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Grid-level Source Tracing and Source Variation of Sand and Dust Storm Affecting in Beijing

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Abstract: In recent years, sand and dust storm (SDS) activity in Northern China has shown a notable increasing trend. Fine-scale source apportionment of SDS events affecting Beijing is crucial for understanding the mechanisms behind this increase, facilitating effective desertification control, and improving early warning systems. In this study, we developed a grid-level source apportionment model utilizing GPU-accelerated computing, distinguishing it from previous studies where source tracing was often restricted to broad geographical regions. Results show that Mongolia and Inner Mongolia contribute 47.3% and 39.7% of Beijing's average dust concentration, respectively. During high-concentration events, Mongolia's contribution surges to 71.9%, while the influence of western Inner Mongolia diminishes to 1.5%. These severe events are primarily driven by the specific corridor of the China–Mongolia border, specifically Dornogovi and Omnogovi in Mongolia, as well as the Sonid Left and Siziwang Banners in Inner Mongolia. Furthermore, three transport pathways were identified, with Central Inner Mongolia and Northeastern Hebei serving as critical transit corridors. The recent increase in SDS events affecting Beijing is directly attributed to rising emissions from these key regions, primarily driven by a higher frequency of gale days and exacerbated by fluctuations in vegetation coverage. These findings provide a solid scientific basis for targeted, cross-border desertification control to mitigate the impact of severe SDS on Beijing.

Key words: Sand and Dust Storms, Source apportionment, GPU-accelerated, Transport pathways, Beijing

1. Introduction

Sand and dust storms (SDSs) are a major type of disastrous weather, significantly affecting transportation, the economy, and human health^{1,2}. East Asia is one of the regions with high SDS activity³. Over recent decades, China has implemented large-scale ecological restoration projects in desertification-prone areas to improve the environment and suppress

dust emissions ^{4,5}. Driven by these restoration efforts alongside favorable climate shifts, SDS frequency in China exhibited a consistent decreasing trend from the 1980s through the 2010s ⁶. However, over the past decade, this trajectory has shifted. Influenced by changing land surface conditions and broader climatic variability, SDS events in China have shown a notable increasing trend, with several high-intensity storms attracting considerable scientific and public attention ^{7–10}.

Given that desertification control is both systematic and resource-intensive, effective management remains challenging under volatile climatic conditions ⁴. Source apportionment has therefore emerged as a critical necessity for both science and policy, by pinpointing the exact origins of dust, control measures can be precisely targeted, significantly improving the cost-effectiveness of ecological interventions. Two primary methods are used for SDSs source tracing, including observation-based ^{11,12} and numerical simulation-based approaches ^{13–15}. For instance, geochemical analysis of the historic March 15, 2021, storm indicated that over 70% of dust particles in North China originated from Mongolia ¹². Similarly, numerical sensitivity experiments suggested that Mongolia contributed 56% of the dust during the 2023 spring season (Chen et al., 2024). , while specific source areas in central Inner Mongolia have been found to contribute up to 20% of Beijing's dust load ¹⁴. These findings have informed China's desertification control policies and international cooperation. While these findings have informed national policies and international cooperation, there is an urgent need for more refined source apportionment to provide mega-cities like Beijing with targeted management strategies ¹⁶.

Despite these advancements, existing studies generally quantify contributions at a coarse, regional scale and remain unable to provide fine-grained source information with specific geographic coordinates. Observation-based tracing is limited by the need for comprehensive, high-resolution spatial mapping of geochemical compositions—data that is particularly difficult to obtain for transboundary sources in Mongolia (Li and Zhang, 2025; Zhao et al., 2019). Meanwhile, numerical simulation-based tracing using sensitivity experiments or tagged tracers is computationally prohibitive for grid-level apportionment. Sensitivity experiments require a separate simulation for every individual grid cell (Wagstrom et al., 2008), while tagged tracers demand an overwhelming number of additional variables. Furthermore, fine-scale sensitivity experiments are often plagued by non-linear variations during transport and diffusion, which introduces significant errors into the final apportionment (Kwok et al., 2015).

To overcome the limitations of existing methods in achieving fine-scale source differentiation, this study developed an innovative GPU-accelerated dust source tracing model. Unlike previous studies where tracing was restricted to broad geographical regions, this method enables refined, grid-level source apportionment with high computational efficiency,

providing specific geographic coordinates for the sources affecting Beijing. To validate this approach, we conducted a comparative analysis using long-term SDS observations from Mongolia and northern China. Furthermore, we utilized the source-tracing results to identify the key regions and mechanisms driving the recent increasing trend of SDS events affecting Beijing. This study enhances the granularity of SDS tracing and provides a robust scientific basis for more targeted and effective desertification control efforts.

2. Method and Data

2.1. GPU-Based Refined Dust Source Tracing Scheme

In this study, we reconstructed the dust numerical model using Python and implemented a tagged tracer method for precise source apportionment. The model was deployed on a GPU-accelerated platform, which significantly enhances computational efficiency, particularly when handling the high-dimensional data associated with a large number of grid-level tracer variables.

The dust emission scheme is based on the Shao11 scheme¹⁷, incorporating localized modifications to surface datasets and key physical parameters¹⁸. For the transport process, we employed the Piecewise Parabolic Method (PPM)¹⁹. Atmospheric diffusion was parameterized using K-theory, while dry and wet deposition processes were simulated following established schemes^{20,21}.

The tagged tracer method, a robust technique in atmospheric chemistry model, was adapted here to track dust particles by labeling emissions from individual model grid cells. This method tracks pollutants by labeling emissions from different regions. In the context of a dust numerical model, we can label dust emissions from each model grid cell. During the dust emission simulation, we simultaneously establish n tracer variables c_{ij} , corresponding to the dust concentration field, where c_{ij} represents the concentration of dust particles emitted from source region i in mode j . The total concentration of dust particles in mode j , denoted as c_j , is the sum of contributions from all sources.

The processes of diffusion, deposition, and transport are calculated based on the total dust concentration c_j . The tracer concentrations c_{ij} undergo emission, transport, diffusion, and deposition simultaneously with c_j , maintaining fully synchronized evolution. To avoid errors caused by discrepancies in magnitude and distribution between c_{ij} and c_j , only c_j is used in the calculations of diffusion, transport, and deposition. The changes in c_{ij} during these physical processes are updated based on the ratio of c_{ij} to c_j from the previous time step (Equation 1). To distinguish the effects of different physical processes, each of the four processes is calculated separately. Subsequently, the contribution of dust source region i to any target area can be derived from the tracer concentration c_{ij} .

$$\Delta c_{ij} = \Delta c_j \frac{c_{ij}}{c_j} \quad (1)$$

where c_j denotes the concentration of dust particles in mode j at a grid cell, c_{ij} denotes the concentration of mode j originating from source region i , Δc_j is the concentration change of mode j due to emission, transport, diffusion, or deposition; and Δc_{ij} is the corresponding concentration change for the fraction originating from source region i .

2.2. Model Description

The model domain covers East Asia, encompassing all major dust source regions in the area with a spatial resolution of 0.25° . The grid-level source tracing scheme was implemented across Mongolia and the Chinese provinces of Inner Mongolia, Gansu, Ningxia, and Shaanxi. This granular approach resulted in a total of 4,423 individual tracer tags, allowing for unprecedented spatial precision in source identification (Fig.1).

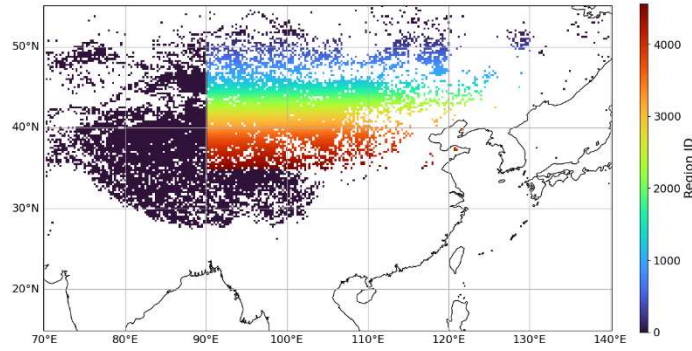


Fig. 1. Model simulation domain and grid-based dust source tagging. Shaded grid cells indicate dust source regions, with different colors representing different tracer tags. Source regions in Xinjiang, Tibet, and other non-target areas are uniformly labeled as tag 1, whereas the remaining source grid cells are labeled from 2 to 4,424 according to their geographic locations.

Surface characteristics were dynamically updated using fractional vegetation cover data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS)²². The numerical simulations were directly driven by ERA5 reanalysis data, providing high-fidelity meteorological forcing for dust emission and transport processes. PM_{10} concentration data were obtained from the China National Environmental Monitoring Centre. SDS weather phenomenon observation data were obtained from the China Meteorological Administration. These datasets were used for model validation and analysis of SDS variations.

2.3. SDS overview and model Validation

A total of 48 sand and dust storm (SDS) events impacting central and eastern China between

2016 and 2025 were comprehensively simulated. Among these episodes, the recorded intensity in Beijing varied significantly; the highest peak PM₁₀ concentration reached 9,000 µg/m³ (March 15, 2023), while the lowest recorded peak was 227 µg/m³ (October 21, 2020). Notably, twelve of these events exceeded a PM₁₀ threshold of 1,000 µg/m³, occurring predominantly during the active dust seasons of 2021 and 2023 (Table S1).

To assess the model's performance, numerical simulations were validated against ground-based PM₁₀ observations from Beijing and several key cities situated near major dust source regions (Table S1, Fig. S1). The comparison demonstrated that the model effectively reproduces the temporal evolution and magnitude of dust concentration shifts. For the entire suite of simulated events in Beijing, the model achieved a correlation coefficient (R) of 0.74, with specific high-intensity events exceeding 0.90. Regarding the inter-event peak concentrations, the correlation coefficient reached 0.87, highlighting the model's reliability in capturing event severity.

The model also exhibited robust performance for cities in closer proximity to the source regions. Correlation coefficients for all events in Hohhot, Yinchuan, and Taiyuan were 0.64, 0.73, and 0.63, respectively. Furthermore, the correlation coefficients for peak concentrations in these cities were 0.58, 0.94, and 0.81, respectively. Collectively, these validation results indicate that the developed model possesses a strong capability to simulate both the intensity variations and the spatial distribution characteristics of major SDS events across East Asia.

3. Results

3.1. Refined Source Tracing of Beijing SDS Events

The high-resolution source tracing results for the simulated SDS events are illustrated in Fig. 2. Over the cumulative study period, Mongolia and Inner Mongolia were identified as the primary contributors, accounting for 47.3% and 39.7% of Beijing's total dust concentration, respectively. The predominant source regions (see Figs S3 and S4 for administrative divisions) include the Dornogovi and Omnogovi provinces of Mongolia, as well as Alxa and Ulanqab cities in Inner Mongolia. Sand source hotspots are concentrated in Xatanbulag (5.6%) in Dornogovi Province, followed by Alxa Right Banner (4.3%) in Inner Mongolia, and then Ulaanbadrax (3.4%), Saixandulaan (3.2%) in Dornogovi, Xanbogd (3.2%) in Omnogovi, as well as Alxa Left Banner (3.2%), Ejina Banner (3.1%), and Sonid Right Banner (2.9%) in Inner Mongolia.

The source dynamics shift notably during the peak intensity of these events. At the timing of peak PM₁₀ concentration of the SDS events, the contribution from Mongolia increased to 62.1%, whereas that from Inner Mongolia decreased to 33.9% relative to average conditions (Fig. 3). During these peak periods, the highest contributions originate from Ulaanbadrax (7.8%) and Xatanbulag (7.5%) in Dornogovi, followed by Xanbogd (4.4%) in Omnogovi, and

Mandax (4.1%) and Saixandulaan (3.7%) in Dornogovi. While these Mongolian sources exhibit enhanced influence during peak times, contributions from Inner Mongolian banners show a relative decline. Alxa Right Banner drops to 3.3%, Alxa Left Banner to 2.5%, Ejina Banner to 2.4%, and Sonid Right Banner to 2.7%.

For high-concentration SDS events (defined as peak PM_{10} concentrations $> 1000 \mu\text{g}/\text{m}^3$), the dominance of Mongolian sources is further amplified, with their total contribution reaching 71.9% (Fig. 4). During these severe episodes, source regions are highly concentrated in Dornogovi and Omnogovi provinces and adjacent counties in central Inner Mongolia. Specifically, contributions from Dornogovi hotspots surge significantly, Ulaanbadrax (11.1%), Xatanbulag (6.4%), Mandax (5.6%), and Saixandulaan (5.2%). Other major contributors include Xanbogd (4.2%) in Omnogovi, as well as Siziwang Banner (2.9%) and Sonid Banner (2.8%) in Inner Mongolia. In stark contrast, the relative contribution from western Inner Mongolia, traditionally major sources like the Alxa Right and Left Banners, diminishes significantly to approximately 1.5% each during these extreme events.

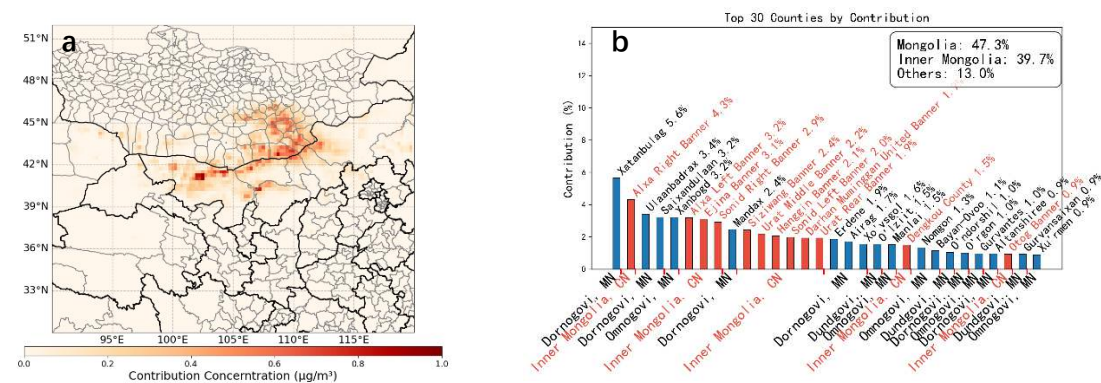
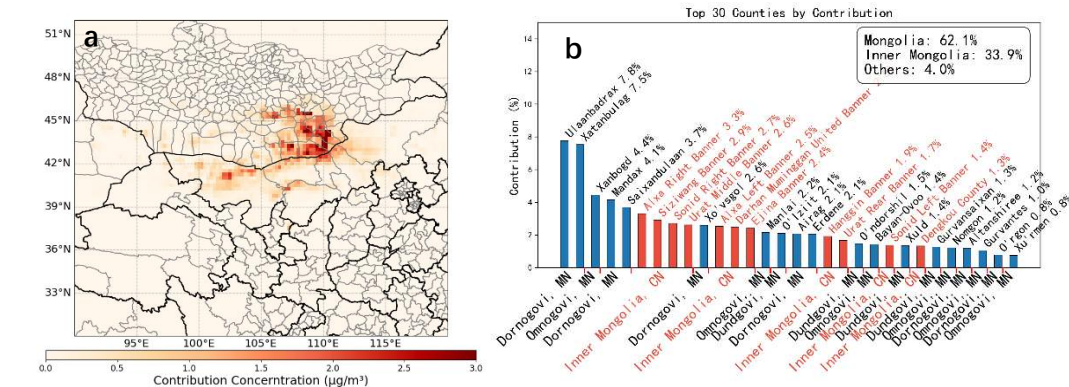


Fig. 2. Average source apportionment of 48 SDS events affecting Beijing (averaged over all time steps influenced by dust events). a, contribution of each grid cell to PM_{10} concentration in Beijing. b contribution proportion of each county or district to PM_{10} concentration in Beijing. Blue bars represent regions in Mongolia, and red bars represent regions in Inner Mongolia.



This geographic synchronization suggests that the border zone possesses unique surface conditions or wind-field alignments that facilitate massive, high-density dust mobilization during specific synoptic conditions. This geographic concentration suggests a dual-track strategy for dust mitigation. To mitigate severe SDS events, ecological restoration and monitoring efforts must be prioritized in the immediate border regions between China and Mongolia. To reduce the overall frequency of all dust events affecting the capital, a broader regional approach remains necessary, encompassing traditional source areas such as the Alxa Plateau.

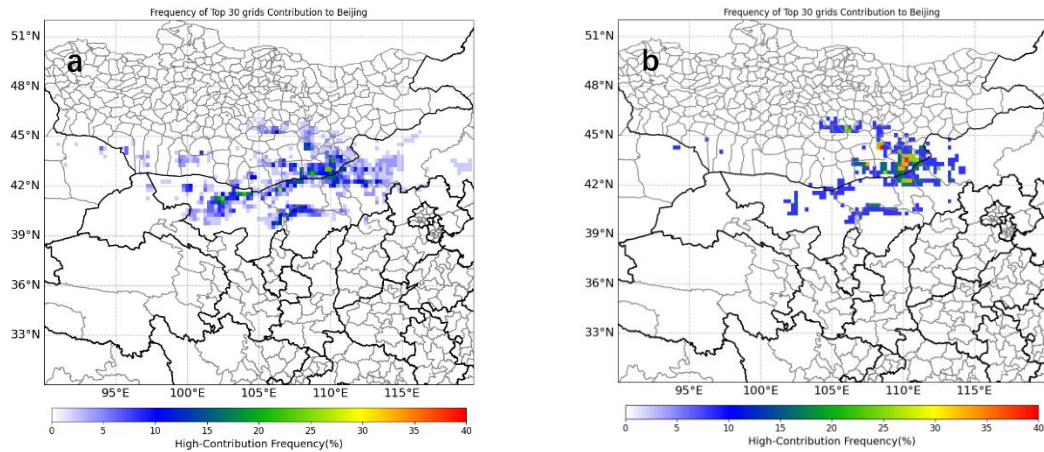


Fig. 5. Frequency distribution of the top 3% (33 grid points) contributors to peak dust concentration in Beijing. The top 3% of grid points account for 25–50% of the total dust concentration. Shading indicates the frequency with which each grid point ranks within the top 3% across all identified events, a for all events, b for high-concentration events.

3.2. Transport Pathways of Dust Weather Affecting Beijing

By statistically analyzing the trajectories of the top 3% contributing grid points (33 cells) and the evolution of dust plumes prior to their arrival in Beijing, the primary transport pathways of SDS events affecting Beijing were characterized.

Four typical high-concentration events originating primarily from Mongolia were selected for detailed analysis (Fig. 6). The Dornogovi provinces, particularly the Xatanbulag and Ulaanbadrax regions, were identified as the primary emission hotspots. From these sources, dust was transported to Beijing via a central corridor spanning central Inner Mongolia and northwestern Hebei. Notably, the SDS event on March 15, 2021, the most severe in the study period, was driven by this pathway. High-resolution source apportionment revealed that Mongolia contributed approximately 90% of the dust concentration during the event's peak, a finding consistent with previous multi-model and observational studies^{7,15}. For the event on May 6, 2021, the key emission source was localized in Nomgon, Omnogovi. The transport pathway for this event exhibited a more westerly-to-southerly trajectory, extending from the

source through central Inner Mongolia, northern Shanxi, and northwestern Hebei before impacting Beijing. These results underscore that while transport pathways are influenced by synoptic wind fields, they consistently converge at critical transit corridors in central Inner Mongolia, northern Shanxi, and northwestern Hebei, which serve as the final gateways for dust entering Beijing.

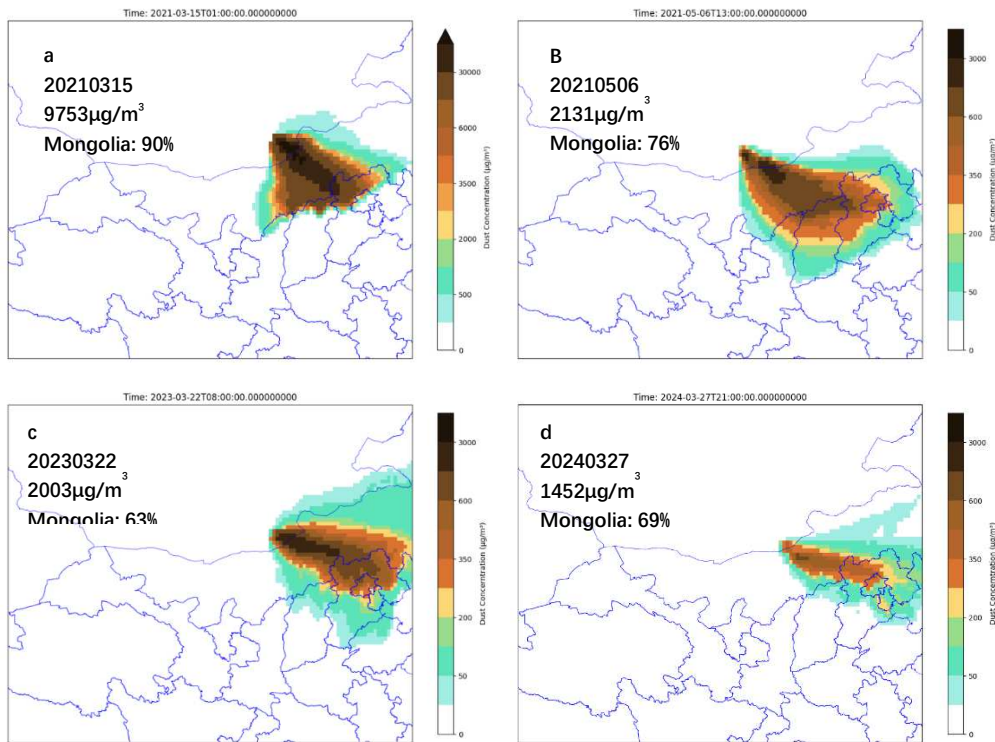


Fig. 6. Transport pathways from major dust source areas to Beijing during typical SDS events dominated by Mongolia-origin emissions. The shading indicates the concentration distribution of dust emitted from key source areas after emission and during transport until arrival in Beijing.

Three high-concentration SDS events primarily originating from Inner Mongolia were selected to characterize their specific transport trajectories (Fig. 7). For the event on May 4, 2017, the Ulan Buh Desert and the Badain Jaran Desert in Alxa Left Banner were identified as the primary source areas. The resulting dust plume was transported to Beijing via central Inner Mongolia and northwestern Hebei, following a pathway predominantly situated north of the Yin Mountains. The event on December 12, 2022, was characterized by a more southerly route. The dust primarily originated from the Hobq Desert and its surrounding regions, traversing the southern slopes of the Yin Mountains and northern Shanxi before reaching Beijing. This highlights the role of the Yin Mountains as a significant topographic feature

influencing the branching of dust transport in this region. For the event on April 10, 2023, two distinct source areas were identified: the Badain Jaran Desert in Alxa Right Banner and Siziwang Banner. The transport pathway for this event largely mirrored the northern route observed during the May 2017 event, moving through central Inner Mongolia. These cases demonstrate that even for domestic sources, transport pathways vary significantly depending on the point of origin relative to the Yin Mountains, though they ultimately converge on the critical northwestern gateways to Beijing.

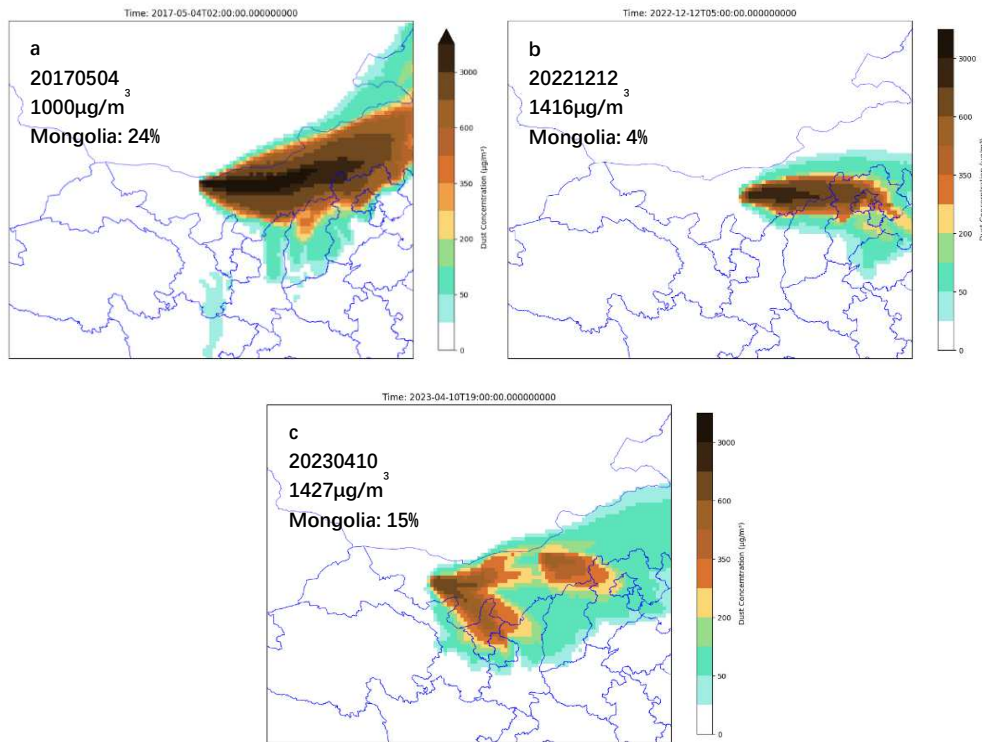


Fig. 7. Transport pathways from major dust source areas to Beijing during typical SDS events dominated by Inner Mongolia-origin emissions. The shading indicates the concentration distribution of dust emitted from key source areas after emission and during transport until arrival in Beijing.

To further validate the model's performance in simulating dust transport pathways, we calculated the correlation coefficients between the peak dust extinction values in Beijing and those at surrounding observation sites across the 48 simulated SDS events.

The results (Fig. 8) indicate that, in addition to sites in the immediate vicinity (e.g., Zhangjiakou) and downwind of Beijing, several sites in central Inner Mongolia (e.g., Ulanqab and Baotou) and northern Shanxi (e.g., Datong) exhibited notably high correlation coefficients ($R > 0.6$). Crucially, the correlation coefficients at these transit sites were higher than those observed at the actual dust source regions in western Inner Mongolia. This

statistical disparity underscores that these specific areas serve as critical transport corridors through which dust must pass before reaching Beijing. Based on the spatial distribution of these high-correlation sites, SDS events affecting Beijing typically propagate toward Tianjin, eastern Hebei, and northern Shandong after passing over the capital. In contrast, the transport pathways directed toward western Hebei and Henan exhibited distinct trajectories from those targeting Beijing, a divergence that remains consistent with established findings in regional dust dynamics research^{23–25}.

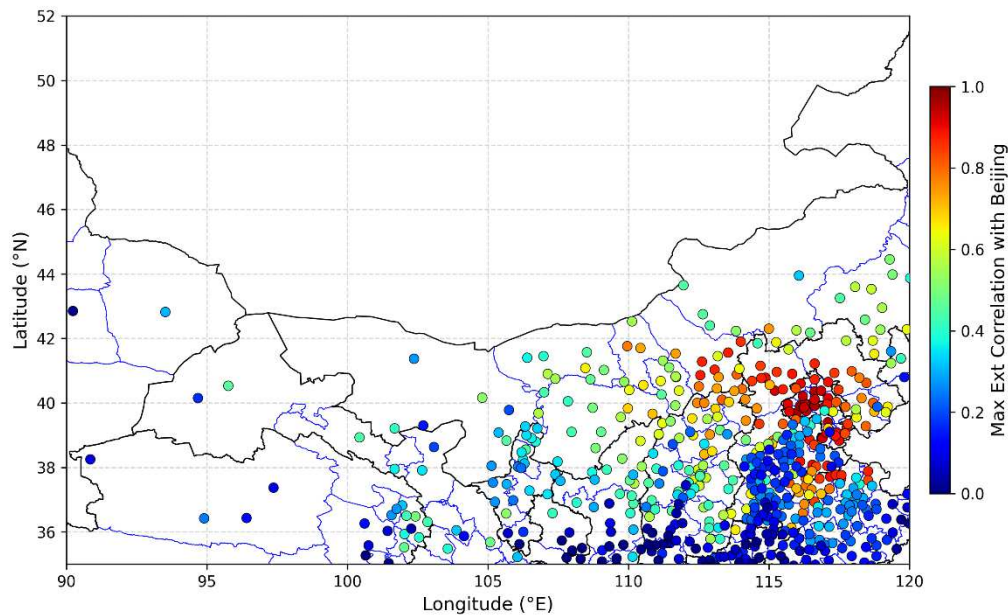


Fig. 8. Spatial distribution of correlation coefficients between the minimum dust extinction coefficient in Beijing and those at other sites during the 48 dust events.

Based on the multi-event analysis, three major transport pathways affecting Beijing were identified. Dust originating from Dornogovi and Omnogovi in Mongolia is transported southeastward through central Inner Mongolia and northwestern Hebei. The Northern Inner Mongolian Pathway, Dust from sources in western Inner Mongolia (Alxa) moves eastward, following a trajectory situated north of the Yin Mountains before converging on the northwestern Hebei corridor. The Southern Inner Mongolian Pathway, Dust from southern sources, such as the Hobq Desert, is transported through the region south of the Yin Mountains, traversing northern Shanxi and northwestern Hebei before reaching Beijing.

Notably, Ulanqab in central Inner Mongolia and northwestern Hebei are common to all three identified pathways. These regions act as a "geographic bottleneck" for dust plumes entering the North China Plain. Observational evidence further reinforces this model-derived finding, the maximum dust extinction coefficients at monitoring stations in these two regions exhibit a strong correlation with those in Beijing. This spatial synchronization between model outputs and high-fidelity observational data provides robust evidence validating the accuracy of the

grid-level source apportionment and the stability of these transport corridors.

3.3. Temporal Trends and Evolution of Dust Source Contributions to Beijing

In recent years, the frequency of dust weather events affecting Beijing has shown an overall increasing trend (Fig. 9,10). The average annual number of events was 3.8 from 2016 to 2020, increasing to 5.6 from 2021 to 2025. Concurrently, PM₁₀ concentrations have also exhibited an upward trend. Only two events exceeded 1000 µg/m³ between 2016 and 2020, whereas ten such events occurred between 2021 and 2025, with four events in 2021 and three in 2023, respectively. In terms of source contributions at peak concentration times, high-concentration dust events were predominantly dominated by Mongolia-origin sources. Among these, nine events were primarily contributed by Mongolia (accounting for more than 60%), while only three events were dominated by China-origin sources (accounting for more than 50%).

Dust events dominated by western Inner Mongolia have remained relatively stable over the past decade, with approximately 1–3 events per year and no significant increasing trend (Fig. 10). In contrast, events dominated by the specific corridor of the China–Mongolia border (Dornogovi, Omnogovi and Dundgovi in Mongolia and Ulanqab, Xilingol in central Inner Mongolia) have shown a marked increasing trend. Specifically, such events occurred 0–2 times per year from 2017 to 2020, and increased to 5, 6, and 4 times in 2021, 2023, and 2024, respectively.

Years with more than five dust events affecting Beijing include 2016 (6 events), 2018 (6 events), 2021 (6 events), 2023 (9 events), and 2024 (5 events). During these periods, the majority of episodes were primarily attributed to the specific corridor of the China–Mongolia border (defined by a contribution threshold >50%). This corridor, comprising the Omnogovi and Dornogovi provinces in Mongolia and the Darhan Muminggan United Banner, Sonid Right Banner, and Siziwang Banner in Inner Mongolia, accounted for 4, 2, 5, 7, and 4 events in each respective year (Fig. 10). In other years, deserts in western Inner Mongolia remained the dominant sources.

The changes in dust source contributions to Beijing over the past decade indicate that high-concentration dust events are predominantly contributed by China–Mongolia border, and years with a high frequency of dust events are also characterized by dominant contributions from the southeastern Gobi Desert of Mongolia and the central Inner Mongolia Gobi Desert region.

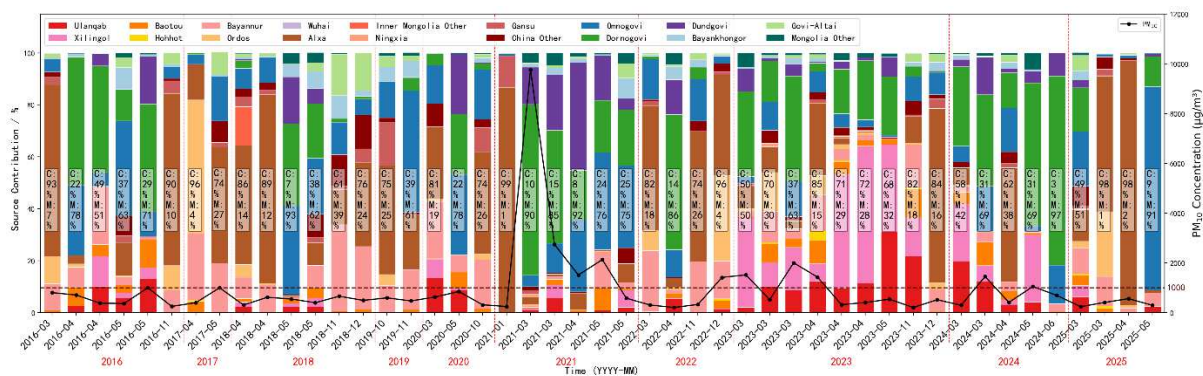


Fig. 9. Contribution proportions of different source regions to Beijing during the 48 dust events (bar chart; colors represent different regions, with warm colors for China and cold colors for Mongolia) and the corresponding maximum PM₁₀ concentration (black solid line; the dark red dashed line indicates the reference line of 1000 µg/m³).

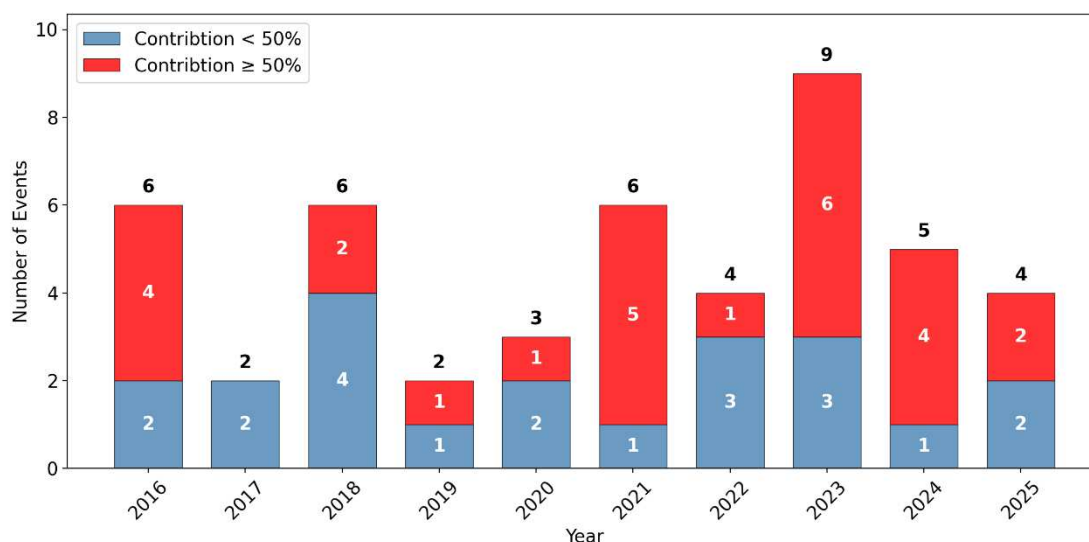


Fig. 10. Annual frequency of SDS events in Beijing from 2016 to 2025. Red bars denote events where the specific corridor of the China–Mongolia border (comprising Omnogovi, Dornogovi, and the adjacent Darhan Muminggan, Sonid Right, and Siziwang Banners) contributed more than 50% to the total dust concentration.

Analysis of the interannual variability of dust event days reveals a high degree of synchronization between Beijing and its primary source regions (Fig. 11). Specifically, the correlation coefficients (R) for monitoring stations across central Inner Mongolia and southeastern Mongolia both exceeded 0.7. This strong statistical correspondence further demonstrates that the year-to-year fluctuations in SDS activity affecting the capital are fundamentally driven by dust emission variations within these specific sectors. These findings reinforce the model-based conclusion that the southeastern Gobi and central Inner Mongolian corridors act as the principal determinants of Beijing's long-term dust trends.

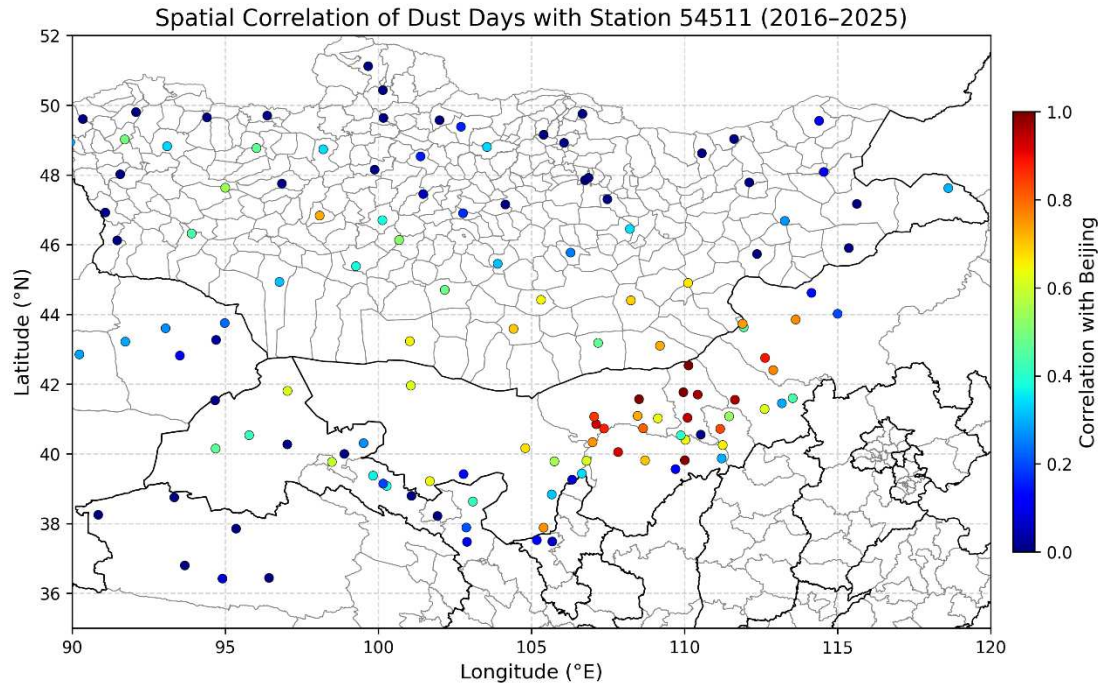


Fig. 11. Spatial distribution of correlation coefficients between the annual number of dust weather days in Beijing and that at major stations in dust source regions from 2016 to 2025.

3.4. Drivers of SDS Trends

To investigate the primary causes of the recent shifts in SDS frequency, we analyzed the interannual variations in vegetation coverage (Fig. 12) and the frequency of spring gale days (Fig. 13) within the identified specific corridor of the China–Mongolia border.

The overall vegetation coverage in these critical corridor is inherently low, particularly in the Xanbogd and Mandax regions of Mongolia, where fractional cover remained consistently below 0.1. Between 2015 and 2024, vegetation levels from 2016 to 2019 were generally slightly higher than those recorded during the 2020–2023 period. Notably, the years 2015, 2020, and 2022, which immediately preceded the years of highest SDS frequency, recorded the lowest vegetation levels of the decade. While this suggests a correlation between reduced land cover and subsequent SDS activity, the total magnitude of vegetation change was relatively modest, typically ranging between 3% and 5%. Among the studied regions, Siziwang Banner exhibited the most pronounced variation, with coverage declining from a peak of 0.23 in 2019 to a minimum of 0.18 in 2023 (a 5% decrease). In the Mongolian source regions, the minimum coverage occurred in 2015, directly preceding the active 2016 dust season. While coverage in 2020 and 2022 was slightly higher than the 2015 minimum, it remained significantly lower than in other years, suggesting that subtle vegetation fluctuations have contributed to a more susceptible land surface for dust emission.

In contrast to the relatively stable vegetation patterns, the frequency of spring gale days in the

key source regions exhibited significant interannual fluctuations. Since 2021, the annual number of gale days has consistently exceeded the levels observed during the 2016–2020 period. In the Siziwang and Sonid Right Banners, the average number of gale days increased sharply from 16.8 to 26.5. Similarly, in the Dornogovi and Omnogovi provinces, the average rose from 14.3 to 17.1. During the peak years of 2021 and 2023, several stations in these key regions recorded decadal highs in gale frequency, with positive anomalies of 7–9 days.

This marked escalation in high-wind events appears to be the primary driver of the recent resurgence in SDS events affecting Beijing. This finding is consistent with recent research by ⁸, which identified strengthened wind speeds as a critical factor in the recent increase of dust weather across China. Our results reinforce the conclusion that while land surface conditions provide the "material basis" for dust, the recent surge in frequency and intensity is fundamentally dictated by intensified meteorological forcing.

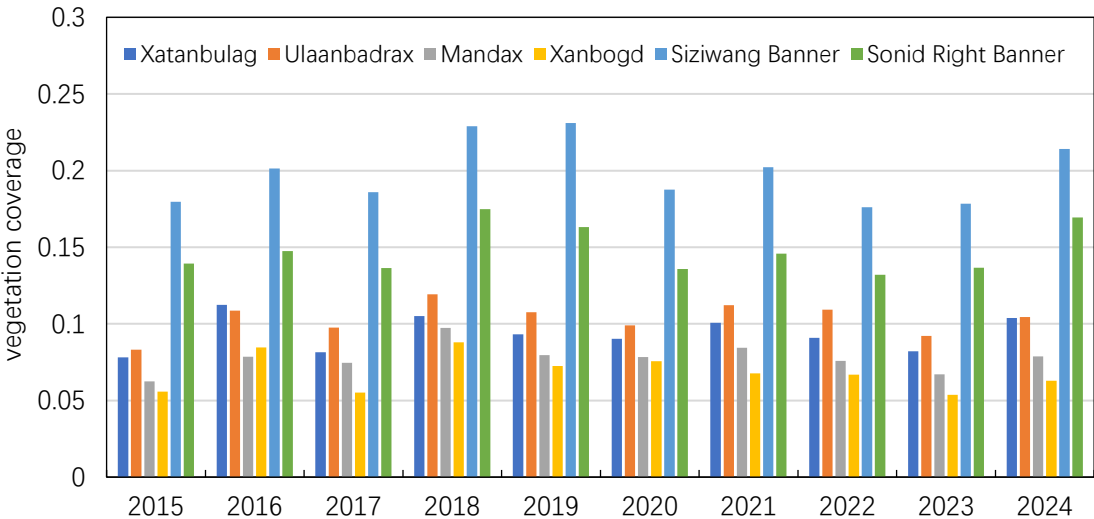


Fig. 12. Interannual variation of annual maximum vegetation coverage from 2015 to 2024 in the Dornogovi, Omnogovi, and Siziwang Banner and Sonid Right Banner in Inner Mongolia.

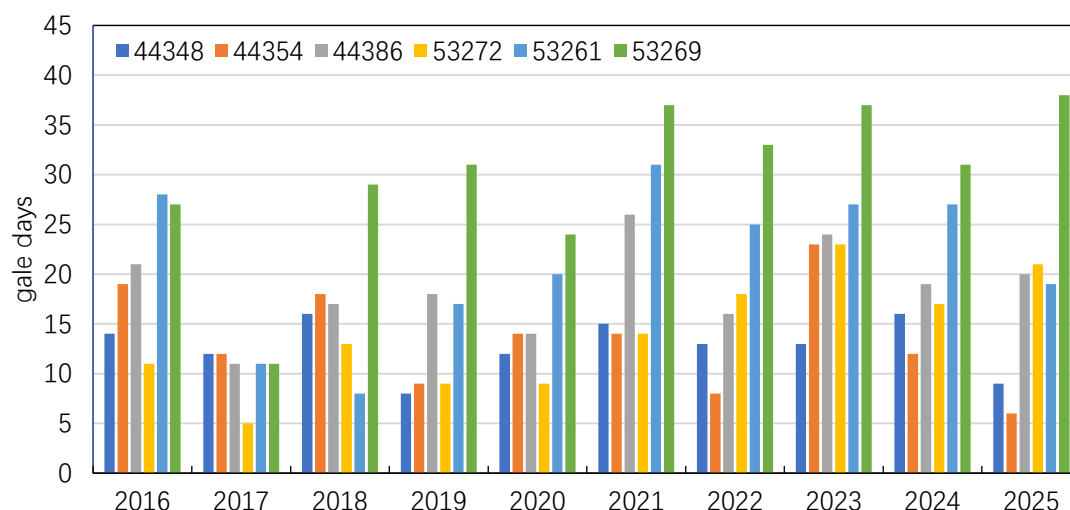


Fig. 13. Interannual variation of spring gale days from 2016 to 2025 at meteorological stations in the Dornogovi (44354, 44348, 44356), Siziwang Banner (53261, 53269) and Sonid Right Banner (53272) in Inner Mongolia (defined as the number of days with wind speed exceeding 12 m/s in 3-hourly observational data).

4. Discussion and conclusion

To further elucidate the origins of Sand and Dust Storms (SDS) affecting Beijing, this study developed a high-resolution, grid-level dust source apportionment model utilizing GPU-accelerated computing. The model was applied to systematically simulate and track the sources of dust events impacting Beijing over the past decade.

Our findings indicate that while Mongolia (47.3%) and Inner Mongolia (39.7%) are the primary contributors under average conditions, Mongolia's influence surges significantly to 71.9% during high-intensity events, driven predominantly by emission hotspots in the Dornogovi and Omnogovi provinces. In contrast, the relative contribution from western Inner Mongolian sources, such as the Alxa Banners, diminishes to approximately 1.5% during these severe episodes. This spatial shift reveals that the source regions driving extreme SDS activity in Beijing are highly localized within the specific corridor of the China–Mongolia border, comprising Omnogovi, Dornogovi, and the adjacent Darhan Muminggan, Sonid Right, and Siziwang Banners.

The characterization of transport dynamics identifies three primary pathways, which consistently converge at the geographic "bottlenecks" of Central Inner Mongolia and Northeastern Hebei before impacting Beijing. The recent escalation in Beijing's SDS frequency is fundamentally attributable to intensified activity within the specific corridor of the China–Mongolia border, where a marked increase in spring gale days has emerged as the most critical meteorological driver. Furthermore, interannual fluctuations in vegetation coverage have exacerbated land surface susceptibility, providing the necessary conditions for

massive dust mobilization during high-wind events.

These findings suggest a dual-track strategy for dust mitigation. To effectively mitigate severe SDS events, ecological restoration and monitoring efforts must be prioritized in the immediate border regions between China and Mongolia, where high-density mobilization is most frequent. However, to reduce the overall frequency of all dust events affecting Beijing, a broader regional approach remains necessary, encompassing traditional source areas such as the Alxa Plateau. Collectively, this study clarifies the mechanisms behind recent SDS surges and provides a targeted scientific foundation for coordinated, cross-border environmental management to mitigate the occurrence and frequency of SDS events.

Date availability

PM₁₀ concentration data were obtained from the China National Environmental Monitoring Centre, <https://air.cnemc.cn:18007/>. Meteorological observation data were obtained from China Meteorological Administration, <https://data.cma.cn>. Vegetation cover data derived from <https://search.earthdata.nasa.gov>. The datasets generated and analyzed during the current study are also available from the corresponding author on reasonable request.

Code availability

The underlying code for this study is available in GitHub and can be accessed via this link <https://github.com/jwang19901205-cyber/tracing-model/>.

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Author contributions

Jikang Wang: Conceptualization, Data curation, Investigation, Methodology, Software, Validation, Visualization, Writing-original draft. Cong Hua, Yong Cao: Investigation, Supervision. Yun Cao: Vegetation cover data analysis.

Competing interests

The authors declare no competing interests.

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