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Sandstorms in Northern China: Seasonal Dynamics of the Environmental Trajectories

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Abstract

Sandstorms significantly impact the economic and ecological landscape of northern China, particularly in arid and semi-arid regions. These events arise from the interplay of climate factors, soil conditions, droughts, desertification, and the sparse distribution of vegetation on sandy fine-grained soils. To effectively understand the dynamics of sandstorms, it is essential to conduct an integrated analysis that encompasses diverse data sources, including statistical climate observations and cartographic information. This paper aims to evaluate the characteristics of sandstorms in China through a comprehensive analysis, focusing on the frequency and intensity of these events in relation to seasonal variations and geographic trajectories. Key data utilized in this study includes climate, soil, and precipitation maps, as well as relevant physical parameters and topographical features. The findings of this research highlight the principal components associated with the occurrence of sandstorms, thereby contributing valuable insights into their management and mitigation strategies: The occurrence of sandstorms is influenced by several key factors: 1) Temperature, which stimulates cold-heat convection and enhances wind energy, 2) Wind power, particularly when it exceeds force 4 on the Beaufort scale, enabling it to raise and transport fine sediments, 3) Soil type, specifically sandy and silt-sized loess particles that can be carried by the wind over vast distances, 4) Geomorphic landforms that modify wind patterns through funneling effects, and 5) Vegetation coverage, which is sparse and unable to provide adequate protection against sandstorms. An analysis of these factors includes variables such as wind speed and power, soil distribution, annual precipitation, mean wind power density, and overall energy capacity. Spatial analysis highlights regions most affected by sandstorms, notably the Tarim Basin (including the Taklimakan Desert), western Inner Mongolia, Ningxia, central Gansu, and parts of Shaanxi (specifically Yan'an, Yulin, and Baoji).

Keywords

Desert ecosystem; Cold environment; China; Geospatial analysis; Land management; Climate change

Kuzey Çin'deki Kum Fırtınaları: Çevresel Yörüngelerin Mevsimsel Dinamikleri

Özet

Kuzey Çin'in kurak ve yarı kurak bölgelerindeki kum fırtınaları, büyük ekonomik kayıplara ve ciddi ekolojik felaketlere neden olmaktadır. Kum fırtınaları, iklim ve toprak yapısının (kuraklık, çölleşme ve kumlu ince taneli topraklarda seyrek bitki örtüsünün dağılımı) kümülatif etkilerinden kaynaklanmaktadır. Kum fırtınalarının yörüngelerini anlamak, istatistiksel iklim gözlemleri ve kartografik verilere dayalı entegre çok kaynaklı bir analiz gerektirir. Bu makale, Çin'deki kum fırtınalarının değerlendirilmesi amacıyla bu tür bir analiz gerçekleştirmektedir. Özellikle, olayların sıklığı ve yoğunluğunun mevsimsel değişimleri ve coğrafi yollarıyla ilgili karşılaştırmalı analizine odaklanılmıştır. Veriler, iklim, toprak ve yağış haritaları, fiziksel parametreler ve topografyayı içermektedir. Sonuçlar, kum fırtınalarıyla ilişkili temel bileşenleri ortaya koymuştur: 1) Soğuk-sıcak konveksiyonunu ve rüzgar enerjisini hızlandıran sıcaklık. 2) İnce tortuları kaldıran ve taşıyan rüzgar gücü (>4 Beaufort ölçeği). 3) Toprak tipi: Rüzgar tarafından kaldırılıp uzun mesafelere (binlerce kilometre) taşınabilen kumlu ve silt boyutunda lös parçacıkları. 4) Rüzgar hunisini şekillendiren jeomorfolojik yer şekilleri. 5) Kum fırtınalarına karşı koruma sağlayamayan seyrek bitki örtüsü. Kum fırtınası oluşumuna katkıda bulunan faktörler analiz edildi ve rüzgar hızı ve gücü, toprak dağılımı, yıllık yağış, ortalama rüzgar gücü yoğunluğu ve enerji kapasitesi dahil edildi. Mekansal analiz, kum fırtınalarından en çok etkilenen alanları ortaya çıkardı: Tarim Havzası (Taklimakan Çölü), ardından Batı İç Moğolistan, Ningxia, Orta Gansu ve Shaanxi'nin bazı bölgeleri (Yan'an, Yulin, Baoji).

Anahtar Kelimeler

Çöl ekosistemi; Soğuk ortam; Çin; Jeo-uzamsal analiz; Arazi yönetimi; İklim değişikliği

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1. Introduction

Sandstorms are increasingly recognized as a global hazard, posing significant risks to public health, the economy, and the environment. Their frequency, repeatability, and intensity are critical factors for effective forecasting, monitoring, and prognosis, particularly in arid and semi-arid regions around the world. A sandstorm is a meteorological phenomenon linked to desertification and land degradation in high latitudes in dry and semi-arid cold regions. Recent studies have focused on improving the ability to predict sandstorm occurrences and mitigate their potential adverse effects (Goudie & Middleton, 1992; McKenna Neuman, 1993; Jacobs, 2004; Bullard et al., 2016). By integrating satellite-based observations with ground-level surface data, researchers have been able to provide a comprehensive spatio-temporal analysis of the 2021 mega dust storm that impacted northern China (Filonchyk et al., 2022).

Sandstorms have a serious influence on the environment and landscapes of China. (He et al., 2015; Li et al., 2025; Zhang et al., 2025). The total area of land affected by sandstorms in China is related to the arid and semiarid areas. The unprecedented scale of recent aeolian events is exemplified by the 2021 super sandstorm, which exerted profound direct and indirect radiative forcing across East Asia (Chen et al., 2025). Recent desertification in China reports a total of 3.32 million km^2 including arid (1.43 M km^2), semi-arid (1.14 M km^2 or sub-humid arid (0.75 M km^2) lands. In total, territory affected by desertification in China covers 34.6% of its territory (G. Wang et al., 2012) which encompass the area from NW to NE above 35° N, covering a total area over 1.6 M km^2 (Wang et al., 2008).

Sandstorms have serious environmental repercussions posing a threat to livelihoods and agriculture (Du et al., 2021), environment (Shi et al., 2023), industry and transport (Xu et al., 2002; Bai et al., 2022), affecting water quality, and causing economic losses (Shi et al., 2004; Lin et al., 2012; Cheng et al., 2013, 2018; Dong, 1997) leading to soil erosion (Goudie, 1983). As detailed by Gui et al. (2022), the extreme aeolian activity in early 2021 surpassed decadal records for particulate intensity, underscoring the ongoing vulnerability of the region to abrupt shifts in atmospheric circulation. The majority of the deserted land is found in the northern regions of China: north-west (NW), north (N), and north-east (NE), although the area of deserts varies along with regional climatic setting (Liu et al., 2022). Recent climate warming caused rise of temperature which increased the periods of droughts. As a result, the desertification in China has increased with reported expansion of deserts from 1560 km^2 in the 1970s to 3,436 km^2 in the 1990s (Lu & Wang, 2020). Sandstorms and desertification have a cumulative effect that leads to degradation of environment through soil depletion and altered land cover types which impacts population (N. Wang et al., 2023).

The major reason for sandstorms in China includes global climate change, lower precipitation, warmer temperature, accelerated cold-heat convection and wind energy during spring (Luo et al., 2025; Li et al., 2021). Such phenomena occur more in the northern regions of the country (Chen et al., 2003; Xue, 1996). As documented by Zhang et al. (2024), decades of meteorological data confirm a significant correlation between high-latitude atmospheric pressure patterns and the periodic surges in dust transport across the Chinese interior. Liu et al. (2004) report strong positive correlation between dust storm frequency and the upwind wind velocity in the NE China and China-Mongolia border to the Taklimakan Desert. While sandstorms are traditionally associated with spring, Zhu et al. (2023) highlight that summer dust events in the Gobi are modulated by teleconnections that dictate the strength of the East Asian summer monsoon. Thus, the transition between El Niño and La Niña conditions creates distinct pressure anomalies that either suppress or enhance the lifting of mineral dust from the Gobi region in China during the summer months.

The anthropogenic activities contributes to the desertification in China. For instance, land cover types in the N and NW regions of the country experienced changes in recent decades (Cai et al., 2024). The main reasons are related to the land disturbances (urbanization and agricultural activities), replacement of the natural types of vegetation and succession of forests (Yang et al., 2024; Ma et al., 2026; Lemenkova, 2025b). The cumulative effect from human-induced and climate-related processes in soil, including soil depletion, salinization and deterioration of its physical structure and texture, which caused desertification and made soil upper horizon more prone to sandstorms (Xu et al., 2019; Xu & Ding, 2018). The implementation of targeted engineering and biological measures has proven effective in suppressing dust emission and wind-driven sediment transport in Northern China's sensitive sandy regions (He et al., 2025).

2. Study area

2.1. Ecosystem vulnerability and the geographic drivers of desertification

China has unique ecosystem structures with habitats susceptible to the effects of climate change, Figure 1.The Gobi and Tarim Basin deserts are the two largest dry environments in NW China. The terrain consists of high-altitude alpine zones in the nearby mountains and extensive grasslands of steppes. The drainage basin of snowmelt rivers (Heihe, Tarim), which preserve local landscapes, such as poplar woods, supports the hydrology of the remote oasis wetlands. Both human activity (heavy water usage, overgrazing, and intensive land use practices) and natural processes (climate change) pose a threat to arid inland ecosystems. Sandstorms are more likely to occur as a result of desertification brought on by the combined effects of these factors.

The Upper Huang Basin (Yellow River) and Gansu corridor are especially susceptible to desertification, which severely impacts agricultural activities reliant on the fertile alluvial deposits. This phenomenon leads to the occurrence of sandstorms that adversely affect sustainable agriculture in these areas. An example highlighted is the dust-sand storms over the Tarim desert in northwest China, depicted in satellite images taken during the spring and winter periods.

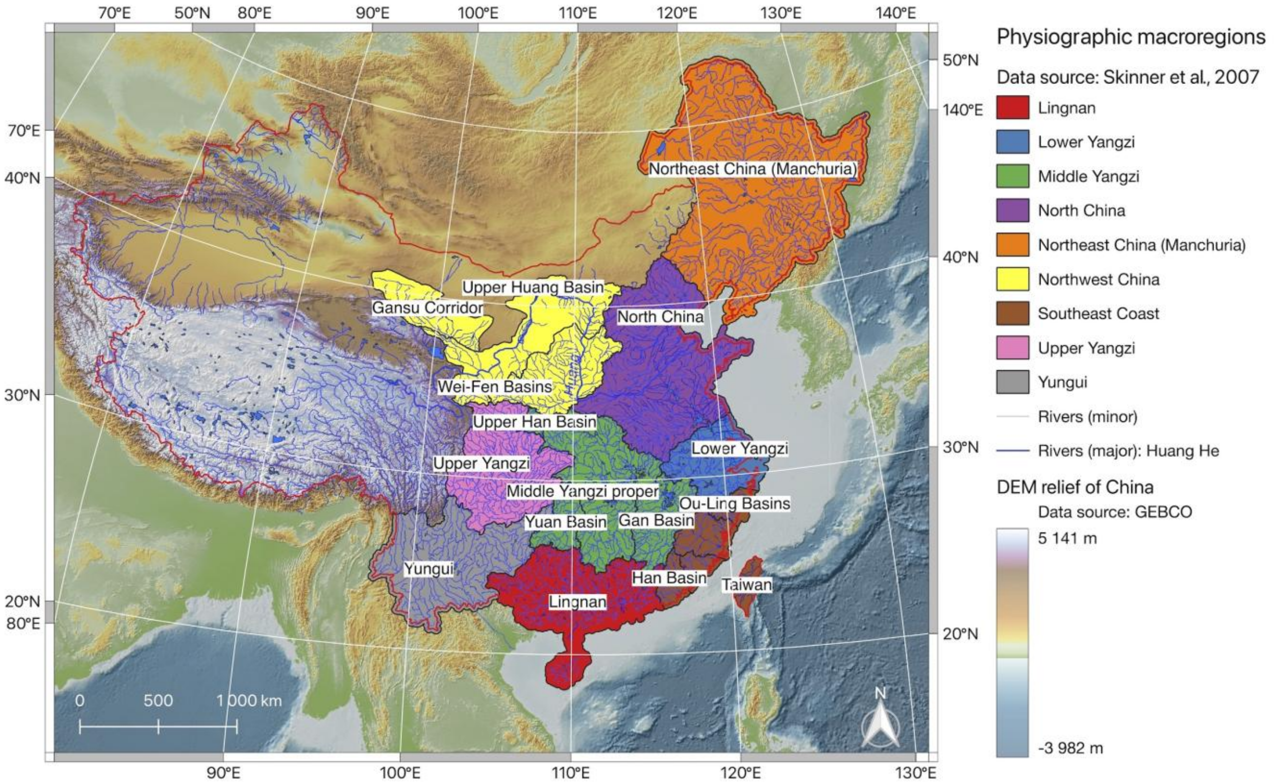


Figure 1: Physiographic regions of China.

2.2. Meteorological and mechanical drivers of sandstorm activity

The increased risk of sandstorm hazards is attributed to three primary factors: soil, vegetation, and climate. Each of these elements plays a significant role in the occurrence and intensity of sandstorms. Climate, particularly precipitation levels, is crucial, as it varies considerably across regions. In northern China, precipitation is limited, creating conditions conducive to sandstorm formation. It also specifies the probability of precipitation in several key northern provinces of China that experience severe sandstorm impacts, focusing on major cities such as Xining (Qinghai), Ürümqi (Xinjiang), Yinchuan (Ningxia), Lanzhou (Gansu), Xi'an (Shaanxi), and Hohhot (Inner Mongolia), Figure 3. The annual level of precipitation in the areas affected by sandstorms is below 400 mm/year (beige colour in Figure 4). Rainfall patterns in northern China differ and show the decadal dynamics which affects the uneven seasonal distribution of rains (Lu et al., 2019; Yang et al., 2025).

The seasonal patterns of rainfall demonstrate a significant peak during the spring months, accounting for 60%-80% of the total annual precipitation. This pattern is notably linked to the occurrence of frequent spring droughts, as highlighted in the research by Qin et al. (2022). As analyzed by Sun et al. (2025), the intensification of spring droughts in recent years has emerged as a primary driver for the increased frequency of high-intensity dust events originating from the Gobi Desert. Additionally, wind plays a crucial role in the formation of sandstorms. The data indicates a strong correlation between mean wind speed and the frequency as well as intensity of sandstorms. Specifically, increased average wind speeds lead to higher occurrences and greater severity of sandstorms in China, as evidenced by studies conducted by Liu et al. (2022), Han et al. (2021), and Yin et al. (2022).

The observations indicate a significant link between temperature variations and the frequency of extreme sandstorms, particularly highlighting that these storms tend to coincide with colder intervals in natural temperature cycles, as evidenced by findings from Zhang et al. (2021). Additionally, there is a robust correlation between annual wind speed and the occurrence of sandstorms in northern regions, with Liu et al. (2004) providing further insights into this relationship. Furthermore, a comparative analysis of data reveals a direct relationship between wind speed and the volume of dust that is transported during sandstorms. This relationship suggests that higher wind speeds are capable of lifting larger quantities of materials, thereby exerting a more pronounced impact on soil conditions, as illustrated in the work of Gu et al. (2021).

2.3. Edaphic characteristics and the role of the Loess Plateau

Another critical physiographic feature facing vulnerability to sandstorms is the Loess Plateau, situated in northern China, southeast of the Gobi, Figure 2. Desert and bordering the Yellow River (Wang et al., 2017; Lemenkova, 2021; Chen et al., 2007). This area is prone to frequent and intense sandstorms, particularly in the spring (Ling et al., 2011; Gao et al., 2024). The primary cause of these storms is the strong winds originating from the arid Gobi Desert and the Mongolian steppes, which are further intensified by soil erosion (Kong et al., 2021; Lemenkova, 2022). The erosion of the Loess Plateau has led to significant loss of topsoil, exposing parent material or soils that are low in nutrient content across many habitats (Fu et al., 2009). In the western Loess Plateau, recent stratigraphic analyses highlight how mineralogical shifts in loess-paleosol sequences reflect long-term changes in dust provenance and climate (Fan et al., 2024).

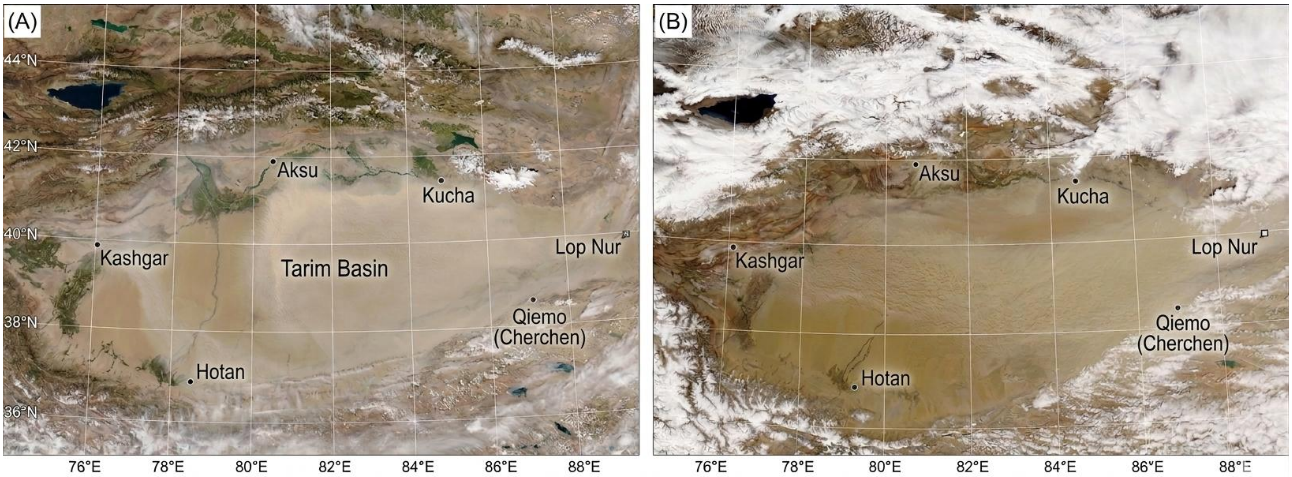


Figure 2: Multi-temporal true-color satellite views showing sand storms over the Tarim Basin: (A): spring period showing Tarim Basin with a dust-covered terrain; (B): winter period with extensive snow coverage on the mountainous ranges.

Consequently, the ecological balance of this region is severely threatened, as the degradation of soil quality hinders vegetation growth and agricultural productivity (Cao et al., 2007). Such conditions create favourable conditions for repetitive storms.

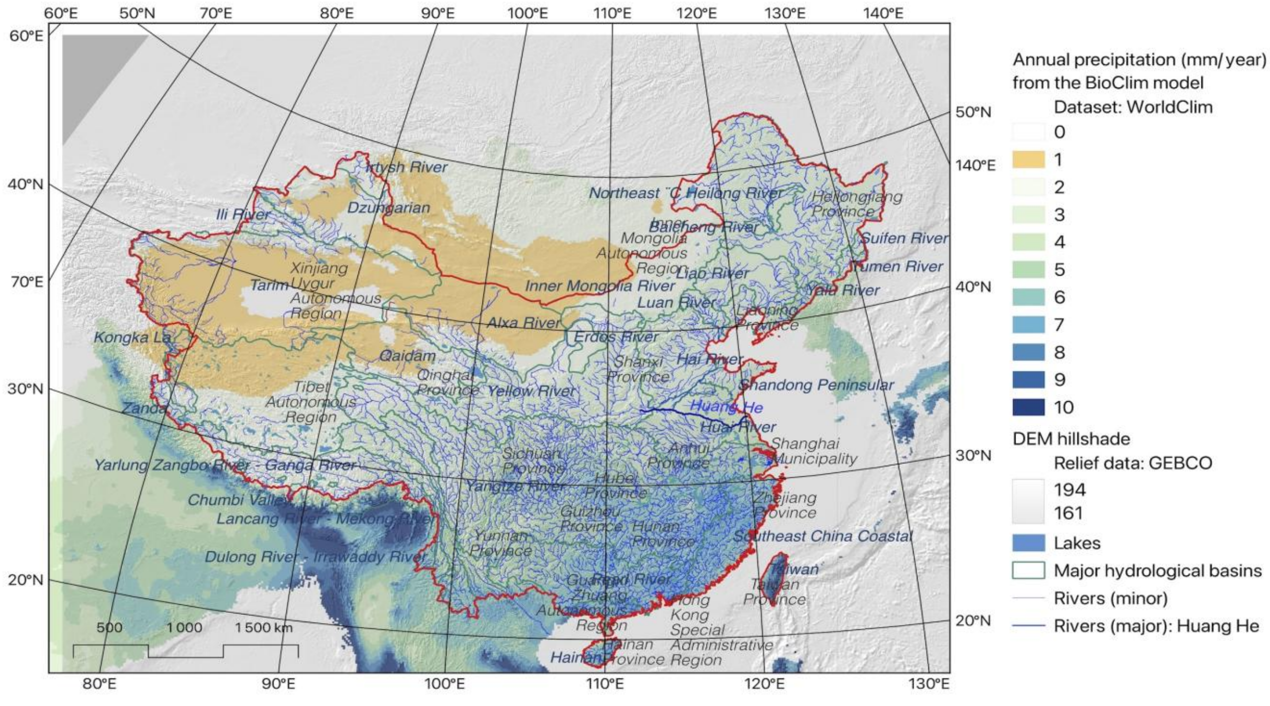


Figure 3: Annual precipitation in China. Data: Bioclim, WorldClime.

In turn, sandstorm contribute to the accumulation of loess as a wind-blown and sand dust forming a layer of clastic silt sediments in the upper soil horizon. Soil distributed in the Loess Plateau is presented by fine, wind-blown loess (Xin et al., 2012). Predictive modeling and historical data analysis indicate that ecological barriers on the Loess Plateau have significantly lowered regional dust concentration thresholds (Zhao et al., 2025). Finally, the nutrient characteristics of soil organic matter have low nitrogen and phosphorus which create limiting factors affecting soil quality and sparse vegetation (An et al., 2022).

2.4. Pedological vulnerability and drivers of soil degradation in the loess plateau

Soil degradation is significantly influenced by its loose structure, rendering it susceptible to both hydrologic and wind erosion, as noted by Kapp et al. (2025). Several geomorphological factors contribute to this depletion, primarily the curvature of slopes, a factor discussed by Xue et al. (2025) and Chen et al. (2008). Yang et al. (2023) provided critical empirical data on the wind speeds required to initiate sand movement, highlighting how the mechanical properties of different desert pavements influence the overall dust flux in Northwest China. For instance, the distinct geomorphic surfaces of the Tarim Basin exhibit highly variable resistance to wind erosion, necessitating a nuanced approach to modeling regional dust emission rates. Additionally, erosion induced by human activities is highlighted as a critical cause by Shi and Shao (2000). Climate impacts, particularly intense spring rainfall and overall precipitation patterns, also play a pivotal role, leading to increased sediment flow in the Yellow River, as elaborated by Huang et al. (2017).

Soil on the Loess Plateau is primarily composed of calcareous silt loams and is categorized into several types: Heilu (Black Loess) soils, Huangmian (Yellow Loess) soils, Lou (Cultivated) soils, Sierozem, Castanozem, and Drab soils. These soils are particularly adapted to semi-arid climate conditions (Be, Bk, C), as illustrated in Figure 4. The surface layer affected by sandstorms is made up of loose sandy sediments, indicating vulnerability to erosive weather events, as shown in Table 1. Characteristically rich in calcium carbonate, the soils exhibit variability in humus depth and clay content; for instance, Heilu soils possess a darker and deeper humus profile, whereas Lou soils demonstrate the impact of deep manure application (Y. Wang et al., 2012). This strong soil profile renders the Loess Plateau soils suitable for intensive agricultural practices due to their high fertility, while simultaneously exposing them to risks from sandstorms. The loess itself is distinguished by its brownish-yellow color, loose structure, and relatively homogeneous texture, all of which stem from its origin as an aeolian deposit. Common soil types in this region include silt loam and silty clay loam.

Table 1: Composition of soil particles in the areas affected by sandstorms in Loess Plateau. (Yang et al., 2001)

Soil type	Region	Grain size (mm) and Composition (%)				
		Mid- size sand 0.5-0.25	Fine sand 0.25-0.125	Very fine sand 0.125-0.063	Dust sand 0.063-0.002	Clay <0.002
Loess	Shenmu, Shaanxi		0.27	51.03	47.83	0.96
Sandy loess	Chuanbei, Yulin			78.48	20.32	1.20

Loess soil, characterized by a silt content of over 60% (particles measuring 0.05–0.02 mm), exhibits a unique vertical joint structure with soil cohesion primarily dependent on calcium carbonate (Loess Plateau Scientific Expedition Team, 1991). This cohesion is compromised when water permeates the soil, leading to the dissolution of calcium carbonate and increasing the soil's susceptibility to erosion. Consequently, loess is prone to collapse when wet, rendering it highly erodible (Yan, 2007). The pedological landscape of the Loess Plateau is defined by a unique vertical and horizontal heterogeneity, where the distribution of soil types—ranging from the relatively fertile cinnamon and Lou soils in the south to the more arid sierozem and loessial soils in the north—is governed by a sharp climatic gradient. These soil profiles are characterized by high silt content and a distinct lack of cohesive structure, making them highly susceptible to mechanical detachment, Figure 4. The topsoil, which often lacks a stabilizing biocrust or dense canopy cover, is comprised of highly erodible, fine-grained sediments that are easily entrained by atmospheric turbulence. When wind velocity exceeds the threshold friction velocity, these loose particles initiate a chain reaction of saltation and suspension. The inherent vulnerability of these loess landscapes is not merely a result of their physical composition, but also their high porosity and low organic matter content, which diminish surface resistance. This makes the region a critical source area for regional dust loading, as environmental forces rapidly mobilize the unprotected surface layer during seasonal wind events.

Soil structure acts as the primary architect for the ecosystems it supports, dictating both the density and diversity of local flora. In environments characterized by nutrient-deficient, coarse-textured sandy soils, the lack of organic matter and poor water retention create a poor nutrition. This constraint permits only the hardiest, most simplistic vegetation to take root. Because these plant communities remain sparse and lack a complex, multi-tiered architecture, they fail to create a cohesive ecological barrier. Consequently, when high-velocity wind events occur, these areas lack the necessary ground cover to dampen surface friction or trap saltating particles, leaving the landscape critically vulnerable to the erosive forces of sandstorms.

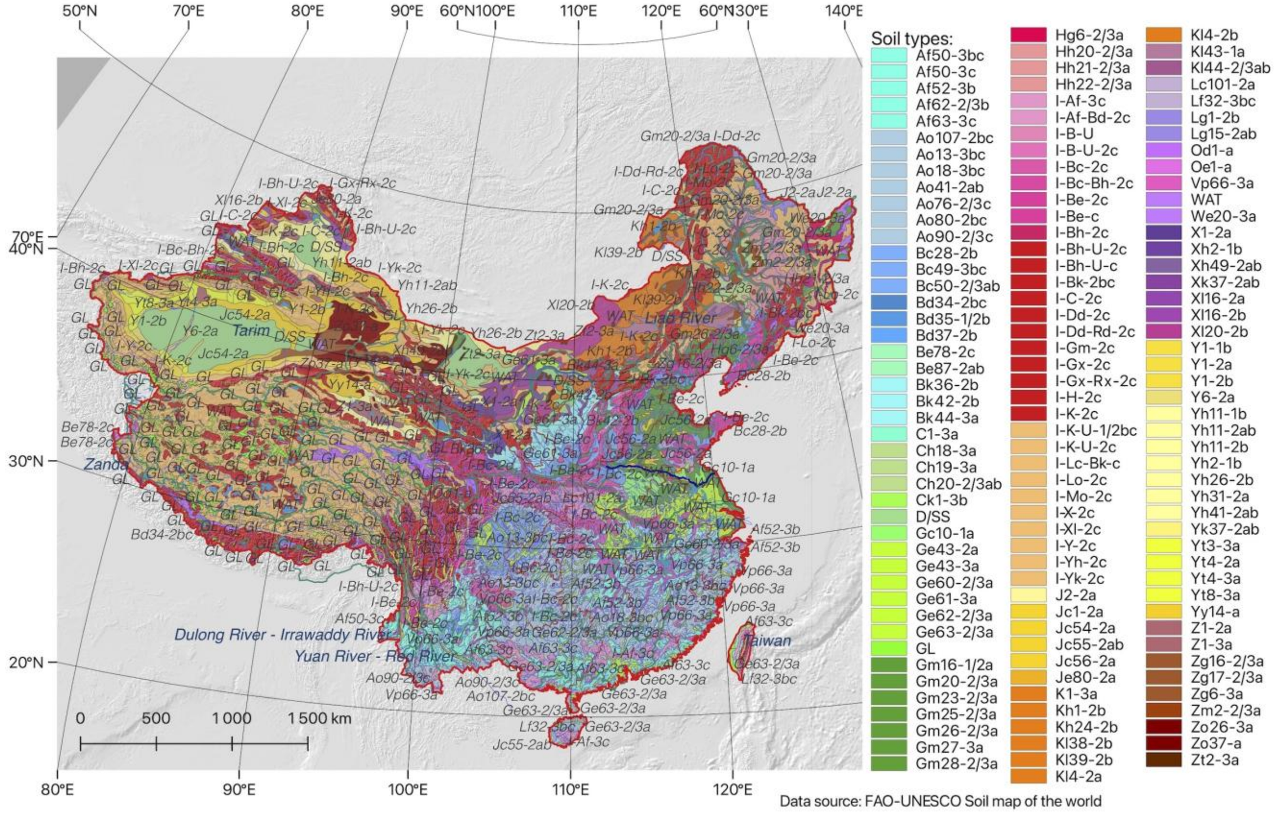


Figure 4: Soil types in China according to the FAO classification scheme.

2.5. Atmospheric drivers and geomorphological constraints of aeolian dust transport in Northwest China

The arid and semi-arid regions of Northwest China, primarily encompassing the Tarim, Junggar, and Badain Jaran basins, are characterized by a hyper-arid continental climate governed by extreme moisture deficits and high pressure gradients. This region's susceptibility to frequent sandstorms is fundamentally driven by its topographic isolation—hemmed in by the Tibetan Plateau and the Tianshan Mountains—which creates a rain-shadow effect, limiting annual precipitation to often less than 100 mm. Analysis of long-term datasets reveals that aeolian activity on the Tibetan Plateau is not isolated but rather closely coupled with broader climate cycles that dictate moisture and pressure gradients (Kang et al., 2021).

The region experiences intense seasonal fluctuations; during the spring transition, rapid surface heating of the expansive Gobi and Taklamakan deserts destabilizes the lower boundary layer, facilitating the vertical transport of lithogenic dust. As demonstrated by Liu et al. (2024), the vertical structure of dust over the Taklamakan is primarily governed by intense thermal convection, which facilitates the injection of particulates into the upper atmosphere for long-range transport. Thd atmospheric instability in this region is frequently catalyzed by the passage of Mongolian Cyclones and the intensification of the Siberian-Alaskan High, which generate sustained surface wind velocities exceeding the threshold friction velocity ($u_* t$) required for saltation. The interannual frequency of dust storms in Northern China is closely modulated by the intensity and position of the Siberian High, which governs the delivery of high-velocity cold air masses to the region (Mao et al., 2022). As wind speeds increase, the lack of vegetative cover and low soil moisture levels—typical of the region's Aridisols—allow for the large-scale entrainment of fine-grained particles into the troposphere. These particles are then transported via the Westerlies, often resulting in long-range dust transport events that affect the air quality of the North China Plain and beyond

2.6. Transboundary aerosol flux: mechanisms and pathways of external dust influx into Northwest China

The influence of externally sourced dust on Northwest China is a significant yet complex component of the region's atmospheric dynamics. While the area is a well-known global source of mineral aerosols, it simultaneously acts as a major receptor for transboundary dust, primarily through the influx of material from Central Asian neighboring basins. The extent of external impact is largely dictated by the Central Asian Westerly Jet and the seasonal positioning of the Siberian

High. These systems facilitate the long-range transport of fine-grained particles from the Karakum and Kyzylkum Deserts, as well as the desiccated basin of the Aral Sea. The shifting landscape of aeolian activity in East Asia is driven by a complex interplay between atmospheric circulation patterns and localized land-surface changes, as detailed in recent review literature (Shao et al., 2023). In the context of arid and semi-arid cold regions, the interplay between environmental factors—such as seasonal climate shifts and land degradation—creates a vulnerable soil setting where the depletion of the upper soil horizon and the loss of physical structural integrity significantly increase the susceptibility of sandy, fine-grained soils to wind erosion (Jiang et al., 2022; Saba et al., 2021; Lindh & Lemenkova, 2021, 2023). Mechanisms of external dust influx include topographic corridors and vertical stratification. The external dust often enters the region through specific geographic "gates," such as the Dzungarian Gate in Northern Xinjiang. This topographic funneling significantly increases the aerosol optical depth (AOD) in the Junggar Basin. Unlike locally generated dust, which often resides in the lower boundary layer, externally sourced dust is typically transported at higher altitudes (2–5 km). This allows it to bypass local geographic barriers and settle over larger areas through dry and wet deposition.

2.7. Geomorphological constraints and synoptic drivers of aeolian transport in Northwest China

The aeolian dynamics of Northwest China are fundamentally shaped by a "basin-and-range" geomorphology, where the topographic isolation of the Tarim, Junggar, and Qaidam basins—hemmed in by the Tibetan Plateau and the Tianshan Mountains—creates a hyper-arid rain-shadow effect, Figure 5. It illustrates the problem of arid and semi-arid climates, where soil degradation is a critical challenge characterized by low organic matter content, reduced microbial activity, and a high susceptibility to wind and water erosion, which collectively undermine ecosystem stability and food security (K. Wang et al., 2023; Lemenkova, 2023, Quoreshi et al., 2022).

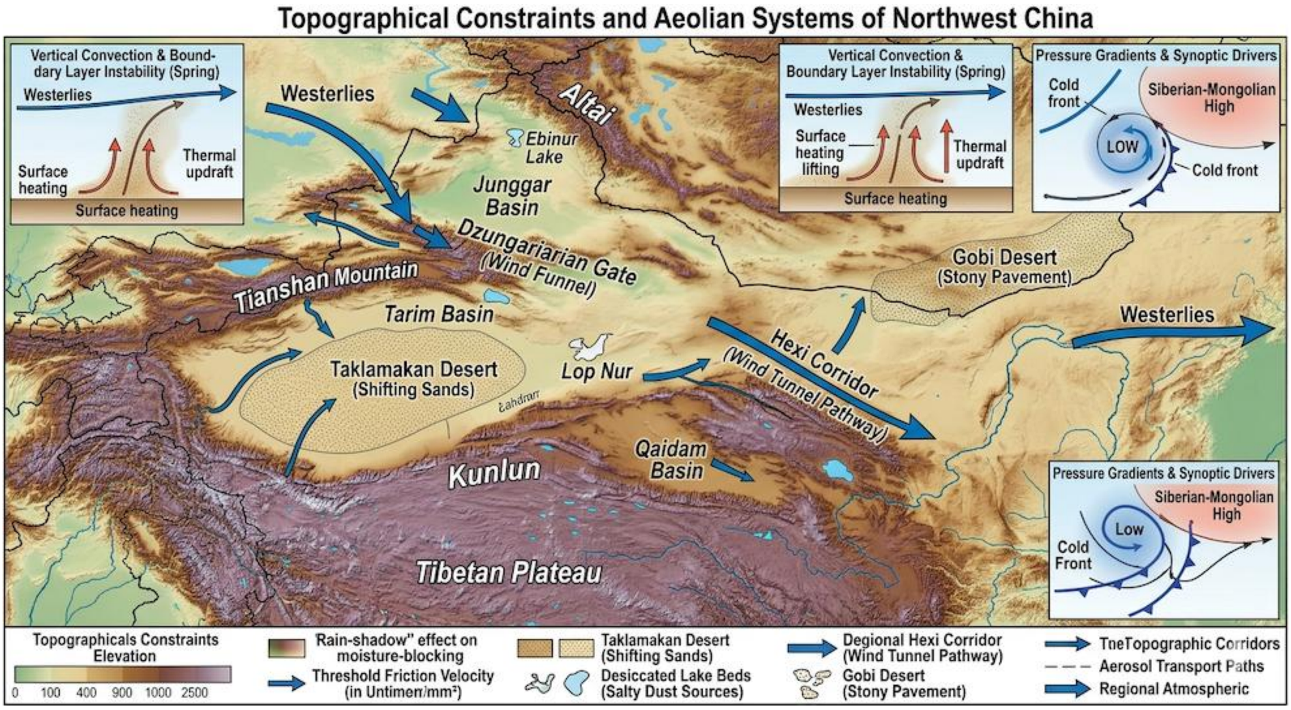


Figure 5: Geomorphological architecture and aeolian transport mechanisms of the Northwest China Dust Corridor.

These basins serve as vast lithogenic reservoirs, with the shifting sands of the Taklamakan and the gravel pavements of the Gobi providing inexhaustible sources of silt and evaporites. Dust transport is catalyzed by steep atmospheric pressure gradients between the Siberian-Mongolian High and localized thermal lows, which generate surface wind velocities exceeding the threshold friction velocity ($u_* t$) required for sediment entrainment. This process is further intensified by the "funneling effect" of topographic gaps like the Dzungarian Gate and the Hexi Corridor, where turbulent cold frontal surges and vertical convection loft fine-grained particulates into the Westerlies for long-range regional dispersal. Guan et al. (2023b) emphasize that identifying high-risk zones through multisource data is essential for targeted ecological restoration and the protection of infrastructure within the Hexi Corridor.

3. Materials and Methods

3.1. Objectives and motivation

The paper addresses the critical issue of sandstorms and desertification in North China's ecosystems, identifying a significant gap in the integrated ecological mapping. Such approach can effectively visualize the connections between sandstorm events and pertinent parameters such as frequency, intensity, and distribution, in relation to climate variables and soil factors. The study has three main objectives: 1) first, to investigate the seasonal variability of sandstorm events specific to the desert regions of North China; 2) second, to perform a spatial analysis that examines the geographical distribution of these hazard events considering the primary influencing factors of soil and climate; and 3) third, to explore the spatial heterogeneity present among the occurrences of sandstorms. Focusing on the seasonal analysis, this research aims to provide insights into the geospatial distribution, intensity, and frequency of sandstorms during the spring, autumn, and winter periods. The ultimate goal is to create a time-series maps that effectively visualize the physical parameters associated with sandstorms during these specified seasons.

3.2. Data analysis

To analyze the distribution of sandstorms, various datasets were combined to identify the correlations between specific environmental conditions that favor these events. Our focus was on the arid and semi-arid regions of the northern Loess Plateau, taking into account key factors such as soil composition and broader geographical contexts within China. The datasets utilized in this study included information from the Global Wind Atlas, soil type classifications provided by the Food and Agriculture Organization (FAO), and annual precipitation data sourced from Bioclim and WorldClime. This comprehensive approach allowed us to map the distribution of sandstorms in relation to the physiographic characteristics of China, highlighting areas that are particularly susceptible to such phenomena.

The spatial and temporal characterization of dust transport in Northwest China is derived through a multi-scalar integration of remote sensing Earth Observation data, Figure 6. Remote sensing data processing is essential for monitoring salt pan crust dynamics, which play a significant role in sediment entrainment within endorheic basins (Nield et al., 2016; Xing et al., 2026, Lemenkova, 2025c). Thus, machine learning algorithms of RS data processing in GIS offer robust frameworks for mapping spatially constrained regions with sandy fine-grained soils (Wang et al., 2021; Lemenkova, 2025e, Wuyun et al., 2022).

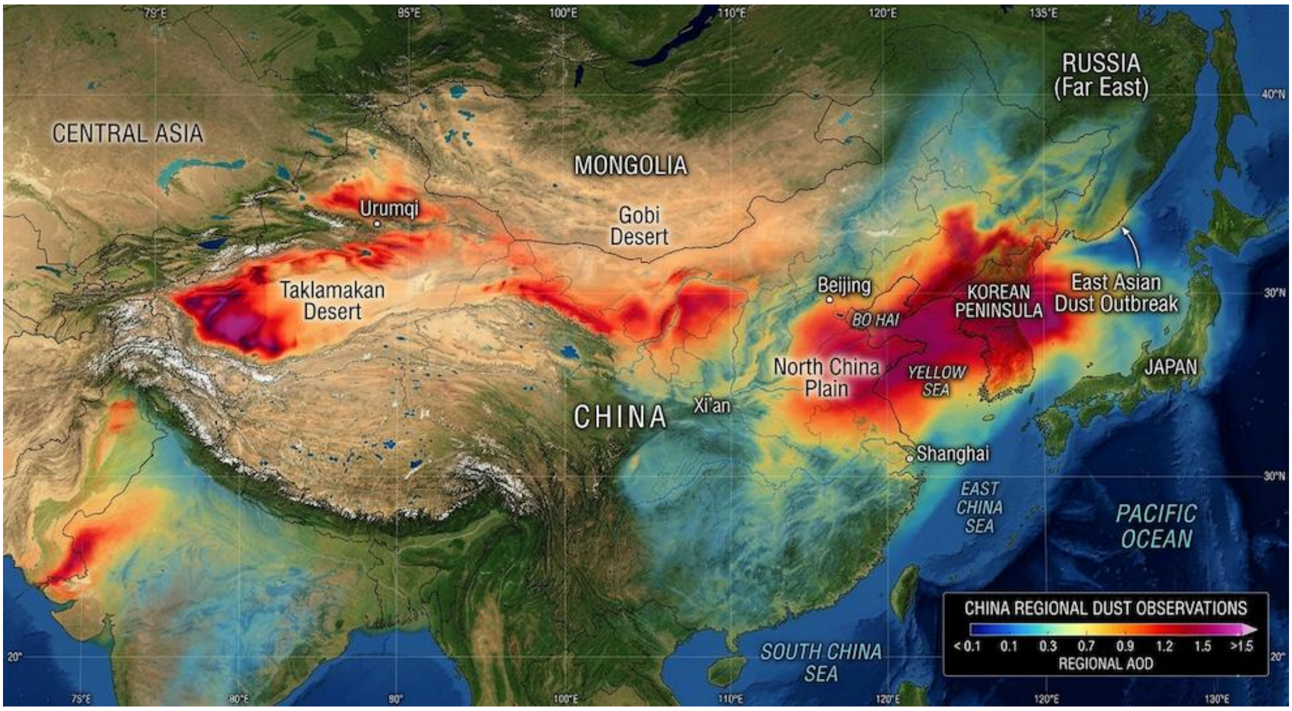


Figure 6: Satellite-derived visualization of regional dust storm activity and aerosol transport across East Asia (AOD Mapping.

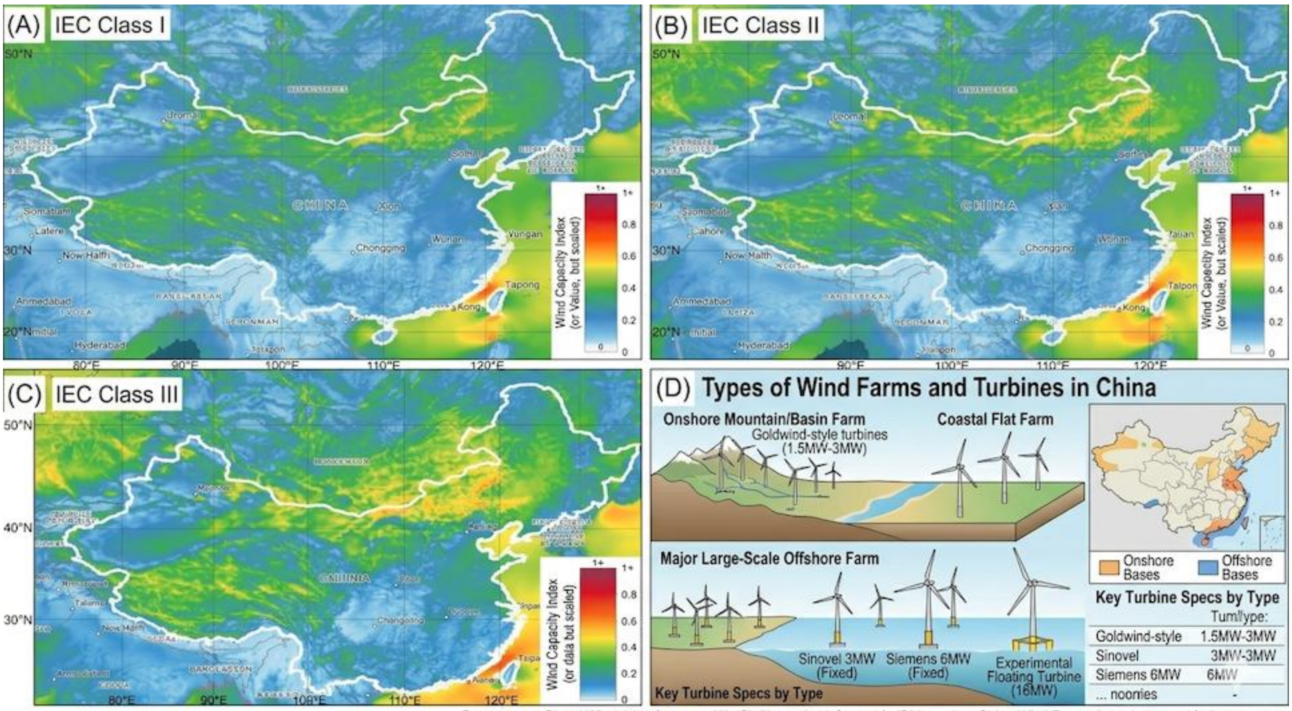
Other data sources include aerosols, high-resolution meteorological observations, and Lagrangian trajectory modeling, as summarised in Table 2. Primary detection utilizes Moderate Resolution Imaging Spectroradiometer (MODIS) and

Visible Infrared Imaging Radiometer Suite (VIIRS) data, where the Dust Enhancement Index (DEI) and Aerosol Optical Depth (AOD) products are calibrated against ground-based visibility and anemometric data to isolate mineral dust from cloud cover. Frequency maps are generated by calculating the decadal probability of discrete events exceeding threshold friction velocities ($u_{*}t$), while transport intensity is quantified by integrating CALIOP vertical lidar profiles with mass flux calculations ($g/m^2 \cdot s$). To resolve the geographic provenance of these particulates, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is employed alongside Potential Source Contribution Function (PSCF) statistics. Statistical multitask learning with statistical parametrization helps evaluate the biophysical factors and sparse vegetation coverage that fail to protect soil from wind erosion (Song et al., 2024; Lemenkova, 2025d; Zhu et al., 2026). Therefore, statistical methodology was applied as it allows for the precise interpolation of source-to-sink pathways, effectively distinguishing between internally entrained lithogenic dust and transboundary aerosols entering through topographic corridors.

Table 2: Data Sources for SDS, Temperature, and Precipitation

Data Type	Primary Source	Specific Platforms / Tools
SDS (Sand & Dust Storms)	CMA / NMC	SDS-WAS (Asia Node): The WMO's Sand and Dust Storm Warning Advisory and Assessment System, hosted by CMA.
	Environmental Monitoring	CNEMC (China National Environmental Monitoring Centre): Real-time PM_{10} and $PM_{2.5}$ data used as a proxy for dust concentration.
	Numerical Models	CMA-CW v1/SDS: A high-resolution (0.15°) prediction system providing 7-day forecasts and historical reanalysis of surface dust flux.
Temperature & Precipitation	CMA National Climate Center	China Climate Bulletin: Annual reports released every January (e.g., the *2025 Bulletin* released Jan 2026).
	Global Sharing Platforms	CMA Global Climate Datasets: Launched in late 2025, offering global merged surface temperature and reanalysis data (V1.5).
Remote Sensing (General)	NSMC (National Satellite Meteorological Center)	FengYun (FY) Satellites: Specifically FY-3 and FY-4 series for AOD (Aerosol Optical Depth) and moisture profiling.

The analysis of data from the Global Wind Atlas indicates that northern and northwestern China are significantly influenced by both northwest (NW) and southeast (SE) winds, which exhibit seasonal directional changes. Specifically, northwest China is primarily affected by northeast-southeast (NE-SE) winds that exhibit a distinct seasonal pattern.



Data source: Global Wind Atlas for maps (A)-(C); illustrative infographic (D) based on China Wind Power Association and industry specs.

Figure 7: Wind energy capacity and Wind Farms in China (A): IEC Class I; (B): IEC Class II; (C): IEC Class III.; (D) Type of Wind Farms and Turbines in P.R.C. Data source: Global Wind Atlas.

During the winter season, the air currents tend to align in a north-northeast to south-southwest (NNE-SSW) orientation, particularly near the 96°E meridian. This configuration is influenced by the cold Mongolian High pressure system, which extends its effects across China, Mongolia, and Siberia. In the eastern region of the Tarim Basin (Xinjiang) and the western part of the Hexi Corridor in Gansu, the prevailing winter wind currents are oriented towards the NNE direction. As Xinjiang acts as a receptor for distal aerosols, the desiccation of the Aral Sea has emerged as a significant source of 'salty dust,' altering the mineralogical composition of regional sandstorms (Li et al., 2024). The desiccation of terminal lakes, such as Ebinur Lake, has led to the emergence of 'saline dust' storms, which carry high concentrations of sulfates and chlorides that pose a severe threat to regional downwind ecosystems (Xie et al., 2022). The turbulence of these winds is visualized in a figure, corresponding to a classification scheme for wind energy (Figure 7), which is summarized with data found in a table. The evaluation of wind energy capacity across China utilizes data that adheres to the International Electrotechnical Commission (IEC) standards, specifically IEC 61400-1, ensuring a standardized approach to measuring and classifying wind energy potential in these areas, Table 3.

In areas of Northwest China exhibiting high dust transport intensity, the phenomenon is driven by a synergistic convergence of geological sediment supply, synoptic-scale meteorological forcing, and the mechanical properties of the land surface. The primary underlying cause is the presence of vast, unconsolidated lithogenic reservoirs—specifically the fine-grained silts of the Taklamakan and the "stony" pavements of the Gobi—which provide an abundant supply of erodible material. These source regions are situated within topographically closed basins where intense solar heating in the spring creates extreme thermal instability, generating updrafts that loft particulates into the troposphere.

This vertical transport is intensified by the "funneling effect" of mountain gaps and corridors, such as the Hexi Corridor, which significantly increases surface wind velocities via the Venturi effect. Furthermore, the intensity is exacerbated by the seasonal strengthening of the Siberian-Mongolian High, which drives high-velocity cold fronts that overcome the threshold friction velocity (u_{*t}) of the region's hyper-arid Aridisols. Anthropogenic factors, including the degradation of biological soil crusts and over-extraction of groundwater from terminal lakes (e.g., Lop Nur), have further increased the availability of fine-grained evaporites and silts, leading to a higher mass flux during storm events and extending the geographic reach of the resulting dust plumes.

In the spring season, the mean wind velocity in certain regions of China rises to between 4.0-6.0 m/s, exceeding the annual mean of 3.3-3.5 m/s. Wind forces during this time often reach 8 on the Beaufort scale, with the most intense winds found along the borders with Russia and Mongolia in the steppe areas, where wind force can peak at 12 on the Beaufort scale in mountain gorges, valleys, and outlets. Notably, the seasonal behavior of wind velocity in northern, northwestern, and northeastern China displays considerable variation, with a substantial portion—40-70% of total wind frequency—occurring at force 8 specifically during spring.

In the summer, the dynamics of wind change as hot air currents shift northward, while westerly winds encounter the Pamir Plateau, resulting in a directional alteration. One significant airflow crosses the Pamir Mountains and moves into the western Tarim Basin, whereas another is funneled into northern Xinjiang via the western Jungger Basin. This complex interaction between wind patterns and geographic features plays a crucial role in influencing the intensity and trajectory of sandstorms in these regions. The prevailing NW-oriented wind significantly impacts the climate and weather patterns in northern Xinjiang, where it contributes to frequent sandstorms. This wind also affects the western Gansu Province, particularly the Hexi Corridor, and the Ningxia Plain of Yinchuan. Additionally, the SE monsoon plays a crucial role in wind dynamics, resulting in a shift of the wind current towards the southeastern direction in the eastern region of the Helan Mountains.

Table 3: IEC Classification of wind energy capacity

Wind energy capacity		Class I	Class II	Class III
V_{ave}(m/s)		10.0	8.5	7.5
V_{ref}(m/s)		50.9	42.5	37.5
$V_{50,gust}$(m/s)		70	59.5	52.5
I_{ref}	A	0.16		
	B	0.14		
	C	0.12		

In the table (IEC61400-1:2005): 1. Rayleigh distribution is assumed: k = 2. 2. Vave(m/s) is the annual mean wind speed at hub height; V_{ref} is the 50-year extreme wind speed over China exceeding 10 min; $V_{50,gust}$ is the 50-year extreme gust in China over 3 seconds; I_{ref} is the mean turbulence intensity of wind at 15 m/s. This classification indicates the strength of wind as a turbulence that varies regionally depending on topographic and climate setting. The IEC Class I has high wind conditions, high annual average wind speed (around 10 m/s or ~22 mph) and a severe extreme gust (around 70 m/s or ~157 mph). Accordingly, Class II has moderate wind conditions with annual average wind speed (around 8.5 m/s), and Class III – 7.5 m/s. Among the compared regions, the highest affected area is the North China and the Upper Huang Basin, followed by the Tibetan Plateau, Figure 8. These regions are affected by regular dust- and sandstorms. The analysis of the geospatial data from the Global Wind Atlas reveals that the number of windy and dusty days in northern China overpasses 200, and severely windy days equivalent to force 8 up to 10 m/s, Figure 8 (A). The spatial and temporal distribution of these soil substrates directly modulates the frequency and magnitude of aeolian transport, establishing a distinct seasonal periodicity in regional dust storm dynamics. This cyclical vulnerability is most pronounced during the winter and spring, as the region experiences a critical asynchrony between peak synoptic wind energy and the minimum threshold of ecological protection.

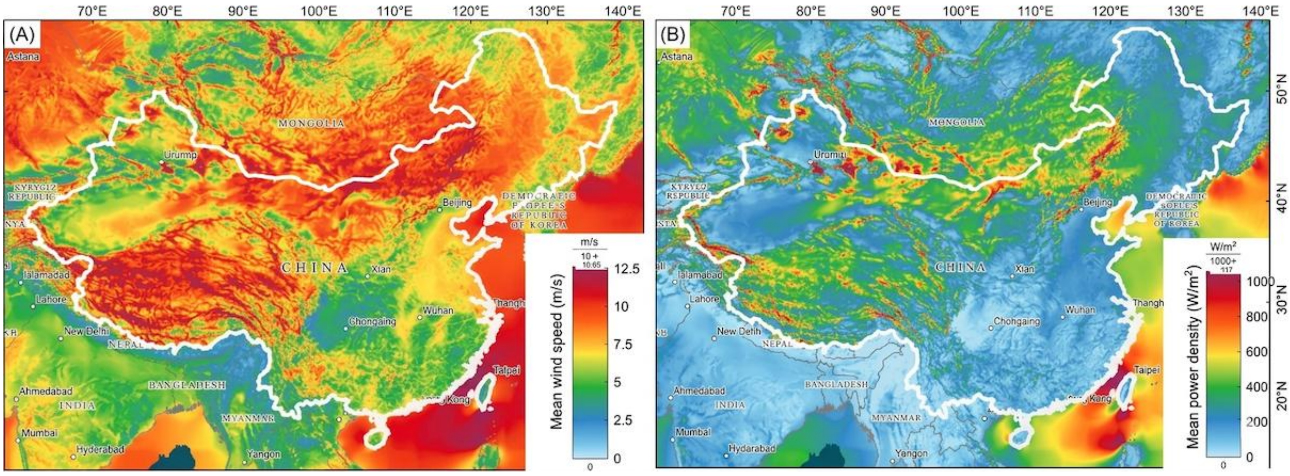


Figure 8: Wind parameters over China. (A): Mean wind speed; (B): Mean Power Density. Data: Global Wind Atlas.

During this period, ground vegetation remains dormant with a negligible Leaf Area Index (LAI), failing to provide the aerodynamic roughness necessary to dissipate surface shear stress. Simultaneously, the desiccation of loose loessial and sandy topsoil reduces inter-particle cohesion, effectively lowering the threshold friction velocity (u_{*} t). Consequently, the intensification of the Siberian High generates powerful cold fronts that act upon this unprotected landscape, maximizing the sand-driving force and facilitating the large-scale entrainment of fine-grained particulates into the atmosphere. The analysis of mean wind power density in northern China shows the highest values reaching 117 W/m², which indicates the total wind energy potential in the areas prone to sandstorms (speed * density) across Loess Plateau and mountainous areas over 1000 m (UNDESA, UNDP, WEA, WEC, 2000), Figure 8 (B). Such setting reveals strong patterns of continental wind corridors in northern China, Figure 9.

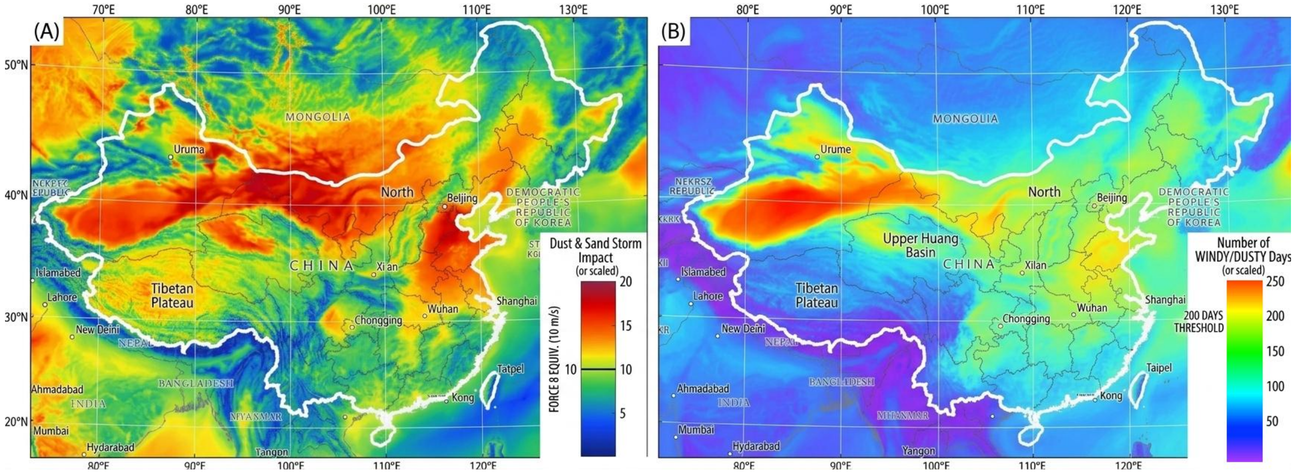


Figure 9: Dust and sand effects over China. (A): Dust and sand storm impact; (B): Number of windy/dusty dats.

4. Results and Discussion

Naturally occurring sandstorms in China are influenced by various factors including climate regime, soil types, topographic relief, and hydrology, specifically the density of river networks and groundwater levels. These environmental elements are interconnected with critical processes such as desertification, land degradation, soil depletion, and droughts. Among these, irregular precipitation, seasonal rainfall patterns, ambient air temperature, and wind regimes stand out as the primary climatic determinants affecting the frequency of sandstorm events. Furthermore, the geographical distribution of sandy, degraded soils coupled with an absence of dense vegetation in arid regions highlights a significant relationship impacting the sandstorm phenomenon in China.

Sparse vegetative coverage contributes significantly to the severity of sandstorms by eliminating physical barriers that would otherwise slow wind and removing root systems that anchor the soil. This process is particularly evident in areas with dry and loose soil, like the Loess Plateau, which are highly susceptible to erosion from strong winds. The typical exposed land found in the arid ecosystems of northern China is frequently affected by winds that exacerbate soil erosion. Consequently, various weather and climate conditions, the presence of sandy, loose soil, high levels of aridity, and the prevalence of strong winds are critical factors influencing the occurrence and intensification of sandstorms, especially over deserted and degraded lands.

Water scarcity in western and northwestern China significantly increases the likelihood of sandstorm occurrences. This phenomenon is exacerbated by global warming and drought, which negatively impact various water sources, including glacier melt, lake shrinkage, and reduced runoff, as noted by Le Houérou (1996). In northwestern China, the hydrologic network heavily relies on high mountain glaciers, making them particularly susceptible to retreat, thus further aggravating drought conditions (Lemenkova, 2025a; Sun et al., 2024). Notable instances of glacier retreat have been reported in several mountain ranges, such as the Altay Mountains, the Pamir, the Qilian Mountains, and the Tianshan Mountains, where the volume of registered glaciers has decreased by 16% (Zhang et al., 2022).

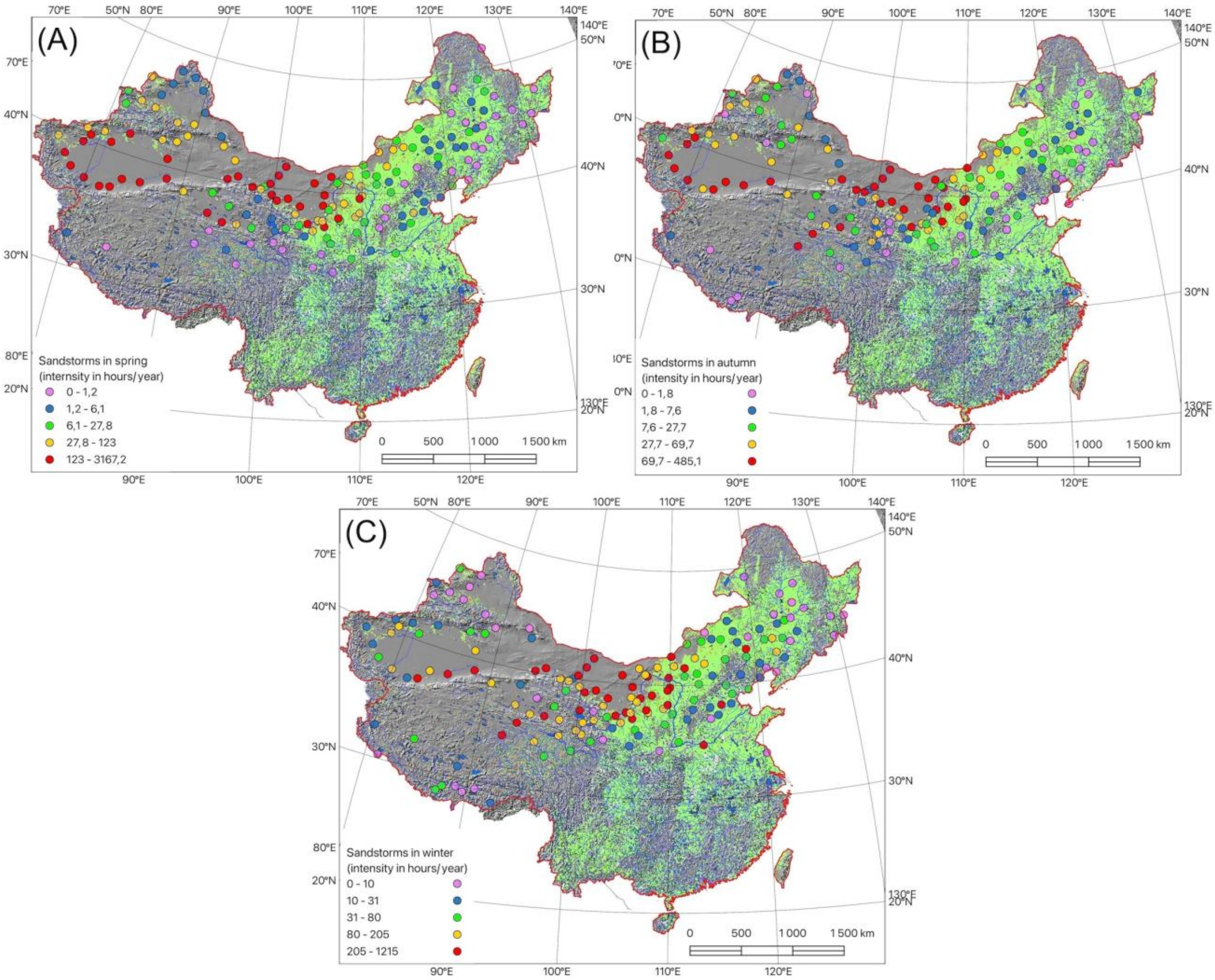


Figure 10. Intensity of sandstorms in China estimated as mean for data period 1982-2023. (A): spring period; (B): autumn period; (C): winter period.

The analysis of the seasonal distribution of sandstorms, as illustrated in Figure 10, indicates significant variability in the frequency of these events across different seasons. The data reveals that the occurrence of sandstorms peaks during the spring months, specifically in April and May, while the frequency decreases during winter and autumn. In autumn, the incidence of sandstorms is particularly low due to the effects of increased rainfall and the resulting vegetation cover, which collectively contribute to the stabilization of soil particles. This stabilization minimizes the potential for dust uplift, thereby reducing the likelihood of sandstorm events during this season. The comparative analysis of climate settings for the capital cities in the Northwest (NW), North (N), and Northeast (NE) provinces of China, particularly affected by sandstorms, is illustrated in Figure 11. This figure reveals key climatic metrics such as annual mean temperatures, probability of precipitation, and average monthly rainfall. Notably, the analysis shows a significant rise in mean temperatures from January to May in the northern provinces that experience the impacts of sandstorms. This increase signifies a changing climate that may influence the frequency and intensity of sandstorms in these regions.

The dynamics of precipitation in sandstorm-affected regions of China, as illustrated in Figure 10, highlight several key areas, particularly the Taklimakan Desert and eastern Xinjiang (Ürümqi), western Qaidan Basin, and the Baidan Jilin Desert (Xining, Qinghai). These regions experience annual rainfall of less than 50 mm and have a probability of precipitation falling below 35%. In the Ürümqi area, precipitation is characterized as sparse and uneven, particularly during the spring months, where it averages below 20 mm. The annual variation in rainfall is significant, exhibiting a range of 30-40% in eastern Xi'an, while it exceeds 40% in other regions, indicating strong variability. The rainy season is inconsistent, predominantly occurring from June to August, coinciding with a decrease in sandstorm frequency. Rainfall events tend to be concentrated over short periods, contributing to a pattern of extreme rainfall followed by prolonged droughts that can extend beyond 200 days, especially in the spring season.

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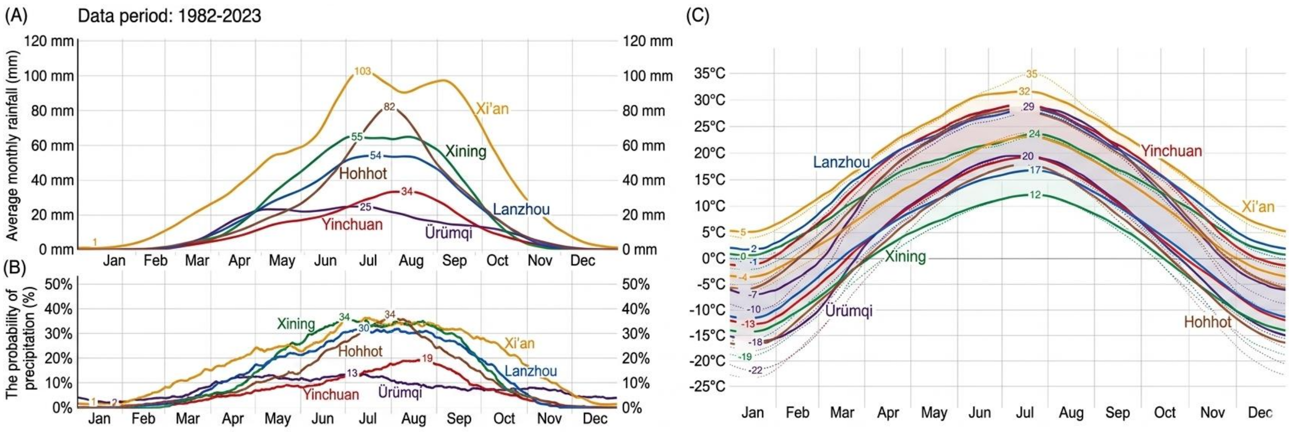

Figure 11. Climate setting in capitals of provinces affected by sandstorms: Xining (Qinghai), Ürümqi (Xinjiang), Yinchuan (Ningxia), Lanzhou (Gansu), Xi'an (Shaanxi) and Hohhot (Inner Mongolia), China. (A): Average monthly rainfall; (B): The probability of precipitation; (C): Average high and low temperature.

During spring, particularly in March and April, the processes underlying sandstorm occurrences are intensified due to rising air temperatures. This increase accelerates cold-heat convection, creating conditions conducive to sandstorms. In contrast, the summer and autumn months bring higher temperatures and frequent rainfall, which settle dust and sand particles, consequently reducing the likelihood of sandstorms. Detailed analyses of maps and graphs illustrating sandstorm frequency in northern China reveal a distinct seasonal pattern, with the highest repeatability of sandstorms occurring in spring. These findings indicate an irregular distribution and occurrence of sandstorms throughout the year, Figure 12.

Spring sandstorms in northern China are intensifying due to climate-driven shifts, specifically lower temperatures and reduced precipitation. These arid conditions exacerbate desertification across the northwest, north, and northeast, where nutrient-depleted soils and sparse vegetation offer little resistance to wind erosion. Key areas experiencing frequent sandstorms include the Tarim Basin, Inner Mongolia, and the Hexi Corridor, which are adjacent to the arid expanses of the Gobi Desert. The severity of aeolian events in Inner Mongolia is characterized by distinct regional clusters, with intensity gradients shifting in response to both local land-surface changes and broader climatic forcing (Liang et al., 2023). Desertification in these regions is predominantly regulated by climatic and hydrologic factors, notably the groundwater system that influences local hydrology and soil moisture levels. Long-range transport studies indicate that fine-grained aerosols originating in the Tarim Basin can maintain significant concentrations over thousands of kilometers, impacting air quality far beyond their source regions (Wu et al., 2024). When soil moisture drops below a critical threshold of 4% of its water-holding capacity, soil transport becomes exacerbated while vegetation growth diminishes. This scenario not only heightens dust transport but also enhances the occurrence of sandstorms. The interplay between climatic conditions and soil characteristics therefore elucidates the seasonal patterns of sandstorms.

To summarize, sandstorms in China are influenced by several external factors categorized into five aspects:

(a) Topography affects land surface distribution by slope curvature and steepness;
(b) Climate influences wind dynamics and sand accumulation;
(c) Geology determines land cover patterns by relief exposure;
(d) Hydrogeological settings control groundwater distribution and levels;
(e) Vegetation serves as a wind barrier and supports soil stability through root systems.

The cumulative effects of geological, topographic, and climate forces significantly influence the dynamics of sandstorms in China, impacting their seasonality, intensity, and frequency. Moreover, sandstorms contribute to and are exacerbated by desertification, making them one of the most severe environmental disasters of the country.

Over recent decades, there has been a notable increase in the frequency, intensity, and distribution of sandstorms, raising concerns among environmental services and Earth monitoring centers in China, Figure 13. Addressing this growing hazard necessitates comprehensive data analysis, which should include statistical examination of climate data, spatial analysis of thematic maps, and remote sensing analysis of satellite images to effectively track the paths of sandstorms in real-time monitoring. A close attention to the environmental problem of sandstorms requires measures to mitigate the effects of these disasters. For example, recent Life Cycle Assessments of the Three-North Shelter Forest

Program underscore the carbon-sequestration potential inherent in long-term dust storm mitigation strategies (J. Wang et al., 2023). Beyond direct sand-binding benefits, the Three-North Shelter Forest Program represents a significant carbon sink, though the net carbon footprint of its implementation and maintenance must be carefully weighed against its mitigation efficacy.

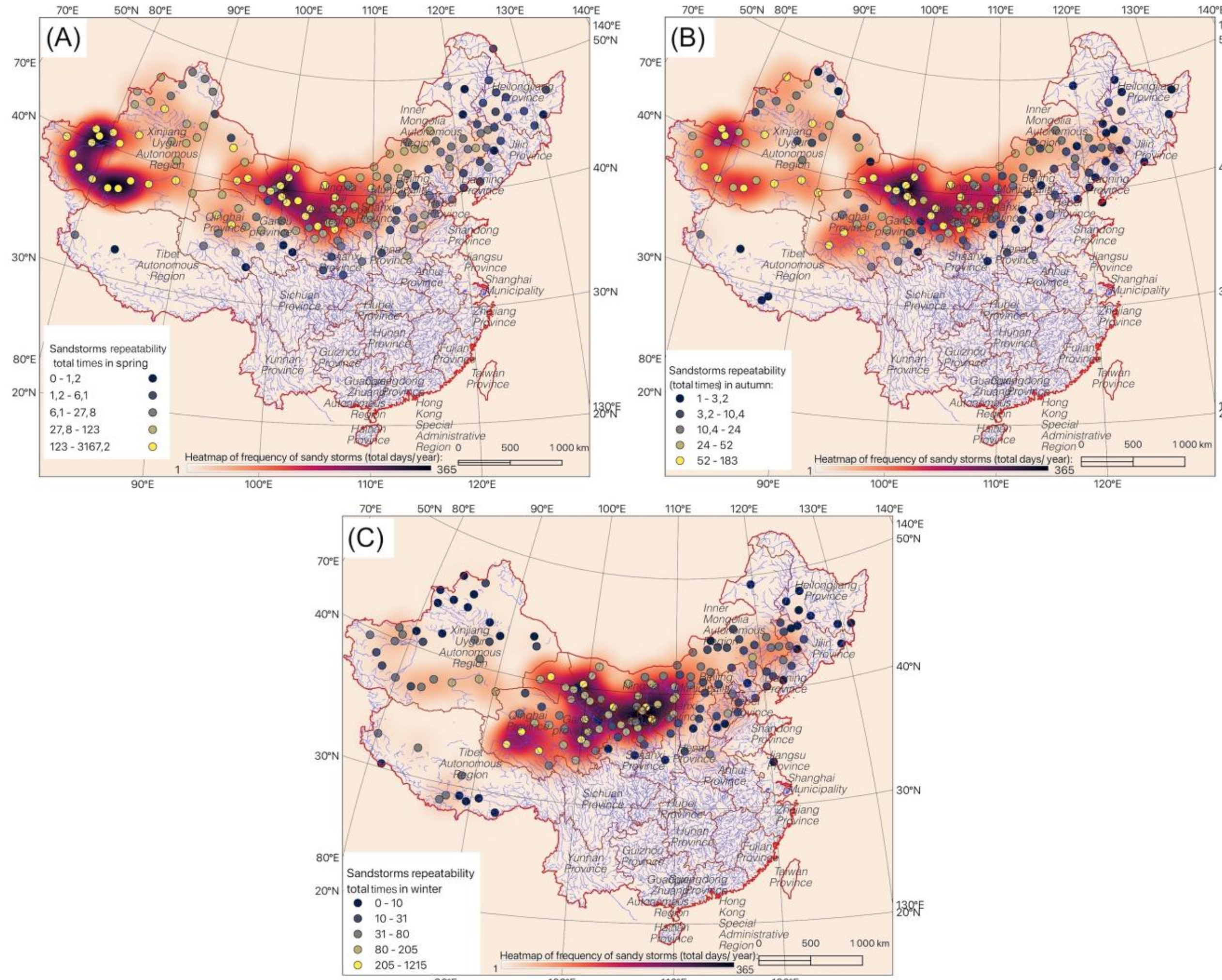

Figure 12. Frequency of sandstorms in China as a dynamics of repeatability of sandstorm times (case of occurrence) per year. (A): spring; (B): autumn; (C): winter.

Key actions include sustainable land management and reforestation, alongside initiatives aimed at combating desertification through smart agriculture practices and improving soil nutrition. Such measures are vital for effective environmental management and the protection of areas in northern China that are susceptible to sandstorms. The observed trends in Chinese sandstorm activity from 1982 to 2023 reflect a complex interplay between long-term ecological restoration and recent climatic volatility. Data aggregated by the China Meteorological Administration (CMA) and analyzed through satellite platforms like MODIS indicate that while the "Great Green Wall" and other reforestation initiatives successfully drove a multi-decadal decline in dust events through the 2010s, the period from 2021 to 2023 has seen a sharp, record-breaking resurgence in frequency and intensity.

This recent spike is attributed to severe meteorological anomalies, including abnormally high temperatures in the Gobi Desert and shifted pressure systems over Mongolia. These factors have not only increased the annual frequency of events—averaging nearly 40 significant storms per year in the early 2020s—but have also expanded their geographic distribution, allowing dust plumes to reach as far south as the Yangtze River delta. Consequently, the mean visibility during these events has plummeted, while the duration of individual storms has increased by approximately 45% compared to the 1990s baseline. This transition highlights a shift from local soil-driven events to large-scale atmospheric phenomena, where extreme wind speeds override traditional land-management successes. However, there is considerable uncertainty about whether sand and dust storms are increasing in intensity and frequency and how much is due to human causes. There is also need for greater clarity on the role that climate change is playing and how changes in dust emissions due to land use and climate change may impact the atmosphere, climate and oceans in the future. Policymakers and other stakeholders need more information on what can be done to reduce the frequency and intensity of sand and dust storms and to protect infrastructure and human health from their effects (Shepherd et al., 2016). Such data, synthesized from ground-based stations and reanalysis products like NCEP/NCAR, underscores that despite significant greening efforts, the intensification of the Siberian High and regional warming continues to drive an expansion of the affected zones across Northern and Eastern China.

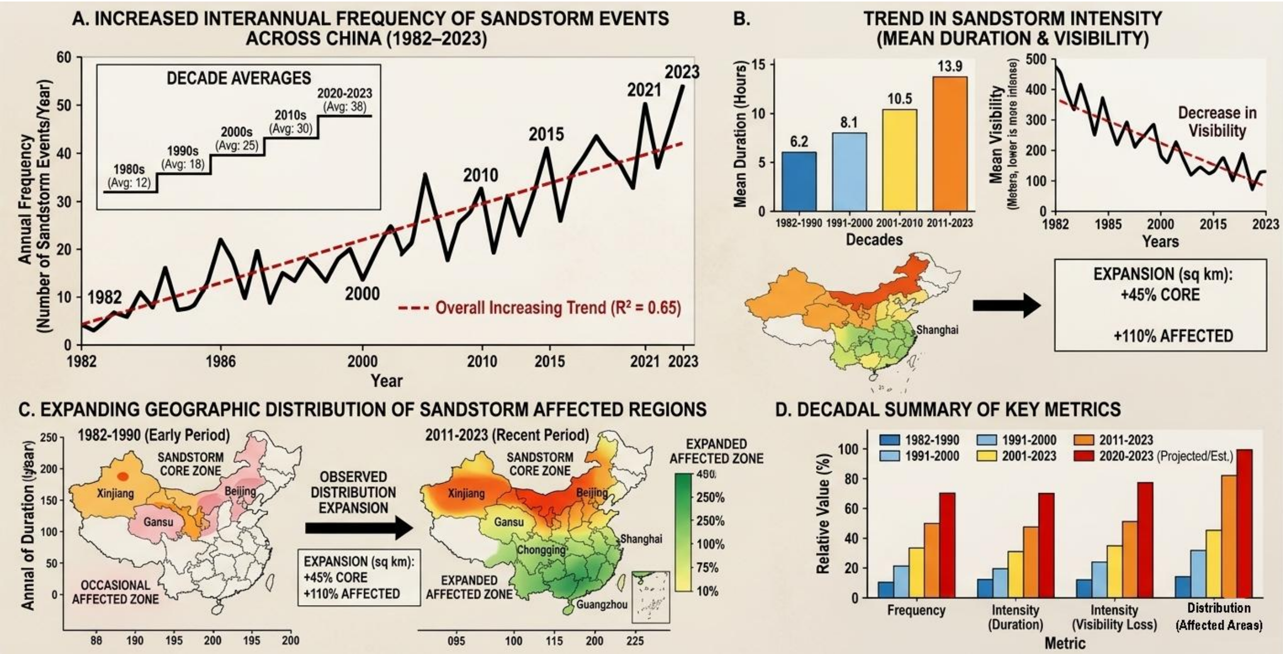

Figure 13. Observed Iincrease in sandstorm frequency, intensity, and distribution in China: 1982-2023. Data sources: China Meteorological Administration, 2020; National Meteorological Information Center (NMIC), 2022; S. Wang et al., 2012; Guan et al., 2023a.

5. Conclusion

This article examined sandstorms in China, emphasizing their connection to environmental factors: geology, climate and desertification processes. It analyzes the relationships among various ecological features in northern desert areas of China, including soil, vegetation, and climate characteristics, along with their distribution across different physiographic regions. This foundation aims to facilitate future research, particularly incorporating multi-source datasets, to enhance the understanding of the state, causes, and severity of sandstorms.

The study contributes significantly to environmental management and policy formulation by analyzing the impacts of sandstorms in northern China, particularly in relation to desertification. It reveals vulnerable areas that are prone to sandstorms throughout different times of the year. Through rigorous spatial analysis, the research identifies regions characterized by soft soils that are severely affected by these phenomena, underlining the necessity for afforestation efforts on sandy surfaces. The study simultaneously evaluates various climatic and biophysical factors influencing the environment, including wind patterns, precipitation levels, soil characteristics, and vegetation presence. By employing a series of maps and graphs, it effectively conveys the findings regarding the dynamics and mechanisms underlying sandstorm occurrences. The comparative geospatial analysis enhances the understanding of how these environmental factors interact to produce sandstorms in the affected areas of China, thus informing potential land management strategies to mitigate adverse effects of such natural events.

Prospective research should aim to upscale these findings by integrating multi-source geospatial datasets to simulate the spatio-temporal dynamics of aeolian transport across the global "dust belt," spanning North Africa, the Middle East, and the endorheic basins of Central Asia, including Mongolia and Kazakhstan. By employing advanced high-resolution modeling, future investigations can delineate precise provenance regions (dust sources) and quantify the differential influence of regional synoptic climates and pedological classifications on emission flux. Furthermore, it is recommended that subsequent studies bridge the gap between environmental geomorphology and land-use policy; this involves evaluating the efficacy of cross-border desertification mitigation strategies and identifying the specific drivers of soil degradation. Prioritizing the preservation of soil structural integrity and the restoration of biological crusts will be central to developing robust, preventive frameworks against the escalating hazards of global sand and dust storms (SDS) in China.

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