

A Basin Amplifier: PM_{2.5} and O₃ Coupling in a Typical Industrial City, Northern China

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Keywords: PM_{2.5}; O₃; Compound Pollution; Basin Terrain; Regional Transport

Abstract: Jincheng, a typical industrial city located at the southern end of the Taihang Mountains and surrounded by mountains, suffers from severe PM_{2.5} and O₃ compound pollution driven by both industrial emissions and basin terrain. Based on six-year (2020–2025) observations, this study identifies pollution episodes using the growth–peak–decline framework, and analyses their meteorological causes and regional transport contributions with HYSPLIT, PSCF and CWT. Results show that: (1) PM_{2.5} annual mean dropped from 46.4 to 30.0 µg/m³, while the 90th percentile of MDA8 O₃ fluctuated and then declined from 175.5 to 155.6 µg/m³. (2) According to the exceedance-day statistics, there were 197 PM_{2.5} exceedance days, 375 O₃ exceedance days and 6 compound pollution days; under the episode-identification framework, sensitivity tests showed that the numbers of steady-state accumulation, photochemical and compound episodes remained stable at about 78–80, 85–106 and 11–12, respectively. (3) CWT analysis indicates that regional transport dominates local accumulation: the regional CWT high-value zones are 90.3 vs. 65.4 µg/m³ for PM_{2.5}, and 167.2 vs. 148.7 µg/m³ for O₃. (4) Enhanced atmospheric oxidizing capacity strengthens the coupled 'radiation–heterogeneous–oxidizing' cycle between PM_{2.5} and O₃. These findings highlight the 'basin amplifier' effect and provide a scientific basis for collaborative PM_{2.5}–O₃ control.

1. Introduction

In recent years, fine particulate matter (PM_{2.5}) and ozone (O₃) have become the two major ambient pollutants in China. Under compound pollution, the two pollutants interact through radiative effects, heterogeneous reactions and atmospheric oxidizing capacity, forming a coupled 'radiation–heterogeneous–oxidizing' cycle [1]. Typical industrial cities in energy-rich regions face particularly severe compound pollution because of heavy coal-based industries and constrained pollutant dispersion. Jincheng, situated at the southern end of the Taihang Mountains, is a representative basin-type coal-chemical industrial city characterised by the 'three mountains enclosing one basin' topography. The combined effect of basin terrain and intensive emissions makes it a unique case for studying compound pollution mechanisms.

Although compound pollution has been widely studied in the North China Plain, the Yangtze

River Delta and the Fenwei Plain [2-4], the terrain–meteorology–chemistry coupling in Taihang-basin industrial cities remains insufficiently quantified. Previous source-apportionment studies in the Beijing–Tianjin–Hebei region have identified industrial emissions and vehicle exhaust as major contributors to PM_{2.5} [5], yet the superposition of 'weak-wind–temperature-inversion coupling' and coal-based industrial emissions in basin-type industrial cities has not been systematically quantified, and compound pollution has rarely been classified through long-term pollution-episode identification rather than mere exceedance-day statistics. This study takes Jincheng as a case to fill this gap.

2. Data and Methods

2.1. Study Area

Jincheng (35°11'–36°04' N, 111°55'–113°37' E) is located in the southeast of Shanxi Province, with a total area of 9,490 km². It is surrounded by the Taihang Mountains (east and north), the Taiyue Mountains (west) and the Zhongtiao Mountains (south), forming a closed basin open to the south. The main industries are coal mining, power generation, chemical production, steel and building materials. The city has a warm-temperate semi-humid continental monsoon climate, with an annual mean temperature of 10.5 °C, annual precipitation of 650 mm and annual mean wind speed of 2.1 m/s.

2.2. Data and Preprocessing

Three types of data were used: (1) Air quality data from six national monitoring stations in Jincheng (2020-01-01 to 2025-12-31), including PM_{2.5} (24-h average) and O₃ (8-h running average, MDA8). (2) Hourly meteorological observations (later aggregated to daily), with missing precipitation in early 2020 supplemented by ERA5 reanalysis. (3) Emission inventory data from statistical yearbooks and environmental authorities. After cleaning and interpolation, 2,192 valid daily records with 29 variables were obtained.

Table 1: Statistical characteristics of different pollution events in Jincheng, 2020–2025.

Pollution type	Exceedance days	Proportion (%)	Mean concentration (μg/m ³)	Main season
PM _{2.5} exceedance days	197	9.0	102.5 ± 28.2	Winter (70.2%)
O ₃ exceedance days	375	17.1	184.7 ± 20.6	Summer (59.1%)
Compound pollution days	6	0.3	PM _{2.5} 84.2 ± 10.7 / O ₃ 169.5 ± 19.0	Autumn (66.7%)
Episodes (sensitivity)	78–80 / 85–106 / 11–12	—	steady / photochemical / compound	—

2.3. Episode Identification and Models

Following the episode-based air quality assessment proposed by Luo et al. [6], each pollution process was divided into growth, peak and decline phases. Episodes shorter than 24 h were excluded. HYSPLIT backward trajectories (96 h, 500 m above ground level, GDAS 1°×1° meteorological data) were clustered, and PSCF and CWT were used to identify potential source regions. A random-forest-based meteorological normalization (with 2020 as the reference year) was

applied to separate meteorological influences from emission effects [7,8]; the resulting meteorological contribution is treated as an upper-bound estimate because of the short six-year window.

3. Results

3.1. Pollution Characteristics and Episode Classification

From 2020 to 2025, the annual mean $\text{PM}_{2.5}$ concentration decreased from 46.4 to 30.0 $\mu\text{g}/\text{m}^3$ (a drop of 35.4%). The 90th percentile of MDA8 O_3 fluctuated at 172–181 $\mu\text{g}/\text{m}^3$ during 2020–2023 and then declined to 155.6–172 $\mu\text{g}/\text{m}^3$ in 2024–2025; the annual mean MDA8 decreased from 114.9 to 97.5 $\mu\text{g}/\text{m}^3$ (about 15.1%). Meteorological normalization suggested that meteorology explained a relatively high share of the $\text{PM}_{2.5}$ decline in 2025 (about 85%–90%) [8], but this should be regarded as an upper bound rather than a precise decomposition of emission contributions. Based on exceedance-day statistics, Jincheng recorded 197 $\text{PM}_{2.5}$ exceedance days (daily mean $\geq 75 \mu\text{g}/\text{m}^3$), 375 O_3 exceedance days ($\text{MDA8} \geq 160 \mu\text{g}/\text{m}^3$) and 6 compound pollution days (both exceeded) during 2020–2025 (Table 1). Under the episode-identification framework, sensitivity tests showed that the numbers of steady-state accumulation episodes ($\text{PM}_{2.5}$ -dominated), photochemical episodes (O_3 -dominated) and compound episodes remained stable at about 78–80, 85–106 and 11–12, respectively, when the threshold varied within 20%–40%. Compound pollution days were concentrated in June and September–October (66.7% in autumn), with moderate temperature (about 19 $^{\circ}\text{C}$), humidity (60%–75%) and low wind speed (1–2 m/s). The meteorological evolution during a typical $\text{PM}_{2.5}$ steady-state accumulation episode is illustrated in Figure 1.

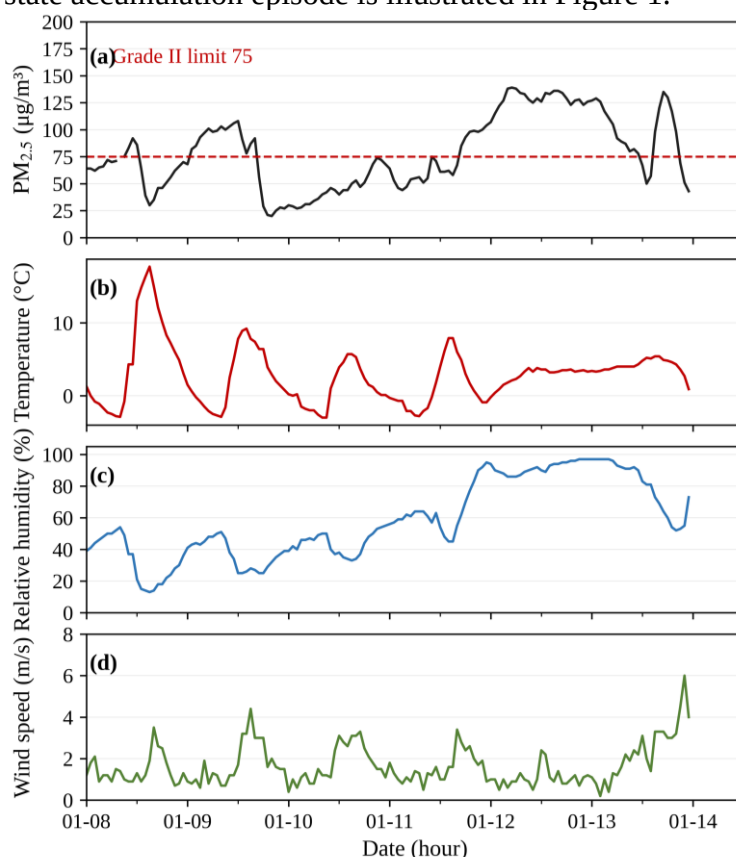


Figure 1: Meteorological evolution during a typical $\text{PM}_{2.5}$ steady-state accumulation pollution episode (Jan 8–13, 2023).

3.2. Meteorological Causes

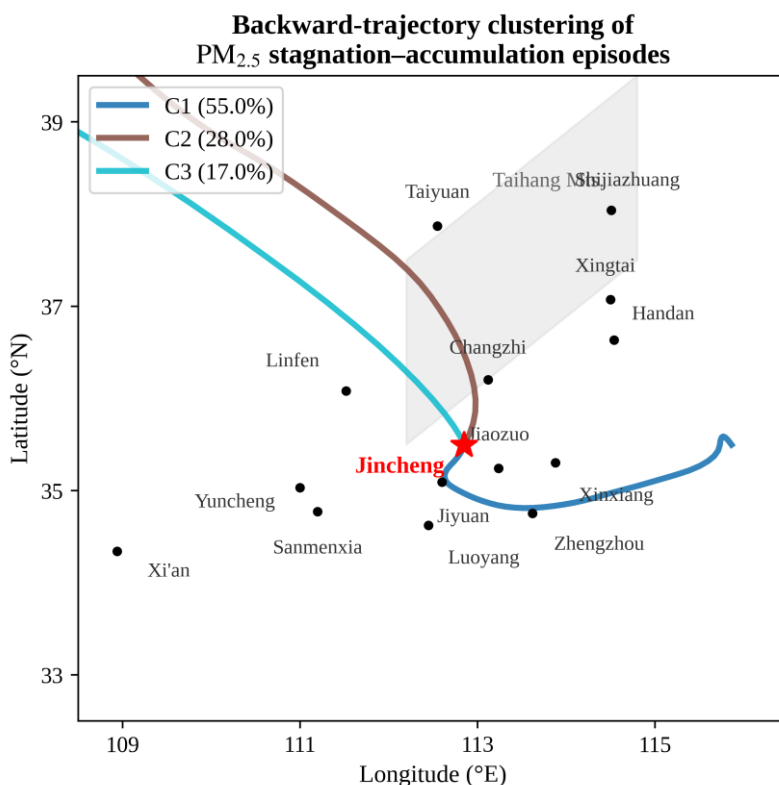
As shown in Table 2, the meteorological conditions differed significantly among the three pollution categories (Kruskal–Wallis test, $p < 0.01$). $\text{PM}_{2.5}$ exceedance days were characterised by low temperature (3.9 ± 5.8 °C), high humidity ($65.3 \pm 18.2\%$), weak wind (1.68 ± 0.98 m/s) and a very low boundary-layer height (385 ± 185 m). O_3 exceedance days had high temperature (23.5 ± 3.5 °C) and stronger wind (2.13 ± 0.62 m/s). Compound-pollution days showed intermediate-to-high temperature (19.2 ± 2.9 °C), relatively high humidity ($71.4 \pm 12.3\%$) and low wind speed (1.80 ± 0.34 m/s). The basin terrain further amplified local accumulation: the surrounding mountains favour daytime valley breezes (southerly) and nighttime mountain breezes (northerly), while frequent temperature inversions under calm conditions trap pollutants in the basin and at the mountain front.

3.3. Regional Transport Contribution

Table 2: Comparison of CWT high-value zones for different pollution events.

Pollution type	Local contribution (mean CWT, $\mu\text{g}/\text{m}^3$)	Regional contribution (mean CWT, $\mu\text{g}/\text{m}^3$)	Main transport direction
$\text{PM}_{2.5}$ steady-state accumulation	65.4	90.3	East + West
O_3 photochemical	148.7	167.2	South
Compound pollution	55.9 / 138.2*	104.0 / 186.6*	Mainly East

Note: * Compound pollution CWT values are given as ' $\text{PM}_{2.5} / \text{O}_3$ '. The regional/local ratios are statistical estimates from CWT analysis and should not be interpreted as an exact absolute decomposition; uncertainties arise from trajectory simulation and grid resolution.



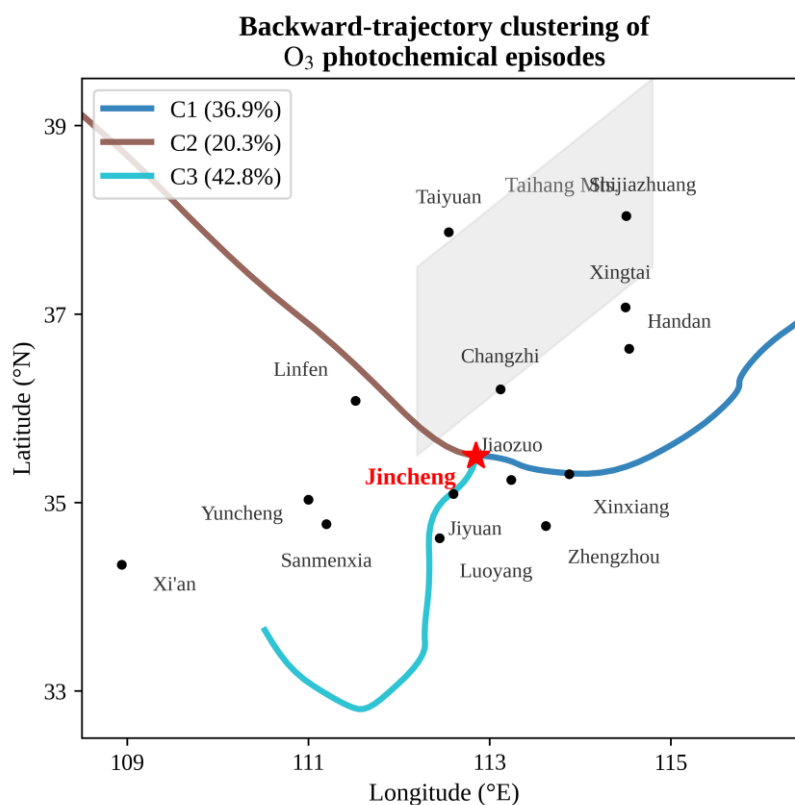


Figure 2: HYSPLIT backward trajectory clustering for PM_{2.5} accumulation and O₃ photochemical pollution episodes.

HYSPLIT clustering of backward trajectories revealed distinct transport pathways. For PM_{2.5} steady-state accumulation episodes, the dominant pathway was the east-short-distance route (C1, 55.0%), with air masses originating from southern Hebei–western Shandong–northern Henan (PM_{2.5} concentration $68.7 \pm 34.3 \mu\text{g}/\text{m}^3$ along the route). For O₃ photochemical episodes, the south route (C3, 42.8%) from central-southern Henan to Hubei dominated (MDA8 $156.1 \pm 38.0 \mu\text{g}/\text{m}^3$). The clustered backward trajectories for PM_{2.5} accumulation and O₃ photochemical episodes are shown in Figure 2. CWT analysis further quantified the contributions (Table 2): the regional CWT high-value zones were about $90.3 \mu\text{g}/\text{m}^3$ for PM_{2.5} (vs. about $65.4 \mu\text{g}/\text{m}^3$ locally) and about $167.2 \mu\text{g}/\text{m}^3$ for O₃ (vs. about $148.7 \mu\text{g}/\text{m}^3$ locally), confirming that regional transport plays a more important role than local accumulation in high-concentration events.

3.4. Coupling Mechanism

The synergistic mechanism of compound pollution can be summarised as a 'radiation–heterogeneous–oxidizing' triple-loop. First, radiation: moderate temperature and solar radiation in June and September–October favour O₃ photochemical production while maintaining high humidity for secondary aerosol formation. Second, heterogeneous reactions: the elevated humidity and abundant PM_{2.5} surface area promote multiphase oxidation of SO₂ and NO_x to sulfate and nitrate. Third, oxidizing capacity: enhanced atmospheric oxidation accelerates the synchronous formation of secondary particles and O₃. These three loops reinforce each other, producing the nonlinear PM_{2.5}–O₃ coupling observed during compound-pollution episodes (Figure 3).

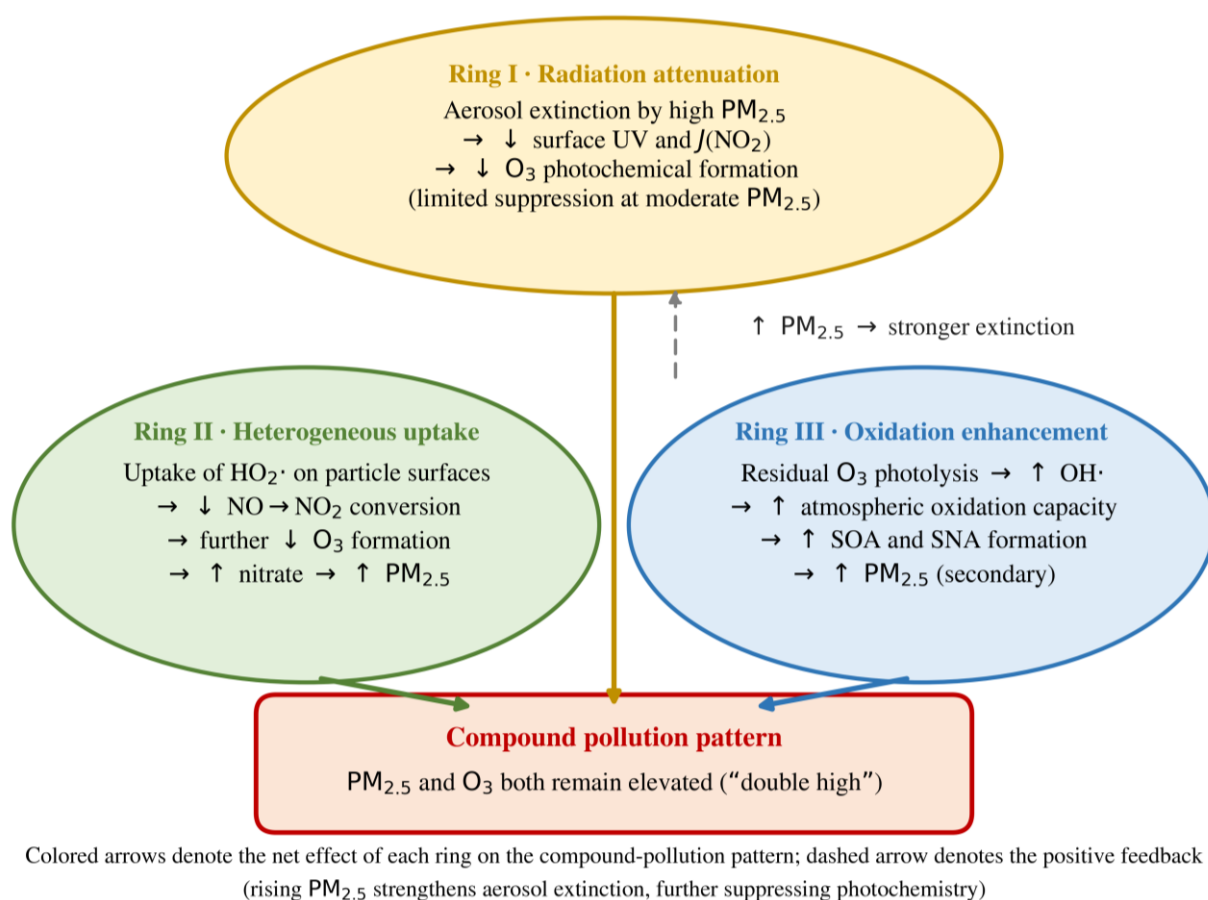


Figure 3: Conceptual model of the "radiation-heterogeneous-oxidation" three-ring coupling mechanism of $\text{PM}_{2.5}$ - O_3 compound pollution.

Note: Conceptual model of the "radiation-heterogeneous-oxidation" three-ring coupling mechanism of $\text{PM}_{2.5}$ - O_3 compound pollution (the three rings act in sequence—radiation attenuation→heterogeneous uptake→oxidation enhancement—forming a positive-feedback cycle; this model is a conceptual synthesis based on a limited sample ($n = 6$) and literature parameters, and the quantitative relationships of each link await verification by radical observations and box-model simulations).

4. Discussion

The 'basin amplifier' concept is the key distinction of this study. In plain city clusters, regional transport can be diluted by stronger winds, whereas in the Taihang-basin setting the closed terrain and frequent inversions confine both locally emitted and regionally transported pollutants, so that even moderate emissions can produce high concentrations. The CWT results (regional > local) further imply that control strategies limited to the city level are insufficient; joint prevention and control across Hebei, Shanxi, Shaanxi and Henan is necessary, especially during the transition seasons (June and September–October) when compound pollution peaks. Nevertheless, the CWT estimates carry uncertainties from trajectory simulation and grid resolution, and the meteorological-normalization results should be interpreted as upper-bound indications rather than exact emission-attribution values.

5. Conclusions

(1) Jincheng's PM_{2.5} decreased markedly from 2020 to 2025, while O₃ remained high before declining slightly; compound pollution was concentrated in June and autumn under moderate-temperature, high-humidity and calm-wind conditions. (2) The basin terrain acts as an 'amplifier' through valley-breeze circulation and double-layer inversions, intensifying local accumulation. (3) Regional transport dominates high-concentration events: PM_{2.5} is mainly transported from the east and west, O₃ mainly from the south. (4) The 'radiation–heterogeneous–oxidizing' triple-loop drives the nonlinear PM_{2.5}–O₃ coupling. Dynamic, meteorology-informed and regionally coordinated control is recommended during transition seasons.

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