

**Measurement report: Investigation of regional pollutant transport to
Beijing, China based on a unique 528-meter platform**

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Abstract

Observations at elevated altitudes can capture the chemical characteristics of regional aerosols more effectively than ground-level measurements, but in situ measurements of aerosols over megacities remain scarce. In this work, aerosol composition and gaseous pollutants measured from 2020 to 2024 at a 528-m landmark tower in downtown Beijing, together with ground-level observations, are analyzed to understand regional pollutant transport. The results reveal that both aerosol mass concentration and composition differ significantly among air masses originating from different directions. Further analysis of sulfur and nitrogen oxidation ratios showed that both were significantly higher in air masses from the south and northeast compared to those from the northwest. This difference is likely attributable to higher relative humidity (RH) in the former, which promotes heterogeneous oxidation of SO₂ and NO₂ during transport. Regional aerosols were downwards transported to ground efficiently through planetary boundary layer (PBL) process during daytime, thereby exacerbating air pollution in Beijing. These findings underscore the critical role of regional transport in shaping Beijing's aerosol burden and highlight how the chemical signatures of transported aerosols reflect their diverse source regions and formation mechanisms.

Short summary

Regional transport is a systemic environmental challenge governed by multiple processes. Observations from a unique 528-m tower in Beijing reveal that aerosols vary among air masses originating from different directions, influenced by regional emission sources and reactions during transport. A comparison of pollutants between the 528-m layer and ground level confirms that transported pollutants are mixed down to the surface during daytime, governed primarily by PBL process.

1. Introduction

The megacity of Beijing and the surrounding North China Plain (NCP) constitute one of the world's most polluted and intensively studied regions for regional air pollution dynamics, owing to its dense population, rapid industrialization, and complex meteorology (Li et al., 2016). In addition to local emissions, regional transport is a major contributor to Beijing's air pollution (Quan et al., 2020). Model simulations indicate that the regional contribution to PM_{2.5} in Beijing ranges from 27% to 78% and has been increasing annually (Li et al., 2013; Zhang et al., 2018a, 2024). This contribution is particularly important during haze events, when regional transport has sometimes been identified as the primary driver. Observation-based studies further show that pollutants such as sulfur dioxide (SO₂) and fine particles (PM_{2.5}; particle matter with the radius equal/less 2.5 μm) are transported northwards along the Taihang mountains, exacerbating air pollution in Beijing (Li et al., 2015; Tan et al., 2021). These studies underscore that mitigating Beijing's air pollution cannot rely on local emission controls alone (Li et al., 2015).

Regional pollutant transport is not merely a local environmental issue but a systemic

atmospheric process governed by interactions among anthropogenic emissions, synoptic-scale weather patterns, topographic constraints, and PBL process (Li et al., 2016). Among these processes, the vertical transport between the PBL and free troposphere (FT) is critically important, but remains poorly understudied (Wang et al., 2024; Quan et al., 2025). This gap stems largely from the need for vertical profiling of atmospheric pollutants to fully characterize the composition and evolution of aerosols, a requirement that poses significant challenges for observational systems, as most measurements have been conducted at ground level. Regional pollutant transport occurs more efficiently in the lower FT, which is supported by both observations and model simulations (Quan et al., 2020; Sun et al., 2022). Quan et al. (2020) observed an elevated pollutant layer (EPL) at an altitude of 1.4-1.7 km over Beijing by lidar and aircraft measurements. Model simulations indicate the EPL in the lower FT formed over the NCP due to a mountain-induced vertical vortex and was subsequently transported to Beijing by southerly winds. Sun et al. (2022) observed high concentrations of sulfate-dominated aerosols in the FT over Northeast China, in contrast to the low aerosol loadings, primarily composed of organic compounds, in the PBL. Their simulations indicate that these elevated pollutants in the lower FT were transported directly from the North China Plain (NCP) by warm, moist air masses. While downward transport of pollutants from the FT to the PBL may be influenced by PBL process or local circulation, the underlying mechanisms remain poorly understood.

Moreover, the chemical composition of aerosol varies substantially in different regions, depending on emission sources and atmospheric chemical reactions (Zhang, 2014). For example, coal combustion emits SO_2 , which is oxidized in the atmosphere to form sulfate, while vehicle exhaust releases nitrogen oxides (NO_x), a precursor to nitrate. Numerous studies utilizing the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model have demonstrated that synoptic-scale meteorology strongly influences the chemical characteristics of particulate matter in Beijing (Ma et al., 2021; Kang et al., 2023). For instance, air masses arriving from southern and southeastern industrial corridors, including provinces such as Hebei, Shandong, and Henan, are consistently associated with elevated concentrations of secondary inorganic aerosols (SIAs), including nitrate (NO_3^-), sulfate (SO_4^{2-}), and ammonium (NH_4^+), due to high precursor emissions of NO_x , SO_2 , and ammonia (NH_3) from coal combustion, vehicle exhaust, and agricultural activities (Du et al., 2019). Conversely, air masses originating from northern or northwestern regions, such as Inner Mongolia or the Gobi Desert, are typically linked to dust-laden conditions and higher contribution of mineral dust components to aerosol loading (Wang et al., 2017). Notably, most observations are conducted at ground level, where local and transported pollutants are well mixed (Quan et al., 2020, 2025). Aircraft observations showed that aerosol compositions varied drastically with altitude, especially near the top of PBL (Liu et al., 2019). Therefore, observations in high layer may capture chemical characteristics of transported aerosols from different regions much better.

To address these research gaps, aerosol composition and gaseous pollutants measured from 2020 to 2024 at a 528-m landmark tower in downtown Beijing, together with ground-level observations of pollutants such as nitrogen dioxide (NO₂), SO₂, and PM_{2.5}, are analyzed in this study to understand regional pollutant transport to Beijing and thereby improve our understanding of near-surface air pollution.

2. Observations and Methods

The comprehensive field campaign was conducted from October 2020 to December 2024 on the roof of the CITIC Tower (528 m a.g.l.). The CITIC Tower (longitude: 116.47 °, latitude: 39.92 °) is situated adjacent to the East Third Ring Road (Fig.1), in a mixed residential and commercial area with no large point source nearby. The measurements included aerosol mass concentration and composition (SO₄²⁻, NO₃⁻, NH₄⁺, Cl⁻, and organic aerosols (Org)), trace gases, including SO₂, NO₂, ozone (O₃), and meteorological variables (temperature (T) and relative humidity (RH)). The observations were conducted mainly in autumn, winter and spring, when air pollution in Beijing is more severe, resulting in fewer data points were collected in summer (Table 1). All pollutants were measured simultaneously, with the same data coverage.

Table 1. Total Observation days at the CITIC station from 2020 to 2024

Year	Month												Total (d)
	1	2	3	4	5	6	7	8	9	10	11	12	
2020	—	—	—	—	—	—	—	—	—	15	20	2	37
2021	12	23	1	—	—	—	—	—	—	10	30	31	107
2022	31	28	31	30	15	—	—	—	8	19	—	—	162
2023	—	—	9	30	29	15	21	—	—	—	—	—	104
2024	31	16	3	30	22	—	—	—	—	5	23	6	136

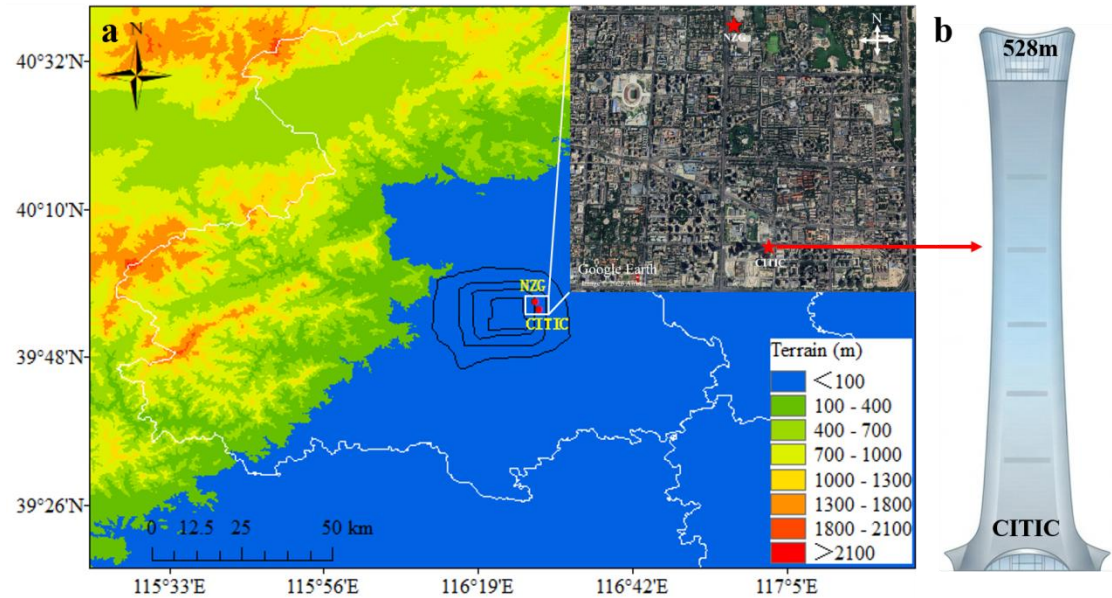


Figure 1. Locations of the monitoring sites used in this study with lack lines, red dots representing the second to fifth rings surrounding central Beijing, and CITIC and

NZG stations, respectively (a); sketch map of the 528-m CITIC Tower (b).

The real-time chemical composition of non-refractory fine particles (NR-PM_{2.5}), including SO₄²⁻, NO₃⁻, NH₄⁺, Cl⁻, and Org, was measured with a ToF-ACSM (Aerodyne Co. Ltd., USA), which relies upon thermal vaporization and 70 eV electron-impact ionization (EI) (Jayne et al., 2000). The ambient particles were sampled into the ToF-ACSM through a PM_{2.5} cyclone (by URG), followed by a Nafion dryer to dry the aerosols. The PM_{2.5} cyclone and the Nafion dryer were connected via a 2-meter-long stainless steel tube with an inner diameter of approximately 7.8 mm (outer diameter: 3/8 inch), and the total sampling flow rate was about 3 L/min. Based on these parameters, the residence time of the sampled air in this tube section is estimated to be approximately 2 seconds. For such a relatively short straight tube and for the predominantly submicron particles (PM_{2.5}) in the aerosol, particle losses caused by turbulent deposition, diffusion losses, or gravitational settling are generally negligible. Therefore, no additional correction for particle losses in the sampling line was applied in this study. The dried ambient aerosol particles are focused into the 600 °C standard/ captive vaporizer through aerodynamic lenses at a flow of ~ 0.1 L min⁻¹, where they are thermally vaporized to produce gaseous fragments. These vapors are subsequently ionized by electron impact at 70 eV using a tungsten filament, after which the resulting ions are analyzed in a time-of-flight mass spectrometer based on their mass-to-charge ratio. The detected ion signals are then converted into mass concentrations using standard calibration and ionization efficiency procedures, as described in Fröhlich et al. (2013) and Williams et al. (2013). The relative ionization efficiency (RIE) calibration of the ToF-ACSM was performed once two weeks.

The mass concentration of PM_{2.5} was monitored by an R&P model 1400a Tapered Element Oscillating Microbalance (TEOM, Thermo Fisher Scientific Co., USA) at a time resolution of 1 min. This instrument was operated with a hydrophobic filter material to reduce the humidity of the incoming sampled air. The filter was replaced and flow rates of TEOM were checked once two weeks. The collocated gaseous species, including SO₂ (TL43i), NO_x (TL42i), and O₃ (TL49i), were measured by various gas analyzers (Thermo Fisher Scientific Co., USA) at a time resolution of 1 min. Meteorological parameters (T and RH) were measured by an Automatic Weather Station (Huayunshengda, China). All instruments at the CITIC are calibrated once two weeks. Data analysis was performed using Python (version 3.13). All raw observations at the CITIC station were averaged to a temporal resolution of 1 hour. Prior to analysis, quality control (QC) procedures were applied to the dataset, which included corrections based on zero calibrations and the removal of anomalous data.

Additionally, ground level observations at NZG station, including PM_{2.5}, SO₂, NO₂, and O₃, with time resolution of 1 hour. The NZG station is located at north of the CITIC with a distance of 4 km (Fig.1). The NZG station (longitude:116.47 °, latitude: 39.97 °) is one of the national-level ambient air quality monitoring stations operated

by the China National Environmental Monitoring Centre (CNEMC). All measurements at the NZG follow mandatory national technical specifications. The QC of observations includes routine zero calibrations, multi-point precision checks, annual accuracy audits, traceable standard-gas transfer through regional QC laboratories, and parallel manual gravimetric comparison for PM_{2.5}. The reliability of CNEMC data has been independently verified in peer-reviewed literature through cross-validation against measurements from the U.S. Embassy (Liang et al., 2016). To maintain consistency, observations at the NZG station during the same period listed in Table 1 were analyzed.

The 2-day (48 h) back trajectories were calculated every hour at 500 m height using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT, NOAA) 4.9 model (Draxler and Hess, 1998), and Global Data Analysis System (GDAS) outputs with 1°×1° resolution and observed PM_{2.5} concentration are used as input (Stein et al., 2015). The trajectories during our observations (shown in Table 1) were then grouped into six clusters using the total spatial variance (TSV) method (Draxler et al., 2012). This method minimizes the inter-cluster differences among trajectories while maximizing the inter-cluster differences, which has been widely used in previous studies (Chen et al., 2015; Kang et al., 2023). The potential source contribution function (PSCF) was used to identify the potential source area (Stohl, 1996). The PSCF method divides the research area into $i \times j$ grids, and the number of air mass trajectories passing through the grid during the research period is counted to calculate the probability of occurrence of pollution trajectories. The time coverage in trajectories clustering and PSCF is same as observations shown in Table 1.

3. Results and Discussion

3.1 Aerosol composition in the 528-m layer over Beijing

The mean mass concentration of NR-PM_{2.5} at the CITIC station was 19.14±28.24 µg m⁻³ during observational period (Fig. 2a). The mass concentrations of Org, SO₄²⁻, NO₃⁻, NH₄⁺, and Cl⁻ were 7.0±9.3, 2.0±3.0, 6.7±10.8, 3.0±4.1, and 0.4±1.1 µg m⁻³ respectively, accounting for 36.8±33.0%, 10.5±10.5%, 34.8±38.1%, 15.9±14.6%, and 2.1±3.7% in mass fraction. The fraction of SIAs, including SO₄²⁻, NO₃⁻, and NH₄⁺, was 61.2% in NR-PM_{2.5}. This proportion is notably higher than observations at ground stations in urban Beijing. For example, in the observation of Ma et al. (2021), SIAs mass fraction ranged from 42% to 56% during two months experiment in Beijing (from January 14 to March 6, 2019). Seasonal aerosol composition in Beijing during 2012 to 2018 shows SIAs mass fractions were 52%, 55%, 49%, and 45% in spring, summer, autumn, and winter, respectively (Zhou et al., 2020).

The diurnal variations of aerosol components are shown in Fig. 2b, which offer insight into potential emission sources, local and regional transport, and aerosol chemical processing. Compared with observations at ground level, the diurnal variations in aerosol components at the CITIC station were remarkably weak (Fig. 2b).

For example, the ratio of the peak (12:00) to trough (06:00) in Org was 1.15, and the ratios in SO_4^{2-} , NO_3^- , NH_4^+ , and Chl^- were 1.09, 1.13, 1.09, and 1.15 respectively. Whereas, such ratios was about 2.0 at ground level (Zhou et al., 2020). Moreover, the peaks of Org, SO_4^{2-} , and Chl^- appear in the daytime, which are also contrary to that at ground level (Zhou et al., 2020; Quan et al., 2024).

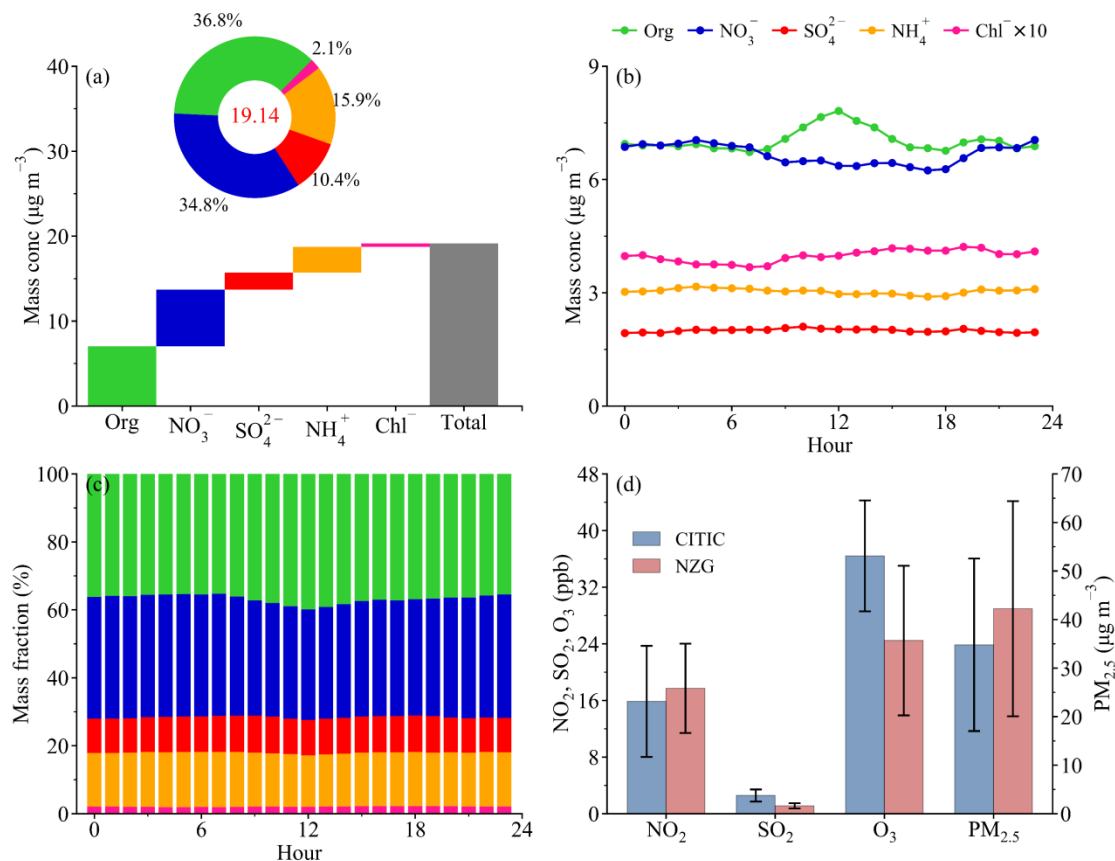


Figure 2. The mean mass concentration and aerosol composition of NR-PM_{2.5} observed at the CITIC station (a); diurnal variations of the mean mass concentration (b) and fraction (c) of aerosol components; and comparisons of the mean NO₂, SO₂, O₃, and PM_{2.5} between the CITIC and NZG stations (d) during observational period (2020-2024). The error bars are the 50% standard deviations.

The diurnal variability in aerosol components is strongly modulated by meteorology, particularly the PBL process (Quan et al., 2013). The PBL height (PBLH) typically decreases at night and grows during the daytime (Stull, 1988). This daytime expansion in PBLH enhances the vertical mixing and dilution of pollutants, thereby reducing their near-surface concentrations (Habineza et al., 2025). However, the circumstances differ significantly at the elevated CITIC station (528 m a.g.l.), which lies above the PBL at night but within it during the daytime. Our previous observations (17 October - 12 November 2020) indicated that the nocturnal PBLH was typically below 300 m, whereas the daytime PBLH was around 1000 m (Ma et al., 2023). At night, near-ground emissions are trapped within the shallow nocturnal PBL, while vertical transport to the overlying layer is substantially suppressed (Quan et al.,

2025), resulting in low concentrations of pollutants at the CITIC station. In the morning, the PBL gradually develops due to increasing solar radiation. During this process, near-ground pollutants are vertically transported up to the CITIC station, thereby enhancing their concentrations. Additionally, enhanced formation of secondary organic aerosol (Cai et al., 2023) and sulfate (Liu et al., 2025) during daytime may also contribute to their daytime peaks. These processes jointly result in weak diurnal variations in aerosol components at the CITIC station. It is noteworthy that NO_3^- at the CITIC station remained at a high level at night but decreased slightly in daytime, which may be related to active nocturnal nitrogen chemistry above the PBL (Ma et al., 2023). Elevated NO_3 levels in the RL (Wang et al., 2018) may also promote organic nitrate formation (Cai et al., 2023), thereby further contributing to the enhanced nighttime nitrate concentrations in this layer. More details on vertical mixing of pollutants will be presented in Section 3.4.

Moreover, pollutants in the 528-m layer may be more strongly influenced by regional transport compared to ground level. To examine this, we compared measurements between the CITIC station and the nearby ground-level NZG station, located approximately 4 km to the north (Fig.1a). Due to the lack of concurrent aerosol composition measurements at ground station in the same period, only $\text{PM}_{2.5}$ and gaseous pollutants were compared. As shown in Fig. 2d, $\text{PM}_{2.5}$ at the CITIC station ($34.8 \pm 35.6 \mu\text{g m}^{-3}$) was lower than that at the NZG station ($42.2 \pm 44.4 \mu\text{g m}^{-3}$) while O_3 showed the opposite trend. For NO_2 and SO_2 , NO_2 at the CITIC station (15.9 ± 7.8 ppb) was 10.4% lower than that at the NZG station (17.7 ± 6.3 ppb), while SO_2 showed a contrasting pattern. SO_2 in the 528-m layer (2.6 ± 0.9 ppb) was 130% higher than that at the NZG station (1.1 ± 0.4 ppb) (Fig. 2d). As a megacity with 7 million vehicles, NO_x , including NO_2 and NO , are key atmospheric pollutants to air quality in Beijing (Shen et al., 2024). Vehicle-emitted NO_2 is rapidly diluted through vertical mixing, explaining its lower concentrations aloft. In contrast, SO_2 emissions in Beijing have been stringently controlled over the past decade. Consequently, ambient SO_2 is now predominantly derived from regional transport rather than local sources (Zhang et al., 2019). The observed pattern, enhanced SO_2 and reduced NO_2 in the 528-m layer relative to ground, confirms that pollutants in the 528-m layer over Beijing are influenced by a combination of regional transport and vertical mixing of locally emitted pollutants.

During regional transport, gaseous pollutants such as SO_2 , NO_2 , and NH_3 undergo chemical reactions to form SIAs (Tan et al., 2021), resulting in a high SIAs fraction in the 528-m layer. Aerosols and their precursors vary substantially across regions due to differences in source and atmospheric processing (Tao et al., 2017). Consequently, aerosol components over Beijing are expected to differ depending on the origin of incoming air masses. To improve our understanding of these processes, aerosol composition under distinct transport pathways is analyzed in the following sections.

3.2 Aerosol composition under different transport pathways

To investigate the regional transport of fine particles to Beijing, the HYSPLIT model (Draxler and Hess, 1998) was used to identify the source regions and transport pathways of air masses arriving over Beijing at altitude of 500 m. Fig. 3 shows the six clustered transport routes. Clusters 1, 3, and 5 correspond to air masses originating from the northwest of Beijing, whereas Clusters 2, 4, and 6 correspond to air masses originating from the south, northeast, and west of Beijing. The trajectory lengths of each cluster reflect the transport speed of the air masses: longer trajectories indicate faster movement. This is corroborated by the mean wind speed (WS) in Beijing under each cluster (Table 2). Wind speeds were higher for Clusters 1 ($3.6 \pm 2.5 \text{ m s}^{-1}$), 3 ($3.0 \pm 2.0 \text{ m s}^{-1}$), and 5 ($4.1 \pm 2.7 \text{ m s}^{-1}$) compared to Clusters 2 ($2.2 \pm 1.4 \text{ m s}^{-1}$), 4 ($2.7 \pm 1.6 \text{ m s}^{-1}$), and 6 ($2.4 \pm 1.6 \text{ m s}^{-1}$). The spatial distribution of potential source contributions at altitude of 500 m in the six clusters was consistent with this classification (Fig. 4). As a comparison, we also investigated the spatial distribution of potential source contributions at the ground level in the six clusters for the same period (Fig. S1). The results show that potential source contributions at the ground level originated more from local sources than those in the aloft layer.

Table 2. The mean wind speed at NZG station, and temperature and RH at the CITIC station in the six clusters

Cluster	Ground WS (m s^{-1})	528m Temp ($^{\circ}\text{C}$)	528m RH (%)
C1	3.6 ± 2.5	8.3 ± 8.1	26.4 ± 14.4
C2	2.2 ± 1.4	12.9 ± 9.4	54.1 ± 18.3
C3	3.0 ± 2.0	6.4 ± 9.8	35.4 ± 16.3
C4	2.7 ± 1.6	9.3 ± 11.1	55.4 ± 20.4
C5	4.1 ± 2.7	2.8 ± 7.8	26.2 ± 9.2
C6	2.4 ± 1.6	4.8 ± 8.2	34.1 ± 14.3

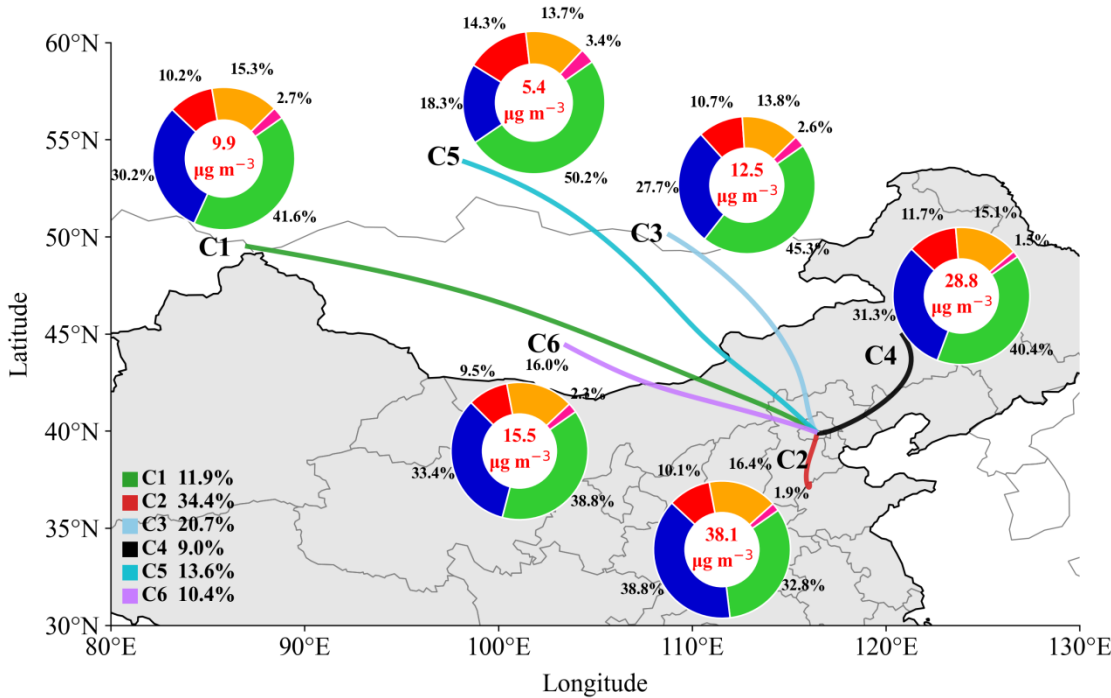


Figure 3. Forty-eight hours back trajectories of air masses over Beijing at altitude of 500 meters in the six clusters (C1-C6), together with the mean NR-PM_{2.5} mass concentration and composition at the CITIC station in each cluster.

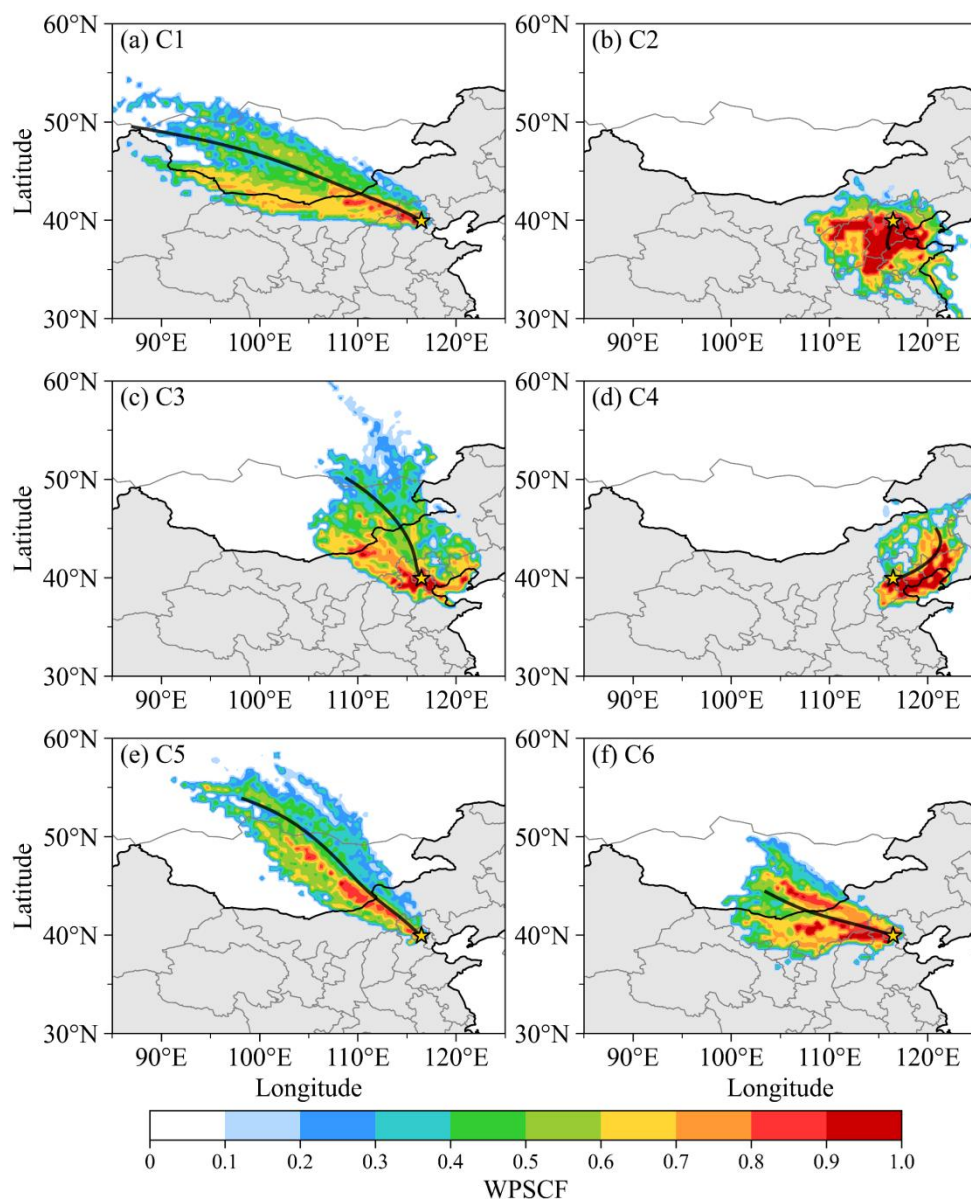


Figure 4. Potential source contribution at altitude of 500 m over Beijing in the six clusters. The color bar (WPSCF) represents weighted potential source contribution function.

The mass concentrations of NR-PM_{2.5} were $9.9 \pm 14.5 \mu\text{g m}^{-3}$, $12.5 \pm 12.0 \mu\text{g m}^{-3}$, and $5.4 \pm 6.8 \mu\text{g m}^{-3}$ in Clusters 1, 3, and 5, respectively, substantially lower than in Clusters 2 ($38.1 \pm 32.7 \mu\text{g m}^{-3}$), 4 ($28.8 \pm 29.5 \mu\text{g m}^{-3}$), and 6 ($15.5 \pm 18.4 \mu\text{g m}^{-3}$) (Fig. 3). These results are consistent with regional emission patterns (Zhang, 2014). The northwestern source regions (including northwestern China, Mongolia, and Siberia) are relatively pristine, and air masses from these areas delivered cleaner air to Beijing (Zhang, 2014). Strong winds associated with these clusters also enhanced the

dispersion of local pollutants, further contributing to lower aerosol loading. In contrast, air masses arriving from the south, northeast, and west originated from heavily polluted regions, thereby transporting polluted air to Beijing. Weaker winds under these clusters favored the accumulation of locally emitted pollutants. Besides mass concentrations, distinct differences in aerosol chemical composition were observed in the six clusters. The fraction of SIAs was lower in the three northwestern clusters ($55.7 \pm 84.3\%$ in Cluster 1, $52.1 \pm 54.4\%$ in Cluster 3, and $46.3 \pm 63.1\%$ in Cluster 5), compared to the other three clusters ($65.2 \pm 54.1\%$ in Cluster 2, $58.1 \pm 56.7\%$ in Cluster 4, and $59.0 \pm 71.7\%$ in Cluster 6) (Fig. 3). Organic aerosol fractions exhibited the opposite trend. Among SIAs, the northwestern clusters showed lower NO_3^- and NH_4^+ , but higher SO_4^{2-} contributions. Specifically, NO_3^- accounted for $30.2 \pm 67.6\%$, $27.7 \pm 43.0\%$, and $18.3 \pm 47.4\%$ of $\text{NR-PM}_{2.5}$ in Clusters 1, 3, and 5, respectively, which was lower than in Clusters 2 ($38.8 \pm 43.4\%$), 4 ($31.3 \pm 40.8\%$), and 6 ($33.4 \pm 58.4\%$). Conversely, SO_4^{2-} fractions were higher in the northwestern clusters ($10.2 \pm 16.1\%$, $10.7 \pm 13.0\%$, and $14.3 \pm 19.6\%$) than in Clusters 2 ($10.1 \pm 11.6\%$) and 6 ($9.5 \pm 12.4\%$), though slightly lower than in Cluster 4 ($11.7 \pm 17.7\%$). NH_4^+ reached its highest fraction in Cluster 2 ($16.4 \pm 16.3\%$).

In addition to aerosol composition, differences of $\text{PM}_{2.5}$ and gas pollutants in the six clusters were also examined (Fig. 5). Similar to $\text{NR-PM}_{2.5}$, $\text{PM}_{2.5}$ concentrations exhibited pronounced variability among the six clusters, ranging from a maximum of $68.2 \pm 40.2 \mu\text{g m}^{-3}$ in Cluster 2 to a minimum of $12.6 \pm 12.1 \mu\text{g m}^{-3}$ in Cluster 5, yielding a maximum-to-minimum of 5.62. In contrast, SO_2 showed much weaker variability, with concentrations ranging from $3.0 \pm 1.9 \text{ ppb}$ (Cluster 2) to $2.0 \pm 1.3 \text{ ppb}$ (Cluster 5), corresponding to a ratio of only 1.47. NO_2 variability was moderate, with a maximum of $22.1 \pm 15.2 \text{ ppb}$ in Cluster 2 and a minimum of $9.7 \pm 11.7 \text{ ppb}$ in Cluster 5 (ratio = 2.27). To access the relative contributions of SO_2 and $\text{PM}_{2.5}$ under different transport clusters, the $\text{SO}_2/\text{PM}_{2.5}$ ratio was calculated. The ratio was higher in the three clusters originating from the northwest, $0.10 \text{ ppb } \mu\text{g}^{-1} \text{ m}^3$ (Cluster 1), $0.11 \text{ ppb } \mu\text{g}^{-1} \text{ m}^3$ (Cluster 3), and $0.16 \text{ ppb } \mu\text{g}^{-1} \text{ m}^3$ (Cluster 5), than in the other three clusters: $0.04 \text{ ppb } \mu\text{g}^{-1} \text{ m}^3$ (Cluster 2), $0.07 \text{ ppb } \mu\text{g}^{-1} \text{ m}^3$ (Cluster 4), and $0.07 \text{ ppb } \mu\text{g}^{-1} \text{ m}^3$ (Cluster 6). This indicates that northwesterly air masses carried relatively less $\text{PM}_{2.5}$, but proportionally more SO_2 , consistent with the enhanced sulfate mass fractions observed in aerosols under these clusters (Fig. 3). Similar pollutant variations in the six clusters were also observed at the ground-level NZG station (Fig. S2); however, the variances of NO_2 and $\text{PM}_{2.5}$ were reduced, which is likely attributed to strong local emissions and chemical formations.

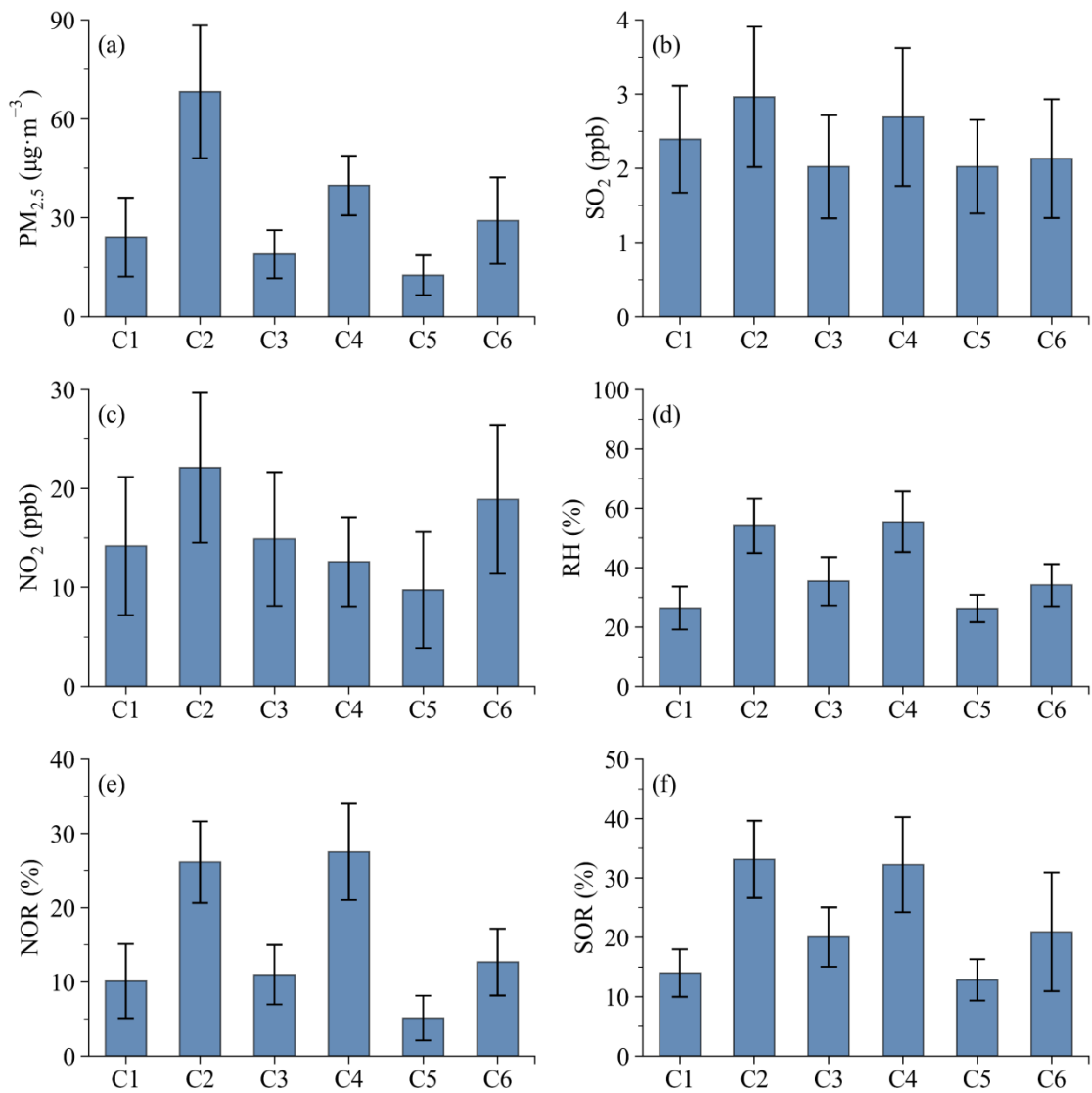


Figure 5. Variations of $PM_{2.5}$, SO_2 , NO_2 , RH, NOR and SOR at the CITIC station in the six clusters, respectively. The error bars are the 50% standard deviations.

The distinct pollutants across clusters reflect the differing emission characteristics of their source regions. Air masses originating from the northwest exhibited a high sulfate mass fraction in aerosols and relatively high SO_2 , suggesting that coal combustion dominates emissions in this region. In contrast, air masses from the south and northeast carried higher $PM_{2.5}$, thereby exacerbating air pollution in Beijing. Regarding aerosol composition, the mass fraction of SIAs increased when air masses arrived from the south and northeast. NO_3^- is formed through the oxidation of NO_x , which is predominantly emitted from combustion-related sources, primarily vehicle exhaust, coal combustion, and biomass burning. Similarly, NH_4^+ derives from the neutralization of NH_3 , which is mainly released from combustion-related sources, agricultural activities (e.g., fertilized soils and animal waste), natural soils, and nitrogen-enriched water bodies (Chen et al., 2022). Consequently, emissions in the southern and northeastern regions are more complex, involving contributions from coal combustion, vehicle exhaust, agricultural practices, and natural sources.

Gaseous pollutants are converted to particles during transport through photochemical and heterogeneous reactions (Tan et al., 2021). To access the influence of chemical reactions on aerosol composition in the six clusters, oxidation ratios of nitrogen (NOR) and sulfur (SOR) were calculated. The NOR and SOR were defined as the ratios of particle phase of nitrogen and sulfur to total nitrogen and sulfur (both gas and particle phases), respectively (Chen et al., 2015); a higher SOR or NOR indicates a stronger conversion of SO_2 or NO_x to their particulate phase. As shown in Fig. 5f, SOR values were higher in Clusters 2 (0.33 ± 0.13) and 4 (0.32 ± 0.16) than in Clusters 1 (0.13 ± 0.08) and 5 (0.12 ± 0.07), suggesting SO_2 was converted efficiently to SO_4^{2-} in the former clusters during transport. A similar pattern was observed for NOR (Fig. 5e). Notably, the RH in Clusters 2 ($54.1 \pm 18.3\%$) and 4 ($55.4 \pm 20.4\%$) was the highest among these six clusters. Further analyses show that both SOR and NOR are closely related to RH (Fig. 6). RH increases markedly when air masses originated from the south and northeast (Fig. 5d), which likely promotes aqueous-phase heterogeneous oxidation of both SO_2 and NO_2 (Pathak et al., 2011; Ma et al., 2021, 2023). Collectively, these results indicate that the observed differences in aerosol composition over Beijing in the six transport clusters are governed by a combination of regional emission sources and chemical reactions during transport.

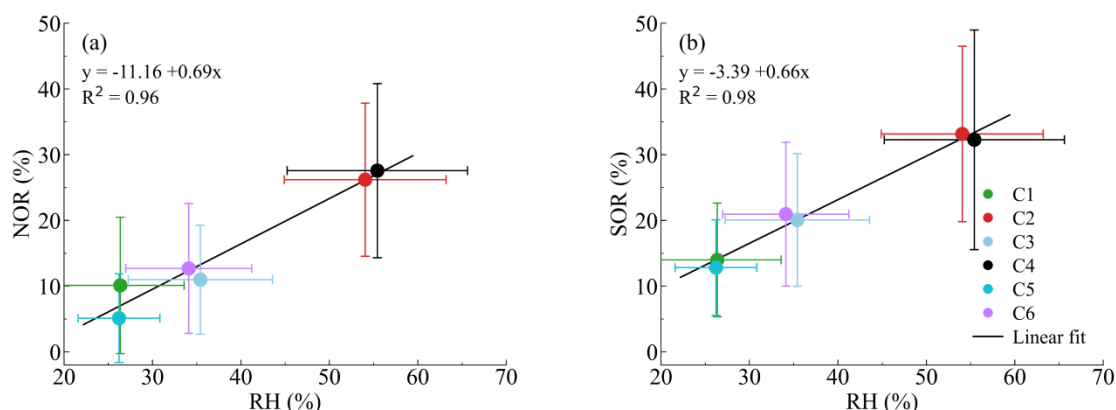


Figure 6. Relationships of the NOR (a), SOR (b) to RH. The colors of dot represent distinct clusters as shown in Fig.3. The error bars are the 50% standard deviations.

3.3 Seasonal aerosol composition

As shown in Fig. 7, both mass concentration and fraction of $\text{NR-PM}_{2.5}$ reflected clear seasonal variations. The mass concentration was lowest in summer ($9.8 \pm 8.2 \mu\text{g m}^{-3}$), followed by winter ($15.6 \pm 19.0 \mu\text{g m}^{-3}$), spring ($20.6 \pm 22.2 \mu\text{g m}^{-3}$) and autumn ($25.4 \pm 37.1 \mu\text{g m}^{-3}$). In summer, frequent precipitation enhanced wet deposition, while increased atmospheric instability promoted vertical diffusion of pollutants, resulting in low aerosol concentration. NO_3^- mass fraction was lowest in summer ($15.1 \pm 23.4\%$), likely due to its semi-volatile property; gas-particle partitioning of nitrate is strongly temperature-dependent, and higher temperature favors the gaseous phase, thereby reducing particulate nitrate. In contrast, SO_4^{2-} mass fraction peaked in summer ($21.9 \pm 23.2\%$), likely due to enhanced aqueous reactions under high RH (Zhang et al.,

2018b). In autumn, atmospheric instability decreases gradually with decreasing solar radiation, leading to aerosol accumulation. For aerosol components, NO_3^- mass fraction increased to $37.9 \pm 71.4\%$, while SO_4^{2-} decreased to $8.1 \pm 18.7\%$, likely driven by concurrent decreases in temperature and RH. In winter and spring, SO_4^{2-} mass fraction increased again ($10.9 \pm 17.7\%$ in winter; $10.9 \pm 13.7\%$ in spring), primarily due to increased SO_2 emissions from intensified coal combustion for residential heating. These observations demonstrate that marked seasonal variations in aerosol species over Beijing are closely linked to differences in emission sources and formation mechanisms.

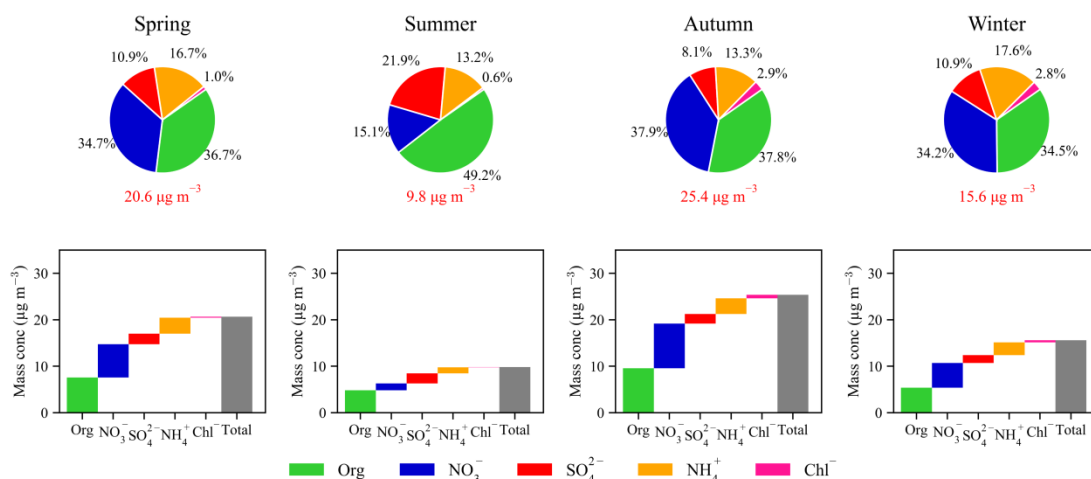


Figure 7. The mean mass concentration and composition of NR-PM_{2.5} in four seasons during observational period (2020-2024).

As discussed in section 3.2, aerosols in the 528-m layer are strongly influenced by regional transport. To further examine how transport pathways modulate aerosol properties across seasons, we analyzed differences in both mass concentration and chemical composition under distinct air mass trajectories (Fig. 8). Due to limited samples, air mass origins were classified into four clusters for each season. In summer, SO_4^{2-} mass fraction exceeded that of NO_3^- in three of the four clusters, with the exception of Cluster 1. Specially, SO_4^{2-} accounted for $23.0 \pm 19.3\%$, $15.3 \pm 23.0\%$, $15.7 \pm 13.7\%$, and $23.6 \pm 18.6\%$, while NO_3^- accounted for $23.8 \pm 25.8\%$, $5.8 \pm 16.1\%$, $8.5 \pm 17.7\%$, and $11.9 \pm 15.0\%$ in Clusters 1-4, respectively. Notably, the two clusters originating from the south (Clusters 1 and 4) exhibited higher SO_4^{2-} fractions than the northwest-derived cluster (Cluster 3). This reversal of the typical pattern is likely attributable to enhanced sulfate formation through aqueous-phase oxidation, as southerly airflows in summer transport moist air masses into Beijing (Fig. 5d).

In autumn, NO_3^- mass fraction increased while SO_4^{2-} decreased sharply in all four clusters. Specifically, SO_4^{2-} accounted for $8.1 \pm 13.4\%$, $13.0 \pm 24.6\%$, $6.9 \pm 10.7\%$, and $8.1 \pm 16.5\%$, whereas NO_3^- accounted for $29.3 \pm 77.4\%$, $16.5 \pm 44.6\%$, $40.3 \pm 54.3\%$, and $40.7 \pm 65.6\%$ in Clusters 1-4, respectively. Consistent with the pattern shown in Fig. 3, NR-PM_{2.5} mass concentrations were higher in the south-originating cluster (Cluster 3,

40.7±46.4 $\mu\text{g m}^{-3}$) and west-originating cluster (Cluster 4, 31.8±41.2 $\mu\text{g m}^{-3}$) than in the two northwest-originating clusters (Cluster 1, 9.7±15.7 $\mu\text{g m}^{-3}$; Cluster 2, 10.2±16.1 $\mu\text{g m}^{-3}$). In terms of aerosol composition, the two northwest-originating clusters exhibited lower NO_3^- , but higher SO_4^{2-} fractions. In winter and spring, SO_4^{2-} mass fraction increased slightly in all four clusters. Consistent with autumn, NR-PM_{2.5} concentrations in the northwest-originating cluster were lower than those in clusters arriving from the south and northeast. Similarly, aerosols in the northwest-originating clusters consistently showed lower NO_3^- and higher SO_4^{2-} fractions. These results demonstrate that seasonal variations in aerosol composition over Beijing are governed by differences in emission sources, formation mechanisms, and the influence of regional transport.

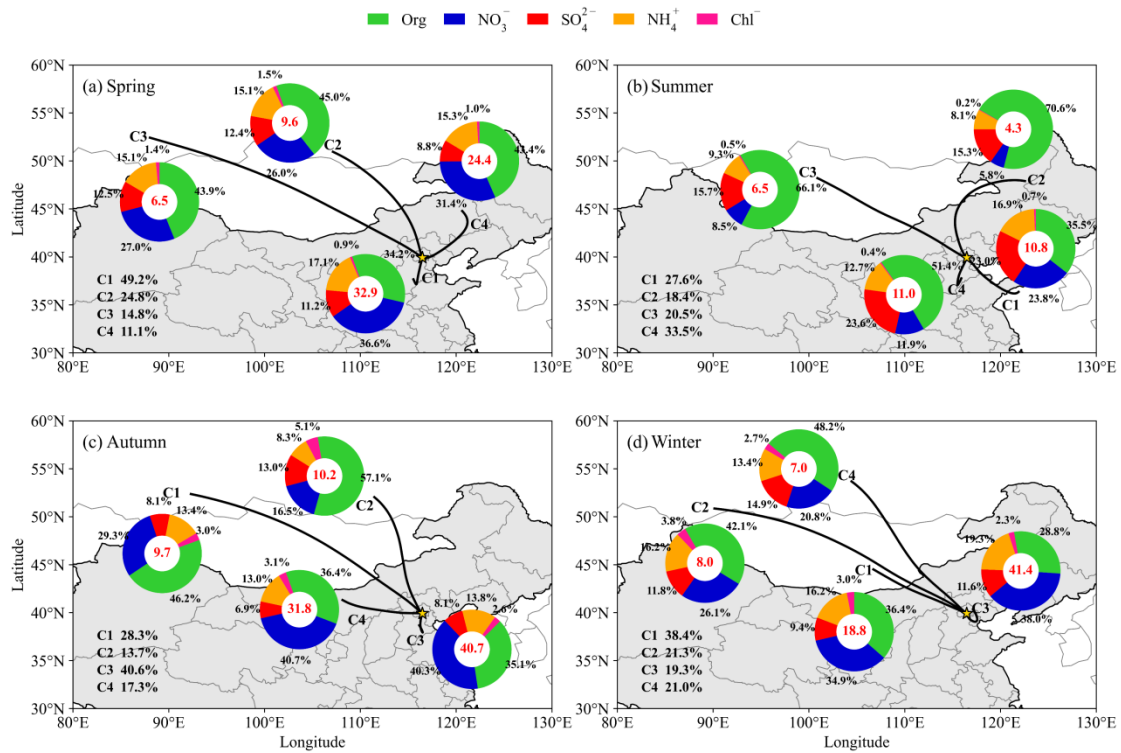


Figure 8. Forty-eight hours back trajectories of air masses over Beijing at altitude of 500 meters in four seasons, together with mean mass concentration and composition of NR-PM_{2.5} in each cluster.

3.4 Vertical mixing of pollutants through the PBL process

Regional pollutants may be transported downwards, thereby exacerbating air pollution in Beijing. To understand this process, diurnal variations of pollutants at the two stations were investigated. Due to the lack of concurrent aerosol composition measurements at ground station in the same period, only PM_{2.5} and gaseous pollutants were compared. Observations showed the differences of pollutants between the two stations decreased in the daytime but increased at night, particularly for gaseous pollutants (Fig. 9). At the NZG station, NO₂ remained high concentration at night and decreased in the morning, and reached a minimum of 11.0±9.1 ppb around 15:00.

After that, its concentration gradually increased. In contrast, NO₂ at the CITIC station exhibited an opposite diurnal pattern. NO₂ increased in the morning, peaked at 13:00 (17.3±17.8 ppb), and then decreased, remaining low concentration throughout the night. It is noteworthy that daytime NO₂ at the CITIC station is higher than at the NZG station, likely due to the conversion of NO to NO₂ during vertical mixing. NO accounts for about 39% of total NO_x at ground level, but decreases to 22% at the CITIC station (Ma et al., 2023). SO₂ showed a contrasting trend to NO₂. At the NZG station, SO₂ increased in the morning, peaked at 13:00 (1.36±0.97 ppb), then decreased and kept in low concentration at night. However, SO₂ was relatively stable, with only a slight decrease around noon, at the CITIC station. SO₂ at the CITIC station is higher than at the NZG station throughout the day, likely due to regional transport. O₃ also exhibited marked differences between the two stations; its concentration at the NZG station was close to the CITIC in daytime, but much lower than the latter at night (Fig. 9c), likely due to NO titration (Brown and Stutz, 2012). Compared with short-lived gaseous pollutants, the difference in PM_{2.5} between the two stations was less significant (Fig. 9d).

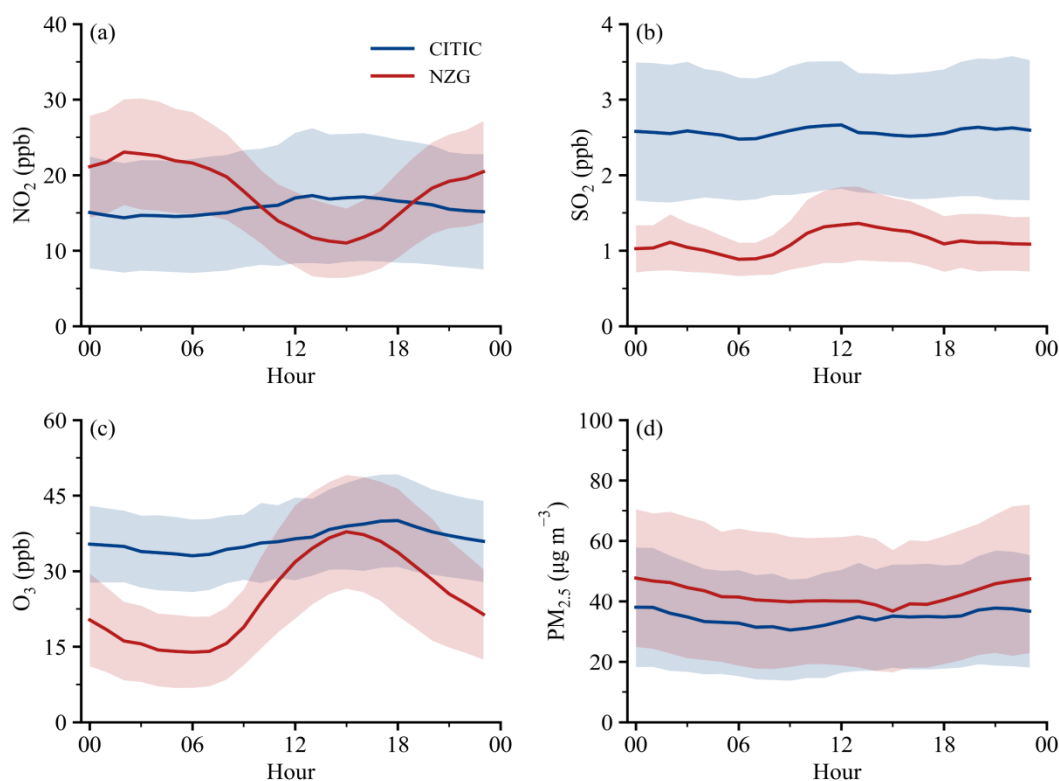


Figure 9. Diurnal variations of NO₂, SO₂, O₃, and PM_{2.5} during observational period (2020-2024) at the CITIC (blue) and NZG (red) stations, respectively. The shaded areas denote 50% standard deviation.

The opposite patterns of NO₂ and SO₂ at the two stations may be caused predominantly by the PBL process. Our previous studies show that the CITIC station resides in the residual layer (RL) at night (Ma et al., 2023; Quan et al., 2025). The decoupling between the RL and nocturnal stable boundary layer (SBL) substantially

suppresses vertical exchange of pollutants between the two layers, leading to large differences of pollutants between the CITIC and NZG stations. In the morning, the daytime convective boundary layer (CBL) develops gradually under increasing solar radiation, and eventually couples the overlying RL. This coupling strongly enhances vertical mixing of pollutants. In this process, locally emitted NO₂ at ground level was upwards transported, leading to the contrasting diurnal patterns of NO₂ between the two stations. By contrast, regional transported SO₂ was transported downwards in this process. Notably, NO₂ at the CITIC exceeded that at the NZG between 11:00 and 18:00, likely due to the conversion of NO to NO₂ during vertical mixing in the presence of high O₃ concentration aloft (Fig. 9c). For PM_{2.5}, its difference between the two stations also decreased at afternoon (Fig. 9d), consistent with enhanced vertical mixing in this period.

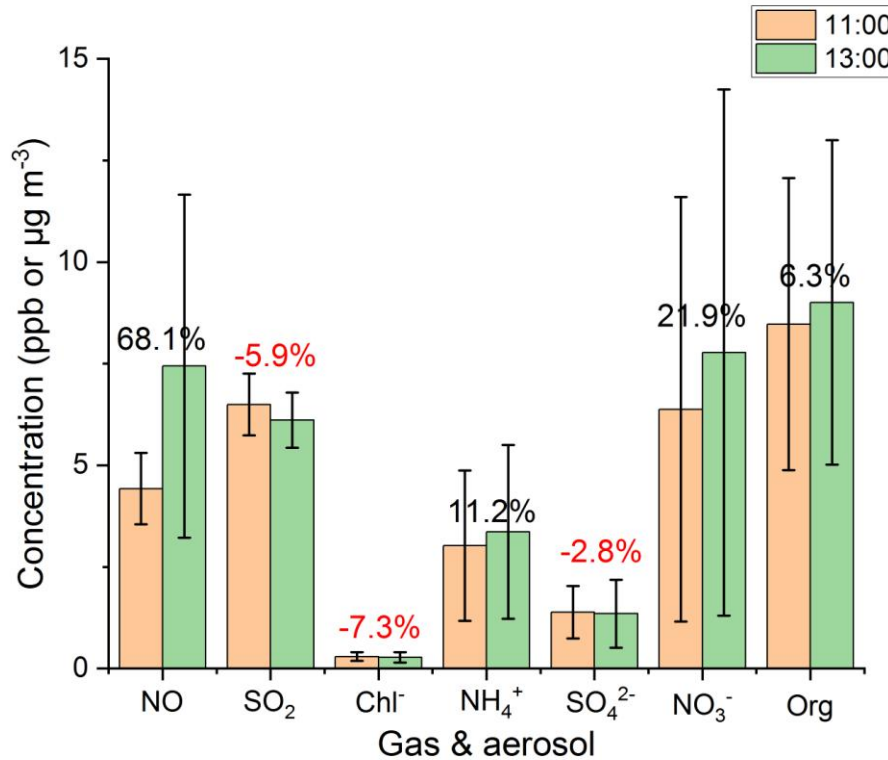


Figure 10. Mean concentrations of gases and aerosol components at the CITIC station at 11:00 and 13:00 from October 17 to November 12, 2020. Values indicate the percentage variations of pollutants between 11:00 and 13:00. Error bars represent 50% of the standard deviations.

To better understand the vertical mixing of pollutants, we further analyzed the diurnal variations in aerosol components from October 17 to November 12, 2020. Driven by the daytime expansion of the PBL in the morning, strong vertical transport typically occurred. This process was identified by an abrupt increase in NO. Given that NO is a short-lived gaseous pollutant, its sharp increase in the 528 m layer serves as an

indicator of upward transport from the surface. Based on the temporal evolution of NO, the strong vertical transport period was determined as 11:00-13:00 (Fig. S3). Accordingly, the variations in pollutants at the CITIC station during this specific period were investigated.

As illustrated in Fig. 10, the NO concentration at the CITIC station surged by 68.1% between 11:00 and 13:00, whereas SO₂ decreased by 5.9% during the same period. These observations substantiate the distinct emission sources of NO_x and SO₂ in Beijing. This divergence is further corroborated by the variations in NO₃⁻ and SO₄²⁻; NO₃⁻ increased by 21.9%, while SO₄²⁻ declined by 2.8%. Additionally, the mass concentration of Chl⁻ decreased by 7.3% during the same period, indicating its primary origin from regional transport. Although the mass concentrations of Org and NH₄⁺ also increased, their growth rates (Org: 6.3%; NH₄⁺: 11.2%) were notably lower than that of NO₃⁻, suggesting that regionally transported aerosols are particularly enriched in Org and NH₄⁺. Consequently, the downward entrainment of these regionally transported aerosols from the upper layer via PBL processes exacerbates surface air pollution in Beijing.

4 Summary

Regional transport of pollutants to Beijing was investigated in this study based on comprehensive observations of aerosol components and gaseous pollutants conducted at a unique 528-m platform over urban Beijing from 2020 to 2024. The main findings are summarized as follows:

(1) Aerosol mass concentration and chemical composition varied markedly with air mass origin. Air masses from the northwest delivered relatively clean air to Beijing, characterized by low aerosol levels but relatively high SO₂. In terms of composition, these northwesterly flows exhibited lower NO₃⁻ and NH₄⁺ fractions but higher SO₄²⁻ and Chl⁻. In contrast, air masses from the south, and northeast transported high aerosols with increased SIAs fractions, including NO₃⁻, NH₄⁺, and SO₄²⁻. These results suggest that emissions in the northwest are dominated by coal combustion, whereas those in the south and northeast involve multiple sources, including coal combustion, vehicle exhaust, agricultural and natural soils, and animal waste.

(2) Both the SOR and NOR were higher in air masses originating from the south and northeast than in those from the northwest, likely due to higher RH in the former, which promotes aqueous-phase heterogeneous oxidation of SO₂ and NO₂. These results indicate that differences in aerosol properties in the six transport pathways are governed by a combination of regional emissions and chemical reactions during transport.

(3) Contrasting diurnal patterns of SO₂ and NO₂ between the 528-m layer and ground level confirm that pollutants are well mixed during the day but strongly suppressed at night due to the decoupling of the RL and SBL. Driven by the development of PBL, locally emitted NO₂ is transported upward during daytime, while regionally derived SO₂ aloft is transported downward toward the surface. These findings demonstrate that regional aerosols over Beijing are transported downward primarily through PBL

processes, thereby exacerbating surface air pollution.

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Author Contribution JQ and PT initiated and conceived the research; JQ, XL and PM led the observations, analyses and writing; YP and QW analyzed the data; PT and LZ revised the manuscript.

Data availability. The observational data at the CITIC station are available from <https://doi.org/10.5281/zenodo.18424062> (Quan, 2026). Pollutant data (PM_{2.5}, SO₂, NO₂ and O₃) at NZG station are available from the China National Environmental Monitoring Centre (<http://www.cnemc.cn/>).

Competing interests

The authors declare that they have no competing interests.

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