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Regime-dependent expression of regional aerosol signals in urban PM_{10} and $PM_{2.5}$ across arid northern China

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Abstract. Air pollution in arid regions emerges from the interaction between regional aerosol transport and local atmospheric processes, yet it remains unclear whether inter-city synchronization reflects direct transport or shared meteorological forcing. This ambiguity limits the interpretation of urban air quality and the design of effective control strategies in dust-influenced environments. Here, we analyze PM_{10} and $PM_{2.5}$ observations across 47 cities in northern China during 2015–2025. We quantify regional coupling using explained variance (R^2) and introduce a differential regional control metric (ΔR^2) to resolve the relative sensitivity of coarse and fine particles to regional forcing. We find that strong inter-city synchronization coexists with substantial heterogeneity in underlying processes. Although the regional signal explains comparable variability in PM_{10} and $PM_{2.5}$, ΔR^2 varies widely across cities (−0.57 to +0.34), revealing distinct pollution regimes. These regimes are systematically linked to aerosol composition and proximity to desert sources, indicating that similar levels of synchronization can arise from fundamentally different mechanisms. Event-scale analysis further shows a nonlinear dependence of aerosol concentrations on wind speed, with extreme PM_{10} occurring under both weak and strong winds. This reflects two contrasting regimes: accumulation under limited ventilation and transport-driven dust events. Together, these results demonstrate that regional synchronization is not a unique indicator of transport but an emergent property of multiple interacting processes. The proposed framework provides a process-oriented basis for distinguishing these regimes and improving the interpretation and management of air quality in arid regions.

Keywords: Aerosol pollution; Regional synchronization; Differential regional control; Arid regions; Dust transport.

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1. Introduction

Air pollution in arid and semi-arid regions represents a complex system in which regional aerosol transport processes interact with local emission sources (Monks et al., 2009; Hassan et al., 2022; Liu et al., 2024). As demonstrated in studies of oasis cities along the southern margin of the Taklamakan Desert, up to 70% of PM_{10} during dust storm periods originates from natural mineral dust, whereas during non-dust conditions anthropogenic sources such as industrial emissions and coal combustion become dominant (Yu et al., 2024). In contrast to humid and industrialized regions, where anthropogenic factors prevail, mineral dust plays a major role in arid environments, being generated in extensive desert systems and transported over long distances by atmospheric circulation (Shao et al., 2011; Ginoux et al., 2012). As noted by Querol et al. (2025) in a recent review, in receptor regions desert dust is typically mixed with locally and regionally emitted particulate matter, which complicates the interpretation of observations. This mixing process has also been confirmed for East Asia, where, according to the synthesis by Chen et al. (2017a), aerosols originating from the Taklamakan and Gobi deserts represent a dominant regional forcing. As a result, particulate matter concentrations in urban areas reflect not only local emissions but also the influence of large-scale processes, making both the interpretation of observations and the development of effective air quality management strategies more challenging.

However, the presence of a regional aerosol background does not necessarily imply that urban concentration variability is directly controlled by particle transport. In arid regions, atmospheric circulation may play a dual role, facilitating aerosol transport while also controlling ventilation and accumulation conditions (Miao et al., 2018; Huang et al., 2018; Liao et al., 2024). In particular, periods of weak wind and stable atmospheric stratification may promote the accumulation of both dust and anthropogenic components, whereas stronger winds can lead to dilution and dispersion. In this context, it remains an open question whether the observed regional coherence of concentrations is driven by direct aerosol transport or by the synchronous influence of meteorological conditions.

Northern China represents a unique natural and climatic system, encompassing one of the largest arid belts in the world, including the Taklamakan, Gobi, Badain Jaran, and Tengger deserts, as well as the Qaidam Basin (Chen et al., 2017a; Zhang et al., 2021; Mao et al., 2025). These regions are major sources of mineral dust, influencing air quality at both local and interregional scales (Uno et al., 2009; Zhang et al., 2018;

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Tian et al., 2021). At the same time, urbanized areas located within or at the margins of these deserts are affected by both regional transport and local factors, including secondary aerosol formation, topographic effects, and urban emissions (Zhang et al., 2003; Li et al., 2010; Meng et al., 2019).

Despite the substantial body of research on dust aerosols and air quality, most studies have focused either on dust source characterization or on the temporal variability of concentrations (Li et al., 2025; Zhang et al., 2025). The spatial coherence of pollution across cities and the mechanisms controlling differences in their degree of coupling to the regional signal remain insufficiently explored (Lin et al., 2022; Zhang et al., 2022). In particular, it is still unclear to what extent the variability of PM_{10} and $PM_{2.5}$ concentrations is governed by regional processes and how this role varies depending on geographic location and aerosol composition.

A particularly important aspect is the comparison between coarse (PM_{10}) and fine ($PM_{2.5}$) aerosol fractions. In arid regions, PM_{10} is primarily associated with mineral dust and regional sources, whereas $PM_{2.5}$ contains a substantial fraction of secondary and anthropogenic components formed in the atmosphere and more sensitive to local conditions (Huang et al., 2014a; Zhang and Cao, 2015; Fomba et al., 2024; Zhou et al., 2026). Field measurements in northwestern China have shown that the mixing of dust and anthropogenic pollutants near desert sources leads to significant changes in aerosol optical and microphysical properties (Li et al., 2010). This distinction provides a basis for using the comparison of these fractions as a tool to disentangle regional and local controls.

In this study, we propose a quantitative framework for analyzing regional synchronization of air pollution and inter-city heterogeneity based on the decomposition of concentration variability into regional and local components. The key idea is to use explained variance (R^2) as a measure of the contribution of the regional signal and to introduce a differential regional control metric (ΔR^2), reflecting the relative dominance of processes affecting PM_{10} and $PM_{2.5}$. This approach enables a transition from a descriptive characterization of pollution to the identification of underlying mechanisms.

The analysis is based on ground-based monitoring data from 47 cities across arid and semi-arid regions of northern China for the period 2015 to 2025. The main objectives of this study are: (1) to assess the degree of regional synchronization of PM_{10} and $PM_{2.5}$ concentrations, (2) to quantitatively separate the contributions of regional

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and local processes, (3) to classify cities according to types of regional control, and (4) to identify the factors driving inter-city heterogeneity.

2. Methods

This study is based on a conceptual framework that separates observed variability in urban particulate matter into regional and local components using a data-driven decomposition approach. The framework combines leave-one-out estimation of a regional signal with variance-based metrics to quantify the relative contribution of large-scale processes and city-specific factors. Differences between PM_{10} and $PM_{2.5}$ responses are further used to diagnose regime-dependent mechanisms of aerosol formation and amplification.

2.1. Study area and data sources

The study covers 47 cities located in arid and semi-arid regions of northwestern China, including Xinjiang, Gansu, Ningxia, and Inner Mongolia, as well as inland basins such as the Qaidam Basin. These regions are characterized by frequent dust activity, strong climatic gradients, and diverse geomorphological conditions. The spatial configuration of the study area, including the distribution of cities and major desert systems, is shown in Figure 1.

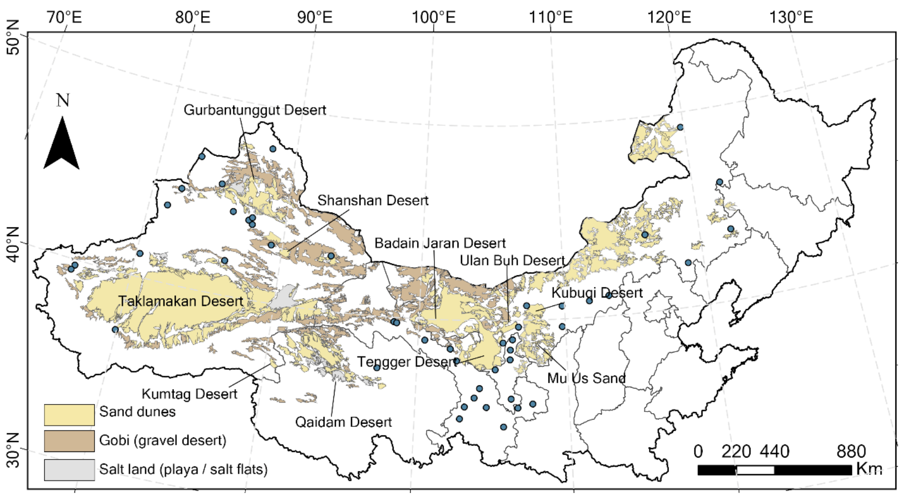

Figure 1. Study area showing the spatial distribution of analyzed cities and major desert regions across arid and semi-arid regions of northern China.

Ground-based air quality monitoring data were obtained from the national network operated by the China National Environmental Monitoring Centre, including hourly

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PM_{10} and $PM_{2.5}$ concentrations for the period from 1 January 2015 to 31 December 2025. Measurements are conducted in accordance with national standards and subject to centralized quality control procedures. Meteorological data were derived from the ERA5 reanalysis (European Centre for Medium-Range Weather Forecasts; Hersbach et al., 2020), using monthly fields at 0.25°×0.25° resolution, including 10 m wind speed. For each city, wind speed was extracted at the corresponding grid point and used to examine its role in aerosol variability and extreme pollution conditions.

Within this study, hourly data were aggregated to daily values and subsequently to monthly means. Geographic coordinates of the cities, including latitude and longitude, were used to analyze spatial gradients.

2.2. Data preprocessing and quality control

Initial data processing included format harmonization, removal of invalid values, and verification of time series continuity, with negative concentration values treated as measurement errors and excluded. Data aggregation was conducted in two stages, with hourly observations averaged to daily values and subsequently to monthly means; a monthly value was considered valid if at least 75% of daily observations were available. To ensure robustness, only cities with more than 85% valid monthly values over the entire study period for both PM_{10} and $PM_{2.5}$ were retained. After applying these criteria and matching with geographic coordinates, a total of 47 cities with time series of up to 132 months were included in the analysis.

2.3. Construction of regional signal

To estimate the regional signal, a leave-one-out approach was applied. For each city i, the regional signal was defined as the average concentration across all other cities:

$$R_i(t) = \frac{1}{N-1}\sum_{j\neq i} C_j(t)$$

where $C_j(t)$ - s the concentration in city j, and N - is the total number of cities.

This approach ensures that the regional signal is independent of the local dynamics of the target city and prevents artificial inflation of correlation estimates.

2.4. Standardization and anomaly analysis

To analyze synchronization of time series, standardized anomalies were used. For each city, the time series was normalized as follows:

$$Z_i(t) = \frac{C_i(t) - \mu_i}{\sigma_i}$$

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where μ_i and σ_i— are the mean and standard deviation of concentrations for city i.

Standardization removes the influence of differences in absolute concentration levels and allows the analysis to focus on temporal coherence. Spatial heterogeneity was assessed based on the distribution of $Z_i(t)$ across all cities at each time step using the interquartile range (IQR).

It should be noted that seasonal components were removed in this study, whereas explicit detrending of long-term trends was not performed. As a result, part of the detected synchronization may reflect not only short-term regional processes but also synchronous changes associated with long-term emission trends, environmental policies, and external factors such as the COVID-19 period.

2.5. Correlation analysis and regional synchronization

The relationship between concentration time series and the regional signal was evaluated using the Pearson correlation coefficient. For each city, the correlation between its time series and the corresponding leave-one-out regional signal was calculated as:

$$r_i = corr(C_i(t), R_i(t))$$

The inter-city correlation matrix was constructed using monthly data and Pearson correlation. Calculations were performed pairwise using all available observations (pairwise complete), allowing for missing data.

2.6. Variance decomposition and differential regional control

To quantify the contribution of the regional signal, explained variance was used:

$$R_i^2 = r_i^2$$

Values of R^2 were calculated separately for PM_{10} and $PM_{2.5}$. To assess differences between them, a differential regional control metric was introduced:

$$\Delta R_i^2 = R_{PM10,i}^2 - R_{PM2.5,i}^2$$

This metric provides a quantitative measure of the relative contribution of the regional signal to variability in different aerosol fractions and allows identification of inter-city variability in pollution formation mechanisms.

2.7. City classification (typology of synchronization regimes)

City classification was based on R2 and ΔR2, taking into account both the absolute strength of regional coupling and the differences between PM10 and PM2.5:

- Strong regional control: $R_{PM10}^2 \geq 0.64$ и $R_{PM2.5}^2 \geq 0.64$;

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- PM_{10}-dominated regional control: $\Delta R^2 \geq 0.10$;
- $PM_{2.5}$-dominated regional control: $\Delta R^2 \leq -0.10$;
- Moderate mixed control: all other cases.

This typology allows identification of groups of cities characterized by different pollution formation mechanisms.

The threshold values used for classification (e.g., $R^2 \geq 0.64$) were selected empirically based on the distribution of values in the dataset and represent the upper range of regional synchronization. These thresholds are intended for illustrative separation of cities into types and do not imply strict physical boundaries between regimes. Therefore, the proposed typology is descriptive in nature and aims to reveal general patterns rather than enforce rigid classification.

To assess the robustness of the typology, a sensitivity analysis was performed by varying the thresholds of R^2 and ΔR^2 within ranges close to the baseline criteria. For each alternative set of thresholds, the classification was repeated and its consistency with the baseline scheme (R^2=0.64, ΔR^2=0.10) was evaluated.

2.8. Long-term mean concentrations and aerosol composition

To analyze inter-city differences, mean concentrations over the entire observation period were calculated as:

$$\overline{PM10\iota} = \frac{1}{T}\sum_{t=1}^{T} PM10_i(t)$$

$$\overline{PM2.5\iota} = \frac{1}{T}\sum_{t=1}^{T} PM2.5_i(t)$$

Based on these values, the ratio was computed as:

$$Ratio_i = \frac{\overline{PM2.5_\iota}}{\overline{PM10_\iota}}$$

which was used as an integrated indicator of aerosol composition.

2.9. Drivers of inter-city heterogeneity

To analyze the drivers of inter-city heterogeneity, the ΔR^2 metric was compared with:

- the $PM_{2.5}/PM_{10}$ ratio
- the mean PM_{10} concentration
- geographic coordinates (latitude and longitude)

Statistical relationships were assessed using the Spearman rank correlation coefficient:

$$p = Spearman(X, \Delta R^2)$$

This approach is robust to outliers and does not require the assumption of linear relationships. Statistical significance was evaluated at the level of $p<0.05$.

2.10. Wind regime analysis and extreme events

To investigate the role of atmospheric circulation in shaping regional synchronization, a regime-based analysis combining extreme event identification and wind-dependent statistics was performed. Regional mean values of PM_{10}, $PM_{2.5}$, and 10 m wind speed were calculated by averaging across all cities, and extreme pollution events were defined as months with PM_{10} exceeding the 90th percentile.

The dependence of extreme event probability on wind conditions was assessed by grouping wind speed values into intervals and calculating, for each interval, the fraction of months classified as extreme. In parallel, PM_{10} distributions were compared between contrasting wind regimes, defined using wind speed quantiles (below the 25th percentile for low-wind conditions and above the 75th percentile for high-wind conditions), with differences evaluated using the Mann–Whitney U test.

Finally, the relationship between wind speed and pollution intensity during extreme events was quantified using the Spearman rank correlation coefficient, allowing identification of robust monotonic dependencies without assuming linearity.

3. Results

3.1. Regional synchronization of PM_{10} and $PM_{2.5}$ concentrations

Analysis of ground-based monitoring data from 47 cities in arid regions of northwestern China over the period 2015–2025 (132 months after quality control) reveals that variability in aerosol concentrations is characterized by pronounced regional coherence. After removal of the seasonal component and normalization of time series (Figure 2a), the interquartile range (IQR), representing spatial variability among cities, remains relatively narrow throughout most of the period (median IQR = 0.75). This indicates that fluctuations in PM_{10} concentrations occur synchronously across most cities and therefore cannot be explained solely by local sources. The observed coherence suggests a dominant influence of large-scale factors; however, it does not uniquely determine the underlying mechanism of their nature. Regional synchronization may arise either from the coherent influence of atmospheric circulation, including aerosol transport (Shao et al., 2011; Zhao et al., 2015), or from simultaneous changes in ventilation and accumulation conditions across cities. Thus, the detected

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synchronicity reflects the presence of a common regional regime but does not directly define its underlying mechanism.

At the same time, temporal dynamics show a clear relationship between the intensity of the regional signal and spatial heterogeneity. In particular, in March 2021, a simultaneous increase in both the amplitude of the regional anomaly (up to 2.20) and spatial variability (IQR = 6.01) is observed (Figure 2a), reflecting the impact of an intense large-scale dust event (Liang et al., 2022; Yu et al., 2023). Such a synchronous response across a large number of cities indicates that extreme concentration levels are primarily driven by regional-scale processes (Wang et al., 2021), while local conditions modulate the magnitude of the response in individual cities.

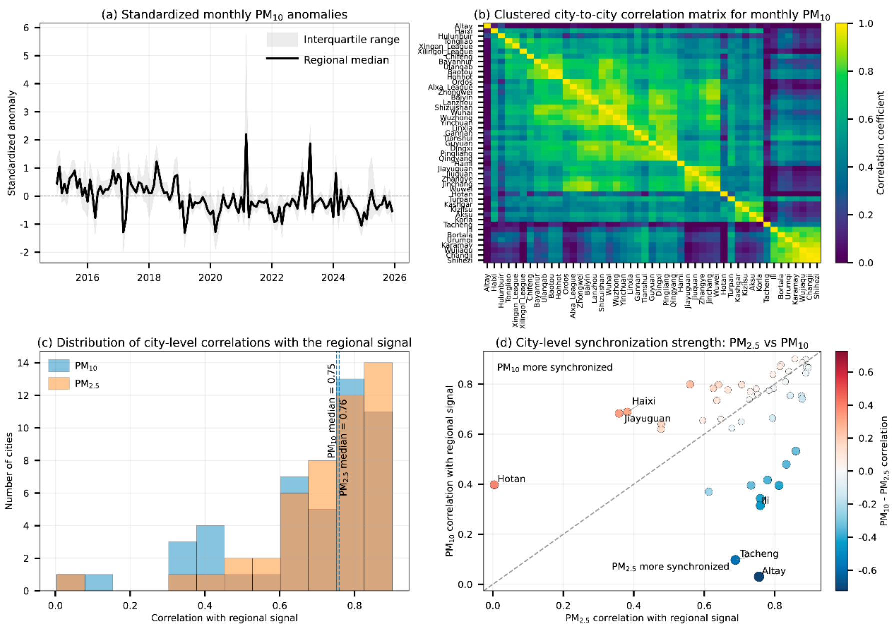

Figure 2. Regional synchronization of particulate pollution across arid cities of China.

The spatial structure of inter-city relationships supports this interpretation. The PM_{10} correlation matrix (Figure 2b) shows a consistently positive relationship among most cities (mean = 0.48, median = 0.50), indicating the presence of a common regional regime. However, the wide range of values (from −0.35 to 0.98) reflects substantial spatial heterogeneity. These differences are likely associated with a combination of factors, including geographic location, orographic barriers, and the degree of involvement of cities in major dust transport pathways (Ge et al., 2014; Kang et al.,

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2021). Thus, the regional signal is not uniform but modulated, with local conditions determining the degree of deviation of individual cities from the common regime.

Quantitative assessment of the relationship between each city and the regional signal (Figure 2c) shows that for PM_{10} the median correlation reaches 0.75 (mean = 0.67), indicating a high degree of synchronization. For $PM_{2.5}$, similar values (median = 0.76, mean = 0.72) suggest comparable coherence; however, lower variability (σ = 0.17 compared to 0.21 for PM_{10}) indicates a more homogeneous spatial distribution of fine particles. This difference reflects the physical nature of the particles, where PM_{10} in arid regions is predominantly associated with mineral dust and regional sources, while $PM_{2.5}$ includes a substantial fraction of secondary and anthropogenic components formed locally and less sensitive to extreme dust events (Zhang and Cao, 2015).

Comparison of synchronization strength between PM_{10} and $PM_{2.5}$ at the city level (Figure 2d) shows no dominant aerosol type. In 24 out of 47 cities, PM_{10} exhibits a stronger relationship with the regional signal, whereas in 23 cities the opposite pattern is observed. The mean difference remains close to zero (−0.05), indicating a balance between dust-related and secondary processes in shaping regional synchronization. At the same time, the wide range of differences (from −0.72 to +0.39) reflects substantial inter-city variability in pollution formation mechanisms.

The inclusion of Haixi Prefecture (Qaidam Basin) reveals an important transitional regime within the regional synchronization system. Despite its location in an arid environment and proximity to potential dust sources, Haixi exhibits relatively low correlation with the regional signal for $PM_{2.5}$ (0.382) and is among the cities with the strongest dominance of PM_{10} (difference between PM_{10} and $PM_{2.5}$ correlations ≈ 0.31). This indicates the dominance of local dust processes and limited coupling with the broader regional dynamics, reflecting the characteristics of inland basins with sparse urbanization (Zhu et al., 2026). In contrast to more integrated urban systems, such as cities in Gansu and Ningxia, Haixi demonstrates reduced participation in the common regional regime, representing a transitional type between locally controlled and regionally synchronized systems.

To further characterize spatial heterogeneity, cities were classified according to their synchronization regimes with the regional signal (Table 1). The classification accounts for both the absolute level of correlation and differences between PM_{10} and $PM_{2.5}$, allowing identification of groups of cities with distinct dominant pollution formation mechanisms. In total, 11 cities exhibit strong regional synchronization, 9 are PM_{10}-

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dominated, 13 are $PM_{2.5}$-dominated, and 14 show moderate mixed control. The full list of cities and corresponding correlation values is provided in Table S1.

Table 1. Typology of cities based on synchronization with the regional particulate pollution signal, defined using R^2 and ΔR^2 thresholds.

Category	**Criteria**	**Number of cities**	**Interpretation**	**Example cities**
Strong regional synchronization	R^2 (PM_{10}) $\geq$ 0.64 and R^2 ($PM_{2.5}$) $\geq$ 0.64	11	Dominant regional control for both fractions	Wuzhong, Guyuan
PM_{10}-dominated synchronization	$\Delta R^2 \geq 0.10$	9	Stronger regional coupling for coarse particles (dust influence)	Jinchang, Alxa_ League
$PM_{2.5}$-dominated synchronization	$\Delta R^2 \leq -0.10$	13	Stronger regional coupling for fine particles (secondary/anthropogenic influence)	Tianshui, Turpan
Moderate synchronization	Otherwise	14	Mixed and intermediate control regimes	Zhongwei, Ulanqab

Cities with strong regional synchronization (e.g., Wuzhong and Guyuan) are characterized by high correlations for both PM_{10} and $PM_{2.5}$, indicating strong coherence with the regional signal. PM_{10}-dominated cities (e.g., Jinchang, Alxa League, and Haixi) exhibit substantially stronger coupling of PM_{10} with the regional signal compared to $PM_{2.5}$, consistent with the enhanced role of coarse particles associated with mineral dust. In contrast, $PM_{2.5}$-dominated cities (e.g., Tianshui and Turpan) show stronger synchronization in fine particles, reflecting a greater influence of secondary and anthropogenic processes. Moderately synchronized cities (e.g., Zhongwei and Ulanqab) display intermediate correlations, indicating mixed control where regional and local factors interact.

Overall, the results indicate that air pollution in arid urban systems is characterized by a pronounced hierarchical structure of synchronization, in which the regional signal defines the overall temporal regime, while local conditions modulate its manifestation at the city level. The inclusion of Haixi further demonstrates the existence of transitional regimes where coupling to the regional signal weakens and the role of local dust sources increases. This highlights the necessity of distinguishing between regional and local mechanisms of aerosol concentration formation, which is addressed in the subsequent analysis.

It is important to note that the leave-one-out regional signal represents a statistical construct reflecting temporal coherence among cities rather than a direct measure of

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physical aerosol transport processes. The observed coherence may arise either from a common regional forcing, such as dust storms and atmospheric circulation, or from the superposition of multiple partially independent modes of variability.

In this context, the regional signal should be interpreted as an integrated indicator of large-scale forcing rather than a direct proxy for transport alone. Distinguishing between transport-driven and regime-driven synchronization therefore requires additional process-based analysis, which is addressed in the following sections.

3.2. Differential regional control of PM_{10} and $PM_{2.5}$

The transition from correlation analysis to explained variance decomposition (R^2) enables a quantitative assessment of the contribution of the regional signal to aerosol concentrations and reveals differences in the control mechanisms of PM_{10} and $PM_{2.5}$. On average, the regional signal explains a comparable fraction of variability for both particle types, but with fundamentally different spatial structures. The mean R^2 value for PM_{10} is 0.49 (median 0.57), whereas for $PM_{2.5}$ it is 0.55 (median 0.58). Despite similar aggregate values, the distribution of the difference (ΔR^2) exhibits pronounced asymmetry and substantial inter-city variability (from −0.57 to +0.34), indicating the existence of distinct pollution control regimes.

At the level of individual cities, differences between PM_{10} and $PM_{2.5}$ are systematic rather than random (Figure 3a). A substantial fraction of cities is distributed along the line of equality, corresponding to a balanced influence of regional processes on both aerosol types. However, deviations from this line form two contrasting regimes, namely PM_{10}-dominated and $PM_{2.5}$-dominated control. In the former case ($\Delta R^2 > 0$), the contribution of the regional signal to PM_{10} variability substantially exceeds that for $PM_{2.5}$, reflecting the dominance of mineral dust and direct dust emissions. In the latter case ($\Delta R^2 < 0$), the opposite pattern is observed, indicating a stronger role of secondary and anthropogenic processes in shaping $PM_{2.5}$ variability.

Ranking of cities by ΔR^2 (Figure 3b) confirms the absence of a single dominant mechanism. The mean ΔR^2 is slightly negative (−0.06), while the median remains close to zero (0.01), indicating an overall balance between the two regimes in the presence of pronounced extremes. In particular, cities such as Jiayuguan ($\Delta R^2 = 0.34$), Alxa League (0.32), and Haixi (0.33) exhibit the strongest PM_{10} dominance, whereas Altay (−0.57), Karamay (−0.50), and Ili (−0.48) are characterized by strong $PM_{2.5}$ dominance. This

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structured distribution indicates that inter-city differences are driven by persistent physical processes rather than random fluctuations.

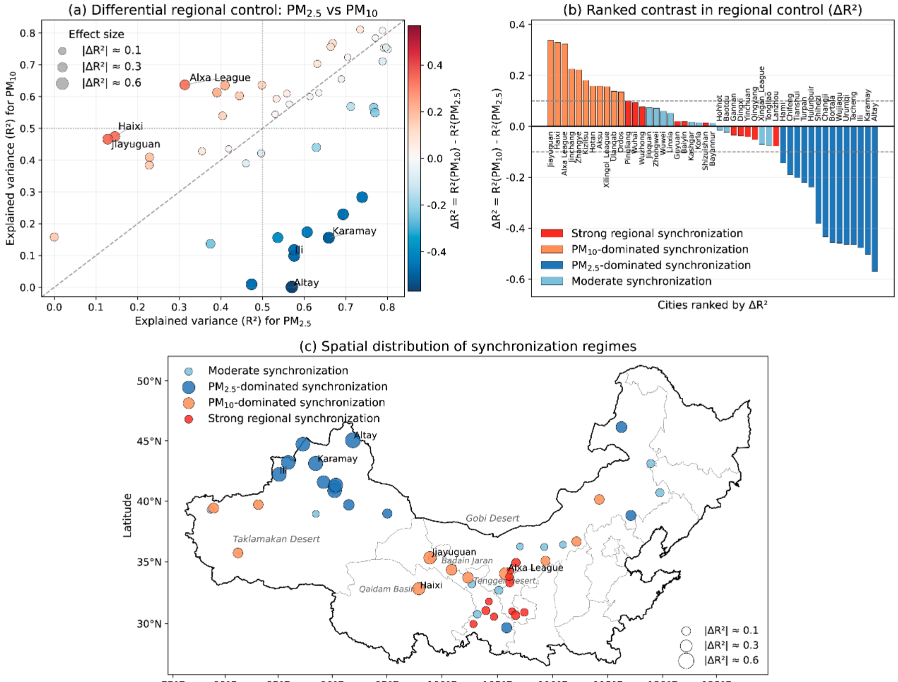

Figure 3. Differential regional control of PM_{10} and $PM_{2.5}$ across arid cities.

Haixi Prefecture, located within the Qaidam Basin, represents a particularly illustrative case. Despite arid conditions and proximity to potential dust sources, Haixi exhibits a moderate contribution of the regional signal to PM_{10} ($R^2 = 0.47$) and an extremely low contribution to $PM_{2.5}$ ($R^2 = 0.15$), resulting in one of the highest ΔR^2 values (0.33) among all cities. This pattern indicates the dominance of local dust processes and weak integration into the regional regime, in contrast to more urbanized areas in Gansu and Ningxia. Haixi thus represents a transitional system in which the regional signal weakens and local sources become dominant.

The spatial distribution of control regimes (Figure 3c) reveals a clear geographic organization. Cities with strong regional control and balanced contributions of PM_{10} and $PM_{2.5}$ are predominantly located along the Gansu–Ningxia corridor, where conditions favor efficient aerosol transport. PM_{10}-dominated cities are concentrated near desert and semi-desert regions (e.g., Alxa and western areas), reflecting the influence of active dust sources. In contrast, $PM_{2.5}$-dominated cities are more frequently

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found in the northern and eastern parts of the study region, where the role of secondary aerosols and anthropogenic emissions increases.

Overall, the variance decomposition demonstrates that regional synchronization does not imply uniform underlying processes. Instead, it reflects a superposition of distinct, regime-dependent mechanisms governing aerosol variability. The ΔR^2 framework therefore provides a quantitative basis for disentangling these mechanisms and linking observed synchronization to physically interpretable controls, including dust transport and local aerosol formation processes.

3.3. Observed drivers of inter-city heterogeneity in differential regional control

To identify factors associated with inter-city heterogeneity in differential regional control, the ΔR^2 metric was compared with indicators reflecting aerosol composition and geographic positioning relative to major dust source regions (Figure 4).

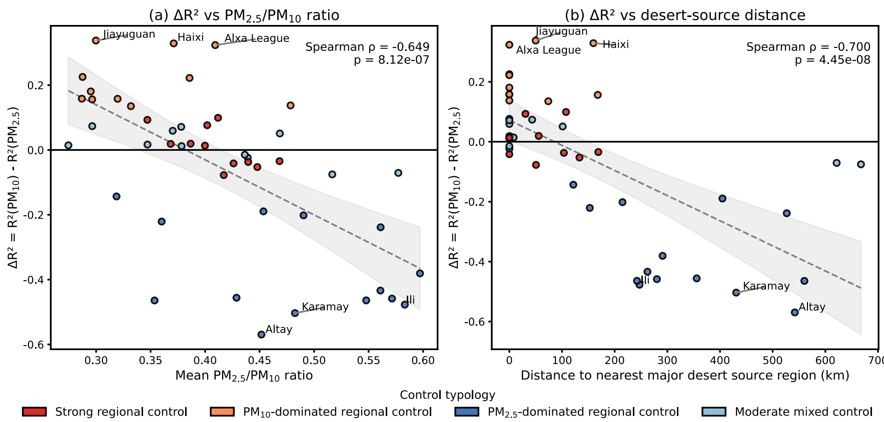

Figure 4. Observed correlates of inter-city heterogeneity in differential regional control.

The strongest statistical relationship is observed with the mean $PM_{2.5}/PM_{10}$ ratio ($\rho = -0.649$, $p < 0.001$; Figure 4a). As the contribution of the fine aerosol fraction increases, ΔR^2 systematically shifts toward negative values, indicating a relatively stronger role of the regional signal in $PM_{2.5}$ compared to PM_{10}. Conversely, lower $PM_{2.5}/PM_{10}$ ratios are associated with positive ΔR^2 values, reflecting enhanced regional control of coarse particles. This relationship highlights aerosol composition as an integrated indicator of the dominant processes shaping particulate variability across cities.

Importantly, a similarly strong relationship is identified with the distance to the nearest major desert source region ($\rho = -0.700$, $p < 0.001$; Figure 4b). Cities located

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closer to major dust sources tend to exhibit higher ΔR^2 values, consistent with stronger regional control of PM_{10} driven by mineral dust emissions and transport. In contrast, more distant cities show increasingly negative ΔR^2 values, indicating a relative shift toward stronger regional expression in $PM_{2.5}$. Compared to latitude-based representations, this distance-based metric provides a more direct geographic proxy of dust-source exposure and transport influence.

Together, these results demonstrate that inter-city heterogeneity in differential regional control is not random but systematically associated with both aerosol composition and spatial positioning relative to major dust-emission regions. The combination of these factors defines a continuum of regimes ranging from dust-dominated systems with strong regional control of PM_{10} to environments where fine particles exhibit stronger regional coherence.

It should be noted that the relationship between ΔR^2 and the $PM_{2.5}/PM_{10}$ ratio may include a mathematical component, as both metrics involve characteristics of $PM_{2.5}$ variability. However, the consistency of this relationship with an independent geographic gradient, represented by distance to desert sources, supports a physically meaningful interpretation and argues against a purely statistical artifact.

Crucially, ΔR^2 should not be interpreted as a direct measure of aerosol transport, but rather as a response metric that quantifies how urban particulate matter variability reflects regional forcing. In this framework, high ΔR^2 values indicate systems in which coarse particles (PM_{10}) respond more strongly to regional-scale variability, consistent with transport-dominated dust regimes, whereas negative ΔR^2 values indicate a relative enhancement of the regional signal in fine particles ($PM_{2.5}$), reflecting accumulation and secondary processes. Thus, ΔR^2 captures the regime-dependent realization of a common regional signal within different urban environments, rather than the transport process itself.

Additional relationships with latitude and mean PM_{10} concentration are presented in the Supplement (Figure S3). While both variables show statistically significant associations with ΔR^2, they are weaker than those observed for aerosol composition and desert-source distance, and likely reflect indirect or proxy effects related to geographic positioning and aerosol characteristics rather than primary controls.

3.4. Ventilation versus accumulation regimes in regional particulate variability

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To refine the physical interpretation of the regional signal, an additional analysis of the relationship between aerosol concentrations and wind characteristics was performed. Analysis of mean relationships between regional PM values and wind speed (Figure S1) shows weak and ambiguous associations for both PM_{10} and $PM_{2.5}$. The observed correlations do not exhibit a consistent increase in concentrations with increasing wind speed, and the use of absolute anomalies also does not reveal a clear positive relationship. This indicates that mean relationships have limited explanatory power for interpreting pollution formation mechanisms.

To address this limitation, an event-based analysis focusing on extreme PM_{10} concentrations (upper 10% of the distribution) was conducted, allowing identification of regimes associated with the highest pollution levels (Figure 5). The results show that extreme concentrations occur across a wide range of wind speeds and are not confined to low-wind conditions (Figure 5a). Moreover, the probability of extreme events does not exhibit a monotonic dependence on wind speed (Figure 5b), ruling out interpretation in terms of a single dominant mechanism.

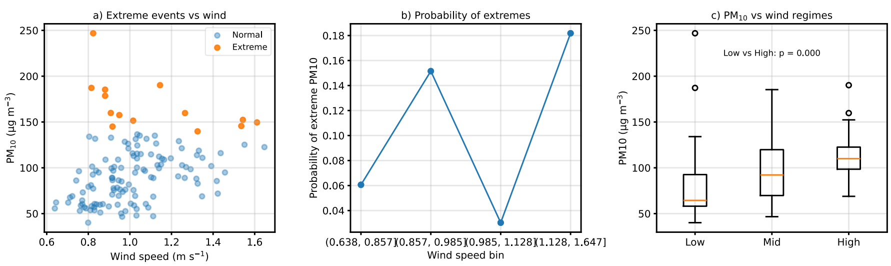

Figure 5. Wind-regime dependence of extreme particulate pollution in arid regions.

Comparison of concentration distributions under different wind regimes (Figure 5c) reveals statistically significant differences between low- and high-wind conditions (Mann–Whitney U test, $p < 0.05$). Under low-wind conditions, higher concentrations are observed on average, indicating accumulation of aerosols due to limited ventilation. At the same time, extreme values are also recorded at higher wind speeds, which are likely associated with episodes of intensified mineral dust transport.

Overall, these results demonstrate the existence of two physically distinct pollution formation regimes. The first regime is associated with accumulation under low-wind conditions and reduced ventilation, while the second regime is driven by enhanced transport of dust aerosols under higher wind speeds. In this framework, atmospheric circulation acts as a dual-role driver, simultaneously governing both accumulation and

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transport processes. This regime-dependent behavior provides a mechanistic explanation for the coexistence of strong regional synchronization and substantial inter-city heterogeneity, linking statistical patterns directly to underlying physical processes.

4. Discussion

The results demonstrate that regional synchronization of particulate matter concentrations in arid urban systems cannot be interpreted solely as a direct consequence of aerosol transport. The absence of a monotonic relationship between wind speed and pollution levels, together with the occurrence of extreme PM_{10} concentrations across a wide range of wind conditions, indicates that variability is governed by a regime-dependent structure rather than a single dominant mechanism. This interpretation is consistent with previous studies showing that atmospheric circulation can simultaneously regulate pollutant transport and boundary-layer ventilation, producing nonlinear responses under contrasting synoptic conditions (Miao et al., 2018; Huang et al., 2018; Liao et al., 2024).

Two physically distinct regimes emerge from the analysis. The first is associated with accumulation under low-wind conditions and reduced ventilation, leading to elevated concentrations of both coarse and fine particles. The second corresponds to transport-driven conditions, in which stronger winds enhance the emission and long-range transport of mineral dust, producing short-term peaks in PM_{10}. Such a dual role of atmospheric circulation is consistent with the established understanding that wind can either suppress pollution through dispersion or intensify particulate loading through dust mobilization, particularly in arid environments (Knippertz and Todd, 2012; Shao et al., 2011; Wang et al., 2025). This duality implies that similar levels of regional synchronization may arise from fundamentally different physical processes.

The comparison between PM_{10} and $PM_{2.5}$ further reveals that the regional signal is not uniformly expressed across aerosol fractions but undergoes a regime-dependent transformation. Coarse particles are primarily associated with mineral dust emission and transport (Knippertz and Todd, 2012; Kok et al., 2012; Wang et al., 2025), whereas fine particles more strongly reflect secondary formation and anthropogenic contributions (Huang et al., 2014b; Zhang and Cao, 2015; Zhou et al., 2019). Observations from northwestern China indicate that dust and anthropogenic aerosols are frequently mixed near source regions, producing fraction-dependent responses in urban environments (Li et al., 2010; Fomba et al., 2024). As a result, the same regional

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forcing can manifest differently depending on aerosol composition, generating substantial inter-city variability despite overall synchronization.

In this context, the ΔR^2 metric provides a quantitative representation of how urban systems respond to regional forcing. Importantly, ΔR^2 should not be interpreted as a direct proxy for aerosol transport, but rather as a response metric describing the relative sensitivity of different particle fractions to regional variability. Positive ΔR^2 values indicate systems in which coarse particles respond more strongly to regional forcing, consistent with dust-dominated regimes, whereas negative values reflect a relatively stronger regional expression in fine particles, associated with accumulation and secondary processes. This interpretation shifts the focus from transport itself to the realization of regional forcing within urban environments.

The observed relationships indicate that this response is systematically associated with both aerosol composition and geographic context. The $PM_{2.5}/PM_{10}$ ratio serves as an integrated indicator of dominant physicochemical processes, while proximity to major desert source regions constrains exposure to dust emissions and transport pathways. This interpretation is consistent with previous studies demonstrating that dust contributions to urban aerosol loading depend strongly on distance from source regions and transport pathways linking the Taklamakan and Gobi deserts to receptor areas across northern China (Chen et al., 2017a; Yu et al., 2019; Han et al., 2025). Their combined influence defines a continuum of regimes ranging from dust-dominated systems near source regions to environments in which fine particles exhibit stronger regional coherence.

Although the relationship between ΔR^2 and aerosol composition may partly reflect mathematical coupling, its consistency with an independent geographic gradient supports a physically meaningful interpretation. Additional variables such as latitude and mean PM_{10} concentration, which show weaker associations, are therefore better interpreted as proxy indicators rather than primary controls. This distinction highlights the importance of separating physically meaningful drivers from secondary correlations when analyzing large-scale observational datasets.

The existence of transitional regimes further indicates that urban systems form a continuous spectrum rather than discrete categories. Such heterogeneity is consistent with previous work demonstrating strong spatial variability in aerosol sources and mixing processes across arid regions (Chen et al., 2017a; Kang et al., 2017; Li et al., 2025; Zhang et al., 2025). In this framework, transitional systems illustrate how

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regional forcing can be expressed predominantly through one aerosol fraction while remaining weakly coupled in another.

It is important to emphasize that the regional signal used in this study is a statistical construct and does not represent a direct measurement of physical transport processes. The observed synchronization therefore reflects coordinated variability arising from multiple factors, including atmospheric circulation, dust emissions, and large-scale changes in anthropogenic activity. In addition, the absence of explicit detrending implies that part of the detected coherence may be associated with long-term emission reductions and policy-driven improvements in air quality across China (Cheng et al., 2019; Li et al., 2019; Zhang et al., 2019).

From a practical perspective, the results indicate that air-quality management in arid regions must explicitly account for regime-dependent pollution formation. Under accumulation-dominated conditions, mitigation should focus on local emissions and processes controlling urban ventilation. Under transport-dominated conditions, greater emphasis should be placed on dust source regions and land–atmosphere interactions governing dust mobilization (Shao et al., 2011; Tian et al., 2021). The coexistence of these regimes implies that uniform control strategies are unlikely to be effective in dust-influenced environments.

5. Conclusions

This study provides a quantitative analysis of inter-city synchronization of particulate matter across 47 cities in arid and semi-arid regions of northern China for the period 2015–2025. The proposed framework, based on explained variance and the differential regional control metric (ΔR^2), enables the separation of regional and local contributions to PM_{10} and $PM_{2.5}$ variability.

The results show that air pollution in arid urban systems is characterized by strong regional synchronization driven by large-scale forcing, while simultaneously exhibiting pronounced spatial heterogeneity in underlying mechanisms. This indicates that observed coherence cannot be attributed to a single process but instead reflects the coexistence of multiple pollution formation regimes.

A key finding is that the relationship between aerosol concentrations and wind speed is nonlinear and regime-dependent. Extreme PM_{10} concentrations occur under both low- and high-wind conditions, reflecting two physically distinct regimes: accumulation under weak ventilation and transport-driven dust events. This demonstrates that

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atmospheric circulation acts as a dual-role driver, simultaneously regulating both accumulation and transport processes.

The analysis further shows that inter-city differences in regional control are systematically associated with aerosol composition and geographic positioning relative to major dust sources. The $PM_{2.5}/PM_{10}$ ratio reflects the dominant physicochemical processes, while proximity to desert source regions constrains exposure to dust emissions and transport pathways. Together, these factors define a continuum of urban response regimes across arid environments.

Importantly, the ΔR^2 metric should be interpreted as a response metric rather than a direct proxy for aerosol transport. It quantifies how urban particulate matter variability reflects regional forcing under different environmental conditions, thereby linking statistical patterns to physically interpretable regimes.

Methodologically, the results demonstrate that combining variance decomposition with regime-based analysis provides a more robust framework for interpreting regional air pollution dynamics than correlation-based approaches alone.

From a practical perspective, the findings highlight the need for regime-specific air quality management strategies in arid regions. Measures targeting dust emission and transport should be complemented by controls on pollution accumulation under weak ventilation conditions. Future work should focus on integrating independent transport diagnostics and further constraining the physical processes underlying the identified regimes.

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Air quality data used in this study are publicly available from the China National Environmental Monitoring Center (CNEMC, https://www.cnemc.cn/), including daily concentrations of $PM_{2.5}$, PM_{10} for 47 cities in northern China during 2015–2025. Wind speed data at 10 m height were obtained from the European Centre for Medium-Range

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Weather Forecasts ERA5 reanalysis dataset, accessed via the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/).City location data were compiled from publicly available geographic datasets. The processed datasets generated in this study, including monthly aggregated time series, regional signal estimates, and ΔR^2 metrics, are available from the corresponding author upon reasonable request. All code used for data processing, statistical analysis, and figure generation is available from the corresponding author upon request.

References

Chen, S., Huang, J., Kang, L., Wang, H., Ma, X., He, Y., Yuan, T., Yang, B., Huang, Z., Zhang, G., 2017a. Emission, transport, and radiative effects of mineral dust from the Taklimakan and Gobi deserts: comparison of measurements and model results. Atmos. Chem. Phys. 17(3), 2401–2421.

Chen, S., Huang, J., Qian, Y., Zhao, C., Kang, L., Yang, B., Wang, H., Ma, X., Yuan, T., 2017b. An overview of mineral dust modeling over East Asia. J. Meteorol. Res. 31(4), 633–653.

Cheng, J., Su, J., Cui, T., Li, X., Dong, X., Sun, F., Yang, Y., Tong, D., Zheng, Y., Li, Y., Li, J., Zhang, Q., He, K., 2019. Dominant role of emission reduction in PM2.5 air quality improvement in Beijing during 2013–2017: a model-based decomposition analysis. Atmos. Chem. Phys. 19(9), 6125–6146.

Deng, Y., Wu, H., Zhao, T., Shi, C., Zhang, Y., Li, F., 2024. Microscopic characteristics and sources of atmospheric dustfall in open-pit mining coal resource-based City in the arid desert area of Northwest China. Sci. Rep. 14(1), 6272.

Dong, Z., Qin, D., Li, K., Kang, S., Wei, T., Lu, J., 2019. Spatial variability, mixing states and composition of various haze particles in atmosphere during winter and summertime in northwest China. Environ. Pollut. 246, 79–88.

Fomba, K.W., Faboya, O.L., Deabji, N., Makhmudov, A., Hofer, J., dos Santos Souza, E.J., Hermann, H., 2024. The seasonal variation of Asian dust, anthropogenic PM, and their sources in Dushanbe, Tajikistan. Atmos. Environ. 333, 120667.

Ge, J.M., Huang, J.P., Xu, C.P., Qi, Y.L., Liu, H.Y., 2014. Characteristics of Taklimakan dust emission and distribution: A satellite and reanalysis field perspective. J. Geophys. Res. Atmos. 119(20), 11,772–11,783.

Ginoux, P., Prospero, J.M., Gill, T.E., Hsu, N.C., Zhao, M., 2012. Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. Rev. Geophys. 50(3), RG3005.

Han, L., Zhang, Z., Liang, A., Lu, J., Dong, Z., Zhang, Z., 2025. Deciphering dust provenance and transport pathways across Northern China‘s source-sink systems. Atmos. Chem. Phys. 25(21), 15343–15357.

Hassan, H., Kumar, P., Kakosimos, K.E., 2022. The impact of local fugitive particulate matter and emission inventories on air quality and health in dry and arid areas. Sci. Total Environ. 824, 153799.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Thépaut, J.N., 2020. The ERA5 global reanalysis. Q. J. Roy. Meteorol. Soc.146(730), 1999-2049.

Huang, F., Gong, C., Ma, W., Liu, H., Zhong, B., Jing, C., Zhang, X., 2025a. Analysis of spatiotemporal distribution trends of aerosol optical depth and

https://doi.org/10.5194/egusphere-2026-3468
Preprint. Discussion started: 11 August 2026

meteorological influences in Gansu Province, Northwest China. Remote Sens. 17(16), 2874.

Huang, J., Wang, T., Wang, W., Li, Z., Yan, H., 2014a. Climate effects of dust aerosols over East Asian arid and semiarid regions. J. Geophys. Res. Atmos. 119(19), 11,398–11,416.

Huang, Q., Cai, X., Wang, J., Song, Y., Zhu, T., 2018. Climatological study of the Boundary-layer air Stagnation Index for China and its relationship with air pollution. Atmos. Chem. Phys.18(10), 7573-7593.

Huang, R.J., Zhang, Y., Bozzetti, C., Ho, K.F., Cao, J.J., Han, Y., Daellenbach, K.R., Slowik, J.G., Platt, S.M., Canonaco, F., Zotter, P., Wolf, R., Pieber, S.M., Bruns, E.A., Crippa, M., Ciarelli, G., Piazzalunga, A., Schwikowski, M., Abbaszade, G., Schnelle-Kreis, J., Zimmermann, R., An, Z., Szidat, S., Baltensperger, U., El Haddad, I., Prévôt, A.S.H., 2014b. High secondary aerosol contribution to particulate pollution during haze events in China. Nature 514(7521), 218–222.

Kang, H., Zhu, B., de Leeuw, G., Lu, W., Shen, X., Guo, Z., 2024. Source contributions to two super dust storms over Northern China in March 2021 and the impact of soil moisture. Sci. Total Environ. 950, 175289.

Kang, L., Chen, S., Huang, J., Zhao, S., Ma, X., Yuan, T., Zhang, X., Xie, T., 2017. The spatial and temporal distributions of absorbing aerosols over East Asia. Remote Sens. 9(10), 1050.

Knippertz, P., Todd, M.C., 2012. Mineral dust aerosols over the Sahara: Meteorological controls on emission and transport and implications for modeling. Rev. Geophys. 50(1), RG1007.

Li, C., Ling, X., Liu, W., Tang, Z., Zhuang, Q., Fang, M., 2025. Long-term spatiotemporal variability and source attribution of aerosols over Xinjiang, China. Remote Sens. 17(13), 2207.

Li, C., Tsay, S.C., Fu, J.S., Dickerson, R.R., Ji, Q., Bell, S.W., Gao, Y., Zhang, W., Huang, J., Li, Z., Chen, H., 2010. Anthropogenic air pollution observed near dust source regions in northwestern China during springtime 2008. J. Geophys. Res. Atmos. 115(D7), D00K21.

Li, M., Zhang, D., Li, C.T., Selin, N.E., Karplus, V.J., 2019. Co-benefits of China's climate policy for air quality and human health in China and transboundary regions in 2030. Environ. Res. Lett. 14(8), 084006.

Liang, L., Han, Z., Li, J., Xia, X., Sun, Y., Liao, H., Zhang, R., 2022. Emission, transport, deposition, chemical and radiative impacts of mineral dust during severe dust storm periods in March 2021 over East Asia. Sci. Total Environ. 852, 158459.

Liao, Z.H., Jia, X.C., Qiu, Y.L., Quan, J.N., Pan, Y.B., Ma, P.K., Wang, Q.Q., 2024. Synoptic controls on warm-season O3 pollution in eastern China: A focus on O3-NOx-VOC chemistry. Atmos. Res. 311, 107660.

Lin, H., Zhu, J., Jiang, P., Cai, Z., Yang, X., Yang, X., Wei, J., 2022. Assessing drivers of coordinated control of ozone and fine particulate pollution: Evidence from Yangtze River Delta in China. Environ. Impact Assess. Rev. 96, 106840.

Liu, M., Wang, X., Wang, Y., 2024. Interactions between aerosols and surface ozone in arid and semi-arid regions of China. Environ. Monit. Assess. 196(4), 390.

Mao, R., Hu, Z., Chen, S., Feng, T., 2025. Dust and polluted aerosols: sources, transport and radiative effects volume II. Front. Environ. Sci. 13, 1762418.

Meng, L., Yang, X., Zhao, T., He, Q., Lu, H., Mamtimin, A., Liu, C., 2019. Modeling study on three-dimensional distribution of dust aerosols during a dust storm over the Tarim Basin, Northwest China. Atmos. Res. 218, 285–295.

https://doi.org/10.5194/egusphere-2026-3468
Preprint. Discussion started: 11 August 2026

Miao, Y., Guo, J., Liu, S., Zhao, C., Li, X., Zhang, G., Ma, Y., 2018. Impacts of synoptic condition and planetary boundary layer structure on the trans-boundary aerosol transport from Beijing-Tianjin-Hebei region to northeast China. Atmos. Environ. 181, 1-11.

Monks, P.S., Granier, C., Fuzzi, S., Stohl, A., Williams, M.L., Akimoto, H., Amann, M., Baklanov, A., Baltensperger, U., Bey, I., Blake, N., Blake, R.S., Carslaw, K., Cooper, O.R., Dentener, F., Fowler, D., Fragkou, E., Frost, G.J., Generoso, S., Ginoux, P., Grewe, V., Guenther, A., Hansson, H.C., Henne, S., Hjorth, J., Hofzumahaus, A., Huntrieser, H., Isaksen, I.S.A., Jenkin, M.E., Kaiser, J., Kanakidou, M., Klimont, Z., Kulmala, M., Laj, P., Lawrence, M.G., Lee, J.D., Liousse, C., Maione, M., McFiggans, G., Metzger, A., Mieville, A., Moussiopoulos, N., Orlando, J.J., O'Dowd, C.D., Palmer, P.I., Parrish, D.D., Petzold, A., Platt, U., Pöschl, U., Prévôt, A.S.H., Reeves, C.E., Reimann, S., Rudich, Y., Sellegri, K., Steinbrecher, R., Simpson, D., ten Brink, H., Theloke, J., van der Werf, G.R., Vautard, R., Vestreng, V., Vlachokostas, C., von Glasow, R., 2009. Atmospheric composition change – global and regional air quality. Atmos. Environ. 43(33), 5268–5350.

Querol, X., Fussell, J.C., Saliba, N.A., Al-Hemoud, A., Nadeau, K.C., Tobías, A., Hopke, P.K., 2025. Desert sand and dust storms and desert dust episodes: Major patterns to be accounted for to protect the health of exposed population: A review. ACS EST Air 2(12), 2731–2752.

Shao, Y., Wyrwoll, K.H., Chappell, A., Huang, J., Lin, Z., McTainsh, G.H., Mikami, M., Tanaka, T.Y., Wang, X., Yoon, S., 2011. Dust cycle: An emerging core theme in Earth system science. Aeolian Res. 2(4), 181–204.

Tian, M., Gao, J., Zhang, L., Zhang, H., Feng, C., Jia, X., 2021. Effects of dust emissions from wind erosion of soil on ambient air quality. Atmos. Pollut. Res. 12(7), 101108.

Uno, I., Eguchi, K., Yumimoto, K., Takemura, T., Shimizu, A., Uematsu, M., Liu, Z., Wang, Z., Hara, Y., Sugimoto, N., 2009. Asian dust transported one full circuit around the globe. Nat. Geosci. 2(8), 557–560.

Wang, J., Gui, H., An, L., Hua, C., Zhang, T., Zhang, B., 2021. Modeling for the source apportionments of PM10 during sand and dust storms over East Asia in 2020. Atmos. Environ. 267, 118768.

Wang, Y., Yan, P., Wu, W., Wang, Y., Hu, C., Li, S., 2025. PM10 dust emission in the Erenhot-Huailai zone of northern China based on model simulation. J. Arid Land 17(3), 324–336.

Yu, H., Wang, J., Geng, C., Yang, W., Wang, X., Yin, B., Bai, Z., 2024. Impact of anthropogenic and natural constituents on particulate matter in oasis cities on the southern margin of the Taklimakan Desert based on MERRA-2 and multi-site ground observation. Atmos. Res. 311, 107685.

Yu, T., Xiaole, P., Yujie, J., Yuting, Z., Weijie, Y., Hang, L., Zifa, W., 2023. East Asia dust storms in spring 2021: Transport mechanisms and impacts on China. Atmos. Res. 290, 106773.

Yu, Y., Kalashnikova, O.V., Garay, M.J., Notaro, M., 2019. Climatology of Asian dust activation and transport potential based on MISR satellite observations and trajectory analysis. Atmos. Chem. Phys. 19(1), 363–378.

Zhang, B., Tsunekawa, A., Tsubo, M., 2008. Contributions of sandy lands and stony deserts to long-distance dust emission in China and Mongolia during 2000–2006. Glob. Planet. Change 60(3-4), 487–504.

https://doi.org/10.5194/egusphere-2026-3468
Preprint. Discussion started: 11 August 2026

Zhang, N., Guan, Y., Jiang, Y., Zhang, X., Ding, D., Wang, S., 2022. Regional demarcation of synergistic control for PM2.5 and ozone pollution in China based on long-term and massive data mining. Sci. Total Environ. 838, 155975.

Zhang, Q., Zheng, Y., Tong, D., Shao, M., Wang, S., Zhang, Y., Xu, X., Wang, J., He, H., Liu, W., Ding, Y., Lei, Y., Li, J., Wang, Z., Zhang, X., Wang, Y., Cheng, J., Liu, Y., Shi, Q., Yan, L., Geng, G., Hong, C., Li, M., Liu, F., Zheng, B., Cao, J., Ding, A., Gao, J., Fu, Q., Huo, J., Liu, B., Liu, Z., Yang, F., He, K., Hao, J., 2019. Drivers of improved PM2.5 air quality in China from 2013 to 2017. Proc. Natl. Acad. Sci. USA 116(49), 24463–24469.

Zhang, X.X., Sharratt, B., Liu, L.Y., Wang, Z.F., Pan, X.L., Lei, J.Q., Wu, S.X., Huang, S.Y., Guo, Y.H., Li, J., Tang, X., Yang, T., Tian, Y., Chen, X.S., Hao, J.Q., Zheng, H.T., Yang, Y.Y., Lyu, Y.L., 2018. East Asian dust storm in May 2017: Observations, modelling and its influence on Asia-Pacific region. Atmos. Chem. Phys. 18(11), 8353–8371.

Zhang, X.Y., Gong, S.L., Arimoto, R., Shen, Z.X., Mei, F.M., Wang, D., Cheng, Y., 2003. Characterization and temporal variation of Asian dust aerosol from a site in the northern Chinese deserts. J. Atmos. Chem. 44(3), 241–257.

Zhang, Y., Chen, X., Zhao, F., Xia, Q., Xing, H., Du, M., 2025. Aerosol spatiotemporal dynamics, source analysis and influence mechanisms over typical drylands. Geosci. Front. 16(1), 101958.

Zhang, Y.L., Cao, F., 2015. Fine particulate matter (PM2.5) in China at a city level. Sci. Rep. 5(1), 14884.

Zhang, Z., Liang, A., Zhang, C., Dong, Z., 2021. Gobi deposits play a significant role as sand sources for dunes in the Badain Jaran Desert, Northwest China. Catena 206, 105530.

Zhao, S., Yu, Y., Xia, D., Yin, D., He, J., Liu, N., Li, F., 2015. Urban particle size distributions during two contrasting dust events originating from Taklimakan and Gobi Deserts. Environ. Pollut. 207, 107–122.

Zhou, L., Zhou, C., Yang, F., Che, L., Wang, B., Sun, D., 2019. Spatio-temporal evolution and the influencing factors of PM2.5 in China between 2000 and 2015. J. Geogr. Sci. 29(2), 253–270.

Zhou, W., Yang, L., Zeng, S., Kan, Y., Yang, L., Zhang, W., Sun, Y., 2026. Decadal transition of summertime PM2.5–O3 coupling and secondary organic aerosol dominance in northwest China. Atmos. Chem. Phys. 26(4), 2425–2441.