust originating from Mongolia exerts a substantial influence on particulate dust load in the central and eastern parts of Inner Mongolia Autonomous Region of China. In contrast, their impact on the northwestern regions of China remains relatively limited. These findings contribute to understanding the source areas of SDS events in East Asia by simulating the dynamic evolution of SDSs and elucidating the relationships between SDS events and local geographical and environmental factors.

Keywords

sand and dust storm (SDS); dust load; Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem); European Centre for Medium-Range Weather Forecasts Reanalysis v5 (ERA5); wind speed; Taklimakan Desert; Mongolian Plateau Citation: HUANG Shaopu, WANG Juanle, WANG Lixin, GUO Yanhong. 2026. Numerical simulation and spatiotemporal tracking of sand and dust storm events in East Asia. Journal of Arid Land, 18(3): 353-371. https://doi.org/10.1016/j.jaridl.2026.03.001; https://cstr.cn/32276.14.JAL.20250455

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Introduction

Sand and dust storms (SDSs) are complex extreme weather events characterized by a sudden seasonal onset. The dust transported by SDSs exerts both direct and indirect impacts on the atmospheric environment (Lelieveld et al., 2015), solar radiation balance (Allen et al., 2015), marine material cycles (Zhang et al., 2020), and human health (Kotsyfakis et al., 2019). Moreover, SDSs exacerbate land desertification and hinder the sustainable development of ecological systems in affected areas (Wu et al., 2021). East Asia constitutes a key global source of dust emissions, releasing approximately 500.00–1100.00 Tg of dust annually—accounting for 25%–50% of global emissions (Ginoux et al., 2004). Dust particles originating in East Asia can be transported across the Pacific Ocean to the North America via large-scale atmospheric circulation (Duce et al., 1980; Bell et al., 2007; Tan et al., 2011). East Asia is an important source of atmospheric dust, including dust from the Taklimakan and Gobi deserts, as well as anthropogenic contributions arising from agricultural activities, mining, and overgrazing (Ginoux et al., 2012; Kok et al., 2021). Although the frequency and intensity of SDSs in East Asia have generally declined over recent decades due to the implementation of a series of ecological restoration projects (Wu et al., 2022), the number of SDS events in the border regions between China and Mongolia has increased recently (Ma et al., 2024). Specifically, transboundary SDS events between China and Mongolia rose significantly from 1987 to 2022, primarily driven by cyclones in northeastern China and eastern Mongolia (Ma et al., 2024). In spring 2021 (13-17 March, 27-29 March, and 15-16 April), three large-scale SDS events occurred across a wide area in East Asia, directly affecting the ecological environment of China and neighboring countries in Northeast Asia (Tang et al., 2022). Therefore, there is an urgent need to monitor and address SDSs in East Asia.

SDS monitoring relies primarily on ground-based station observations and satellite remote sensing (Al-Khudhairy et al., 2023; Broomandi et al., 2023; Attiya and Jones, 2024). Traditional ground-based station observations have the advantages of quantifying sand and dust concentrations and maintaining long-term observational records (Mikalai, 2022); however, most ground-based stations are located in remote areas, posing challenges related to maintenance and delayed data updates. Furthermore, the limited spatial coverage of these stations results in incomplete representation of areas affected by sand and dust processes, hindering large-scale SDS studies (Eckert et al., 2015). With the advancement of remote sensing technologies, SDS events can be rapidly evaluated and mapped when imagery is available, leveraging spectral information to detect and invert large-scale SDS events (Li, 2018). Nevertheless, this method remains limited in its capacity for quantitative analysis of sand and dust concentrations (Tang et al., 2022), and capturing the dynamic evolution of an SDS using discrete satellite images continues to present significant challenges.

Recently, numerical simulations have gained prominence among researchers (Umberto et al., 2023; Krishna et al., 2024) due to their ability to model SDS events over extended spatial and temporal scales and to quantify sand and dust concentrations. The Weather Research and Forecasting Model coupled with Chemistry (WRF-Chem) is a widely used numerical system capable of simulating historical weather conditions and forecasting future trends (Pang et al., 2014; Cao et al., 2025). WRF-Chem incorporates several dust emission schemes, including the Shao scheme (Shao, 2004), the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model (Ginoux et al., 2004), and the Marticorena-Bergametti (MB) scheme (Marticorena and Bergametti, 1995). Wind tunnel experiments underpinning the Shao scheme identify three dust emission mechanisms: aerodynamic entrainment, saltation bombardment, and aggregate particle fragmentation (Shao, 2004). The GOCART model relies heavily on empirical assumptions for its internal physical parameters, often leading to deviations in the simulation of sand and dust processes (LeGrand et al., 2019). The MB scheme estimates surface dust emissions by calculating saltation flux when the friction velocity exceeds a threshold value; it is sensitive to soil particle size and surface roughness but insensitive to surface moisture and vegetation cover (Marticorena et al., 1997). Although computationally simple, the MB scheme lacks flexibility in defining

physical parameters. Wu and Lin (2014) found that the Shao scheme can simulate dust emissions and transport, whereas the GOCART model ignores potential dust sources in parts of Mongolia within East Asia. The Shao scheme, grounded in a comprehensive theoretical framework, explicitly accounts for wind entrainment, large-particle saltation, and aggregate-particle fragmentation (Yin et al., 2022). Hamidi et al. (2017) applied the Shao scheme and concluded that a severe dust storm in Middle East during 3–8 July in 2009 emitted more than 9.67 Tg of dust.

Kang et al. (2014) improved simulation accuracy by incorporating a dead-leaf effect factor into the Shao scheme, achieving close alignment between modeled and observed PM10 concentrations.

Additionally, researchers have optimized the wind erosion weighting factor (γ) in the Shao scheme, finding that γ=1 enhances model applicability in Northwest China (Zhao et al., 2020a).

Another study successfully used the WRF-Chem with the Shao scheme to reproduce the spatial and temporal variations of dust events in Northwest China in May 2018 (Zhao et al., 2020b).

Model simulation methods can better simulate sand and dust emissions; however, tracking simulations and analyses of the influencing factors for multiple spring SDS events remain limited.

Consequently, the spatial and temporal characteristics of spring SDS in East Asia, along with the geographical and environmental factors controlling its occurrence, remain poorly understood. In this study, numerical simulations and multisource data were used to track SDS events in East Asia from March to May 2023. The distribution of sand sources, dynamic evolution characteristics, and the influence of geographical and environmental factors in the region were determined. This study provides a comprehensive assessment of the mechanisms driving spring SDS events in East Asia, offering new insights to improve dust emission parameterizations in regional models and to develop effective mitigation strategies to reduce the impacts of SDSs on human health, air quality, and regional climate.

Data sources and model description

Study area

This research selected the strongest monthly SDS events from March to May 2023 in East Asia (36°–47°N, 75°–120°E) as case studies. The terrain of the study area is dominated by basins, plateaus, and intermontane depressions, with elevations ranging from approximately 800 to 2000 m.

The climate of this region is characterized by strong continental arid conditions, with an annual mean temperature ranging from approximately -2°C to 12°C. Both seasonal and diurnal temperature variations are pronounced, with summer maximum temperatures exceeding 40°C and winter minimum temperatures dropping below -40°C. Annual precipitation is generally low, typically 20–200 mm. The region experiences strong near-surface winds, with an annual mean wind speed of approximately 3-7 m/s; the winds occur frequently in spring, making this period the peak season for SDS events. The main study area' s land cover types (Liu et al., 2020) and locations of the deserts are shown in Figure 1 [Figure 1: see original paper]. The land cover of the Taklimakan and Kumtag deserts in China, the Gobi Desert, and the western desert of Mongolia is predominantly barren.

The soil types include sand, sandy clay loam, sandy loam, silty clay loam, and loam (Tang et al., 2022). Due to these land cover and soil characteristics, deserts in East Asia can emit a large amount of dust under certain meteorological conditions.

Data sources

2.2.1 Ground-based station observation data Ground-based station observation data included atmospheric particulate matter concentrations and wind speeds. PM10 mass concentration data were obtained from four ground-based stations in the Inner Mongolia Autonomous Region of China: Hohhot, Ordos, Baotou, and Wuhai. To ensure comparability between simulated results and observed data, this study selected the period from 9 to 14 April in 2023 for the validation of the simulated SDS events. This time window was chosen to maintain the continuity and completeness of station observations, thereby ensuring the reliability of the analysis. Wind speed data were obtained from the National Centers for Environmental

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Land cover types in the study area and the locations of the deserts

Information (www.ncei.noaa.gov/cdo-web). The retrieved wind speed data had a temporal resolution of 1 h and covered the selected periods of 19-24 March, 9-13 April, and 13-17 May in 2023, synchronized with the SDS events. 2.2.2 Himawari-8 satellite remote sensing data Himawari-8 (https://www.eorc.jaxa.jp/ptree/) is the world' s first next-generation geostationary meteorological satellite (Bessho et al., 2016), providing a spatial resolution of 500 m and a temporal resolution of 10 min (Qiu et al., 2018). RGB false-color composites generated using the BT15-BT13, BT13-BT11, and BT13 bands from Himawari-8 enable dynamic remote sensing monitoring of sand and dust (Wang et al., 2022). Because of cloud interference over the study area, observations at 06:00 (UTC) on 20 March and 09:00 on 15 May, 2023, were selected. 2.2.3 Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) aerosol vertical extinction coefficients The CALIPSO satellite carries an orthogonally polarized cloud-aerosol Light Detection and Ranging (LIDAR), an imaging infrared radiometer, and a wide-field camera capable of emitting laser beams at 532 and 1064 nm. The 532 nm channel provides orthogonal polarization capability.

Its L1B, L2VFM, and L2 Layer/Profile products are widely used to observe dust aerosols (Allen et al., 2015). In this study, the vertical extinction coefficient and aerosol types at 532 nm were used to analyze the transport pathways and vertical structures of SDSs. The satellite overpass times were 07:23 on 20 March and 07:38 on 16 May, 2023. The analyzed altitudes ranged from the surface to 8 km. CALIPSO data were obtained from https://search.earthdata.nasa.gov/search/.

2.2.4 Model data

Meteorological input data for the model were derived from the European Centre for MediumRange Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) dataset in GRIB2 format. The ERA5 (Soci et al., 2024), a fifth-generation global climate reanalysis dataset produced by the ECMWF, provides hourly estimates of numerous atmospheric, terrestrial, and oceanic climate variables dating back to 1950. In this study, meteorological data with a temporal resolution of 3 h and a spatial resolution of 0.25°$×$0.25° were used, including air pressure, wind speed, wind direction, temperature, boundary layer height, mean sea level pressure, and sea surface temperature.

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2.2.5 Description of variables

events. It summarizes the availability of dust load, wind speed, satellite data, PM10 observations, and mask experiment for each month, clearly showing the availability and coverage of each variable. The selection of variables depends on the differences in cloud cover and the continuity of the ground-based station records.

Overview of the variables used for the three selected sand and dust storm (SDS) events in spring 2023

Month

Dust load

Wind speed

Satellite data

March

Shown

Shown

Shown

April

Shown Shown

Mask experiment

Shown

Shown

Shown

Model description and configuration

2.3.1 Model description

The WRF-Chem model, released as part of the Weather Research and Forecasting system (Krishna et al., 2024), can simulate historical weather conditions and predict future trends. The Shao scheme considers variations in bare soil exposure, soil moisture, particle cohesion, and soil aggregation. It can simulate dust emissions with relatively high accuracy under surface warming and strong wind conditions in the arid and semi-arid regions of East Asia (Shao, 2009). The Shao scheme proposed a size-resolved dust emission parameterization that accounts for particle bombardment and aggregate disintegration.

In the Shao scheme, dust is categorized into five size bins, with particle size ranges of 0.0–2.0, 2.0–3.6, 3.6–6.0, 6.0–12.0, and 12.0–20.0 μm. (d , d) = c η $(1 - \gamma) + \gamma$ p f (di) g Qds $(1 + \delta)$, γ f ,i pm (di) u*2 where F (di, ds) denotes the vertical sedimentation flux of di generated by the saltation impact of sand particles with size ds (kg/(m2 • s)); cγ is a proportionality factor; ηf,i represents the mass fraction of sand particles emitted from the soil into the atmosphere; γ is a weighting factor related to the size distribution of SDS, indicating the difficulty of releasing aggregated particles; pf (di) is the mass fraction of releasable dust-sized soil particles at size di; pm(di) is the size fraction of mobile particles contributing to saltation at size di; g is the acceleration due to gravity (m/s2); Qds is the horizontal dust flux (kg/(m • s));* u is the friction velocity (m/s); and δm is the bombardment coefficient.

(d) = F $\int$ (d i , d s) ps (d) δ d ,

1 + 14u* ps

δ m = 12u*2

ps

(ln d − ln D)2 exp − 2δ 2j j =1 2$\pi\delta$ where F (di) denotes the vertical sedimentation flux of di (kg/(m2 • s)); ps(d) is the plastic pressure of the soil (Pa); d is the particle size (µm); pm(d) and pf (d) refer to the minimum and fully

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distributed particle size (µm), respectively, which are used to compute the plastic pressure of the soil ps(d); pb is the bulk density of soil (kg/m3); ps is the soil plastic pressure (Pa); G is the total vertical sedimentation flux across all particle sizes (kg/(m2 • s)); N is the number of particle size bins; ωj denotes the proportion of the jth particle size distribution (%); δj is the logarithmic width of the jth particle size interval and is dimensionless; and D is the representative particle diameter of the jth particle size class (µm).

In this study, the relative contribution of upstream dust sources was determined by comparing the dust load before and after the mask experiment. For each observation site, the relative contribution of the upstream dust sources was calculated as follows:

DustloadTD1 − DustloadTD 2 C (%) = × 100% , DustloadTD1 where C is the dust contribution amount (%); and DustloadTD1 and DustloadTD2 are the dust loads before and after the mask experiment (mg/m2), respectively.

2.3.2 Model configuration

The WRF-Chem v3.5.1 model was employed for the numerical simulations. The simulation domain was defined using a Lambert Conformal projection with a central point at 38°N and 105°E. The simulation area comprises a single-layer horizontal grid of 480$×$320 points with a horizontal resolution of 15 km; 35 vertical levels were used, and the model' s top pressure was fixed at 50 hPa. The model integration time step was 60 s, and the output frequency of the historical files was 1 h. The land-use data were based on MODIS12Qv006 from 2021, replacing the default Weather Research and Forecasting land-use classification. Table 2 lists the datasets used for the physical parameterization schemes.

Chemistry (WRF-Chem) Option name Microphysics

Namelist variable

Scheme

mp_{physics}

Jade Lim and Hong (2005)

Reference

Long-wave radiation

ra_{{{lw}}_{{physics}}}

Michael et al. (2008)

Short-wave radiation

ra_{{{sw}}_{{physics}}}

Goddard

Matsui et al. (2018)

Boundary layer

bl_{{{pbl}}_{{physics}}}

Singh et al. (2024)

Land surface

sf_{{{surface}}_{{physics}}}

Chen et al. (1996)

Cumulus convective

cu_{physics}

Grell-3D

Tian et al. (2021)

Note: WSM5, Weather Research and Forecasting Single-Moment 5-class Microphysics scheme; RRTM, Rapid Radiative Transfer Model for long-wave radiation; Goddard, Goddard short-wave radiation scheme; YSU, Yonsei University Planetary Boundary Layer scheme; Noah, Noah Land Surface Model; Grell-3D, Grell 3D Ensemble Cumulus Parameterization scheme.

Results

Model simulation results and verification

The simulation results for the SDS impact range and remote sensing observations from the Himawari-8 satellite are presented in Figure 2 [Figure 2: see original paper]. Both the simulations and observations indicate that at 12:00 on 20 March 2023, the SDS was concentrated over the Taklimakan, Kumtag, and Gobi deserts. Another SDS event, which occurred on 10 April, was primarily located in the Gobi Desert. These results demonstrate that the WRF-Chem model effectively simulates the spatial extent of SDS events while overcoming cloud interference in satellite-based monitoring.

Atmospheric particulate matter concentrations (PM10) from both simulations and ground-based station observations during the SDS events are shown in Figure 3 [Figure 3: see original paper]. Between 9 and 14 April, peak PM10 concentrations occurred on 10 and 14 April across the four stations: Hohhot, Ordos, Wuhai, and Baotou. The simulated peak PM10 concentrations aligned well with the observed values, confirming that the WRF-Chem can accurately reproduce the dust load levels of SDS events.

2 Comparison of simulated sand and dust storm (SDS) impact ranges (indicated by dust load) and remote sensing observations from the Himawari-8 satellite in spring 2023. (a), simulation at 12:00 (UTC) on 20 March; (b), Himawari-8 satellite observation at 12:00 on 20 March; (c), simulation at 10:00 on 10 April; (d), Himawari-8 satellite observation at 10:00 on 10 April. The red areas in the right panel indicate dust.

3 Comparison between simulated and observed PM10 concentrations at different ground-based stations between 9 and 14 April, 2023. (a), Hohhot; (b), Ordos; (c), Wuhai; (d), Baotou.

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The vertical profiles of the aerosol extinction coefficient and corresponding satellite orbits derived from CALIPSO during the SDS events (19–24 March and 13–17 May) are shown in both orbital paths was dominated by dust. The dust layers were primarily located at altitudes of 1-6 km above ground level. These observations further validate the simulation results.

4 Aerosol extinction coefficient profiles and satellite orbits derived from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) during the SDS events in spring 2023. (a), extinction coefficient profile at 07:23 on 20 March; (b), extinction coefficient profile at 07:38 on 16 May; (c), satellite orbit derived from CALIPSO at 07:23 on 20 March, showing as the black dotted line; (d), satellite orbit derived from CALIPSO at 07:38 on 16 May, showing as the black dotted line. AOD, aerosol optical depth.

Wind speed and dust load

The simulation of the SDS events from 19 to 23 March in 2023 is shown in Figure 5 [Figure 5: see original paper]. The dust load peak region originated from the Gobi Desert, Kumtag Desert, Taklimakan Desert, and western Mongolian desert, with the Taklimakan and Gobi deserts as the principal sources. The initial dust load peak region from the Taklimakan Desert was observed at 06:00 on 19 March and moved eastward. By 18:00 on the same day, the Kumtag Desert had become the primary source.

On 20 March at 06:00, the dust load peak region from the Gobi Desert was dominant. The SDS event subsequently affected most northern regions of China and extended southward to Hubei, Anhui, Jiangsu, and northern Zhejiang provinces by 22 March.

The simulation of the SDS events from 13 to 17 May in 2023 is illustrated in Figure 6 [Figure 6: see original paper]. The dust load peak region primarily originated from the Kumtag Desert in China and the Gobi Desert in Mongolia. At 14:00 on 14 May, the dust load peak region from the Gobi Desert of Mongolia began to spread eastward, establishing it as the dominant dust source. By 10:00 on 15 May, the

5 Simulated SDS events indicated by dust load from 19 to 23 March, 2023. (a), 06:00 on 19 March; (b), 18:00 on 19 March; (c), 06:00 on 20 March; (d), 18:00 on 20 March; (e), 06:00 on 21 March; (f), 18:00 on 21 March; (g), 06:00 on 22 March; (h), 18:00 on 22 March; (i), 06:00 on 23 March.

6 Simulated SDS events indicated by dust load from 13 to 17 May, 2023. (a), 20:00 on 13 May; (b), 04:00 on 14 May; (c), 14:00 on 14 May; (d), 00:00 on 15 May; (e), 10:00 on 15 May; (f), 20:00 on 15 May; (g), 06:00 on 16 May; (h), 16:00 on 16 May; (i), 02:00 on 17 May.

dust load peak region from the Kumtag and Gobi deserts intensified, with its center gradually shifting eastward. The contribution from the Kumtag Desert decreased, whereas deposition in the Gobi Desert increased and became dominant. This SDS event primarily affected the northern Mongolia and the northern regions of China (including the Inner Mongolia Autonomous Region, northern Ningxia Hui Autonomous Region, and northern Gansu Province). observation stations. At the Bayannur Linhe station, three PM10 concentration peaks were recorded: the first at 14:00–15:00 on 9 April, the second at 12:00 on 10 April, and the third at 12:00–14:00 on 13 April. Similarly, at the Hohhot Baita station, peaks occurred at 18:00–22:00 on 9 April, 15:00–18:00 on 10 April, and 12:00–24:00 on 13 April. At both observation stations, the peak dust load (PM10 concentration) lagged behind the peak wind speed, suggesting a causal relationship between them.

7 Comparison between wind speed and simulated PM10 concentration at Bayannur Linhe (a) and Hohhot Baita (b) observation stations from 9 to 14 April, 2023

Cross-border transmission

The cross-border SDS events between China and Mongolia occurred primarily in April during the spring season. The SDS event from 9 to 15 April was selected as the focus of this study. By designing a numerical experiment in which dust emission sources in Mongolia were masked in the model, we analyzed changes in regional dust emissions and evaluated the variation in the intensity of transboundary SDS transport between China and Mongolia.

The simulated regional dust emissions before and after masking the Mongolian dust source regions at 12:00 on 9 April are shown in Figure 8 [Figure 8: see original paper]. The results indicate that masking the dust sources in Mongolia led to a significant reduction in dust load across the study area. During this period, the primary regions of China affected by sand erosion included the Gobi Desert (in central and western Inner Mongolia Autonomous Region) and Kumtag Desert (in Xinjiang Uygur Autonomous Region), Northwest China. Owing to cross-border transport of dust from the Gobi Desert in Mongolia, substantial differences in dust load intensity were observed in central Inner Mongolia Autonomous Region before and after masking the Mongolian dust source regions. Furthermore, the transboundary SDS event exhibited pronounced spatial variability in its transport process.

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8 Regional dust load before and after masking the Mongolian dust source regions. (a), regional dust load before masking the Mongolian dust source regions; (b), regional dust load after masking the Mongolian dust source regions.

To further examine the SDS event, we analyzed the dust intensity from the simulations at six sites in China distributed from west to east: Ejin, Ordos, Huhhot, Beijing, Erenhot, and Tongliao (Fig. 9 [Figure 9: see original paper]). The results indicated that sandstorm particle intensity generally increased from west to east. Within China, dust emissions followed a spatial pattern characterized by higher intensity in the central regions and lower intensity in the western and eastern regions. Among the selected sites, Erenhot and Tongliao were the least affected by dust emissions originating from China. In contrast, dust emissions from Mongolia increased gradually from west to east, with Ejin experiencing the least impact and Erenhot and Tongliao the greatest. Cross-border dust originating from Mongolia accounted for more than 90% of the total dust load in Erenhot and Tongliao sites and more than 40% of the total dust load in Ordos, Huhhot, and Beijing sites.

Throughout the event, the temporal evolution of dust activity closely matched the patterns of 850 hPa wind speed, suggesting that the dynamics of the mid- to lower-tropospheric wind field play a dominant role in driving the emission and transport of dust particles during the SDS event. The dust load peaks coincided with periods of stronger 850 hPa winds, suggesting that variations in the synoptic-scale wind field directly governed both the magnitude and timing of dust emission and its long-range transport. Based on the spatial distribution of dust during this SDS event, it can be concluded that Mongolian dust sources significantly influenced dust load in the central and eastern Inner Mongolia Autonomous Region of China. In contrast, their impact on the other northwestern regions of China was relatively limited. Furthermore, the analysis of time-series data from the selected observation sites reveals that Erenhot was the first location affected by cross-border dust following the onset of the SDS event, followed sequentially by Tongliao, Huhhot, Ordos, and Beijing sites (Fig. 9). Throughout the SDS event, all regions impacted by cross-border dust experienced multiple peaks in dust load, driven by strong winds over the Mongolian Plateau. However, due to the finite availability of surface dust in the source regions and the reduction in surface wind speeds, the magnitudes of these dust load peaks declined over time. The main transport pathways of this cross-border SDS event followed northwestern and northward trajectories.

Discussion

Changes in dust sources

In the spring of 2023, northern China experienced 10 SDS events—the highest frequency for the same period in the past decade (Yin et al., 2023)—reflecting a typical manifestation of the increasing prevalence of extreme dust weather events in recent years. This trend continues to exacerbate the instability and disaster risk associated with SDS events on the Mongolian Plateau.

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9 Dust loads before and after masking the Mongolian dust source regions at multiple observation sites (a–f), and the 850 hPa wind field during the start (9 April 2023; g) and end (15 April 2023; h) times of the SDS events. The x-axis in panels (a)-(f) represents the timing of the SDS events, spanning the period from 9 to 15 April, 2023. ERA5, European Centre for Medium-Range Weather Forecasts Reanalysis v5.

To investigate these high-frequency SDS events, this study employed multisource remote sensing data and the WRF-Chem model to identify their driving factors. We not only quantified the spatiotemporal evolution of these events but also assessed the contributions of dust sources from different regions and their impacts on the cross-border SDS transport, thereby providing a scientific basis for formulating comprehensive and targeted anti-desertification strategies.

Existing studies have identified the Badain Jaran, Tengger, Taklimakan, and Gobi deserts as the primary SDS sources in East Asia, whereas the Qaidam Basin, Mu Us Sandy Land, Hobq Desert, and Horqin Sandy Land were considered as the secondary sources. Chen et al. (2017) used the WRF-Chem model to refine the seasonal variation characteristics of dust sources, reporting that the spring sediment flux in the Gobi Desert is 70.54 Tg/a, accounting for 42% of the total dust flux in East Asia. Some studies have concluded that the Taklimakan Desert exhibits the highest dust emission flux, followed by the Qaidam Basin and the western part of the Hexi Corridor, while the Mu Us Sandy Land, Yinshan Mountain Range, Hunshandak Sandy Land, and Horqin

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Sandy Land contribute the least (e.g., Wang et al., 2015). However, most prior research has focused on single dust sources or localized events; systematic analyses of source contributions, cross-border transport, and spatiotemporal evolution under conditions of multiple, high-frequency SDS events remain limited. The primary dust sources for the SDS events in March and May 2023 are shown in Figure 10 [Figure 10: see original paper]. The results indicate that the main dust sources were China' s Taklimakan Desert and Mongolia' s Gobi Desert, with the activity center shifting eastward over time. Notably, the SDS event in March generated substantial dust emissions from the western desert of Mongolia, affecting the northern and eastern regions of Mongolia as well as the eastern Inner Mongolia Autonomous Region of China—a region that has received relatively little attention in previous studies and warrants further investigation.

10 Distribution of primary dust sources for the SDS events in March and May 2023 and wind speed observation stations

Influencing factors of SDS events and cross-border transportation

The processes of dust emission, transport, and deposition during the SDS events are influenced by multiple interrelated factors with complex interaction mechanisms. Frequent cold-front transits in spring, combined with the absence of vegetation cover on bare land in northern China, create favorable meteorological and geographical conditions for SDS transport (Gao et al., 2000).

Similarly, a study of the severe SDS events in East Asia from 14 to 16 March 2021 found that high wind speeds are responsible for elevated dust emission flux and concentration (Tang et al., 2022). Although wind speed is a critical factor influencing SDS events, it is not the sole determinant. SDS activity in spring is also influenced by abnormal precipitation during the preceding summer in the China-Mongolia border region (Liu et al., 2004). Moreover, temperature variations can alter vegetation cover in dust source areas, thereby affecting the frequency and intensity of the SDS events (An et al., 2018).

While wind speed largely governs the dust load during an individual SDS event, high wind speeds do not necessarily correspond to higher dust loads across different SDS events in the same season. In this study, wind speed data from the Baita, SHINE, Takelama, Mandula, and Qiaobashan stations (Fig. 10) were analyzed for the periods of 18–19 March and 14–15 May, 2023 (Fig. 11 [Figure 11: see original paper]). The results indicate that the dust load in March was significantly higher than that in May, even though wind speeds in March were either comparable to or lower than those in May.

Moderate-resolution Imaging Spectroradiometer Normalized Difference Vegetation Index

(MODIS NDVI) data were analyzed to explore the causes of this discrepancy. Using the Google Earth Engine, we calculated NDVI differences within a 10 km radius of each station based on data from the two weeks preceding each SDS event. Except for the Taklimakan Desert, the NDVI values in major dust source areas were higher in May than in March (Guo et al., 2021). The resulting increase in surface vegetation cover likely offsets the impact of wind speeds on sediment concentration, thereby explaining the lower dust loads observed in May.

11 Wind speed difference (wind speed in May minus wind speed in March) at five observation stations. The y-axis represents the difference in wind speed between the locations on 18–19 March and 14–15 May.

Cross-border SDSs between China and Mongolia occur predominantly in spring. Sparse vegetation cover makes the land surface highly susceptible to wind erosion in arid and semi-arid regions such as the Mongolian Plateau. The intensification of the Mongolian cyclone system, coupled with progressive land surface degradation and the frequent occurrence of large-scale atmospheric phenomena —such as cut-off lows—has led to a rapid increase in the frequency and intensity of SDSs along the China–Mongolia border (Liu et al., 2025). In 2021, a severe cross-border SDS originating in Mongolia affected 12 regions of China, covering an area exceeding 3.8$×$106 km2 (Chen et al., 2023). In recent years, the acceleration and expansion of desertification in Mongolia' s arid and semi-arid regions have provided a substantial source of aeolian material, contributing to the increased frequency of cross-border SDSs under strong wind conditions. These events primarily affected the northern regions of China, including Inner Mongolia Autonomous Region and Hebei Province (Wang et al., 2024).

During the SDS events from 9 to 15 April in 2023, the dominant transport pathways were the northwestern and northward routes. Near-surface wind speed and direction data were extracted from the ERA5 dataset for this period (Fig. 12 [Figure 12: see original paper]). The results indicate that the Gobi Desert experienced predominantly westerly and northwesterly winds, with wind speeds exceeding 4–6 m/s—a critical threshold for dust mobilization identified during non-sandstorm years (Hara et al., 2025). Zones of elevated wind speed closely corresponded to areas of high dust load. The findings of this study are generally consistent with those of previous research (Tetsuya and Naoko, 2005; Su et al., 2025), but our study further reveals the detailed spatial distribution of wind speed gradients during cross-border dust transport. The analysis indicates that wind speeds were highest in the core dust source areas, corresponding to the highest dust load. Wind speeds gradually decreased toward the Tongliao station, resulting in substantial dust deposition in this area and the formation of a dust load peak. Unlike previous studies that primarily focused on large-scale circulation patterns or single-point observations (Asia et al., 2024; Ma et al., 2024), this study elucidates the controlling role of near-surface wind speeds in attenuating dust transport from Mongolia to China, not only providing a more detailed depiction of cross-border dust deposition patterns but also highlighting the critical role of regional wind speed reduction in controlling cross-border dust settling.

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12 Spatial distribution of near-surface wind speed and wind direction from 9 to 15 April, 2023 based on ERA5 data

In this study, the dust emission differences from the mask experiment reflected the contribution of upstream dust sources to the affected areas rather than local dust emissions. Both local emissions and upstream transport jointly influenced the spatial distribution of dust loads. The start and end dates of the mask experiment coincided with the duration of the cross-border SDS event in April, thereby limiting the ability to accurately quantify dust contributions along the transport pathways. Future work will implement high-precision mask experiments to clarify the contribution of emissions along these dust transport pathways.

Based on the findings of this study and the current state of the SDS events in East Asia, China and Mongolia should expand their ground-based observation station networks and jointly establish a collaborative platform to enhance bilateral cooperation in scientific research and operational management, thereby mitigating SDS hazards. Furthermore, given regional geographical characteristics, suitable sand-fixing plant species should be deployed to construct ecological barriers against wind and sand. Public awareness and education regarding SDS prevention along dust transport pathways should be strengthened to reduce the impacts on local populations.

Conclusions

Exploring dust sources and the driving factors of the SDS events is of great scientific significance for the prevention and mitigation of SDSs-related disasters. Using the WRF-Chem model and ERA5 data, this study numerically simulated the dust load and spatial extent of three SDS events that occurred in East Asia in the spring of 2023. Observation data from ground-based stations and satellite remote sensing data were used for comparison and verification, and the causes of dust formation were analyzed using wind speed and MODIS NDVI data. This study revealed the influence of wind speed and surface vegetation cover on dust load across different SDS events, clarifying the controlling role of wind speed distribution in cross-border dust transport and deposition during high-frequency SDS events. Among the three SDS events, the SDS in March 2023 exhibited the greatest intensity and widest spatial impact. The primary dust sources were the Taklimakan Desert in China and the Gobi Desert in Mongolia. In contrast, the SDS event in May showed the lowest intensity, with primary dust sources including the Kumtag Desert in China and the Gobi Desert in

Mongolia. Although wind speed was a key determinant of dust load during individual SDS events, higher wind speeds across different SDS events did not necessarily correspond to high dust loads. Increased surface vegetation cover offset the effect of wind speed

on sediment concentration, indicating that dust emission is jointly influenced by both wind speed and surface vegetation cover. During the SDS event in April, the dominant transport pathways followed northwestern and northward trajectories. Dust originating from Mongolia substantially influenced particle matter concentrations in the central and eastern parts of Inner Mongolia Autonomous Region of China; however, their impact on the northwestern regions of China remains relatively limited.

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

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HUANG Shaopu, WANG Juanle; Visualization: HUANG Shaopu; Writing - original draft preparation: HUANG Shaopu; Writing - review and editing: WANG Juanle, WANG Lixin. All authors approved the manuscript.

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