





32 **Keywords: air quality, ozone, multipollutant trends, city-level divergence, China**

33 **1. Introduction**

34 Over the past decade, air quality in Chinese cities has undergone substantial changes.
35 Owing to large-scale national policies for atmospheric pollution control, concentrations
36 of particulate matter (PM_{2.5} and PM₁₀), sulfur dioxide (SO₂), nitrogen dioxide (NO₂)
37 and carbon monoxide (CO) have decreased markedly in most cities across the country
38 (Zheng et al., 2018; Zhang et al., 2019; Geng et al., 2024; Zheng et al., 2024). These
39 changes represent one of the most prominent examples of rapid air-quality
40 improvement under conditions of large-scale urbanization and intensive industrial
41 activity. However, the reduction of most conventional pollutants does not imply that
42 the entire urban air-pollution system has changed in the same direction.

43 A key exception is ground-level ozone (O₃). Unlike primary pollutants and
44 particulate pollution, O₃ is a secondary photochemical pollutant whose formation is
45 controlled by nonlinear interactions among NO_x, VOCs, solar radiation, temperature,
46 aerosol loading and meteorological conditions (Sillman, 1999; Li et al., 2019a; Wang
47 et al., 2022a). Therefore, reductions in primary pollutant and aerosol emissions do not
48 necessarily lead to a decrease in O₃. On the contrary, reduced aerosol loading may
49 promote photolysis, alter the oxidative capacity of the atmosphere and modify the
50 conditions for O₃ formation (Lou et al., 2014; Li et al., 2019b; Ivatt et al., 2022).

51 The significance of this problem extends beyond a simple assessment of pollutant
52 concentrations. PM_{2.5} and O₃ remain among the most important components of air-
53 pollution risk to public health (Cohen et al., 2017; Niu et al., 2022). Although PM_{2.5}
54 reductions have brought substantial benefits, the simultaneous increase in O₃ may partly
55 offset overall progress in reducing the health-related air-pollution burden (Achebak et
56 al., 2024; Silver et al., 2025). In addition, elevated O₃ can reduce agricultural
57 productivity, damage vegetation and forest ecosystems, and cause economic losses
58 through reduced crop yield and forest productivity (Tai et al., 2014; Mills et al., 2018;
59 Feng et al., 2019). Therefore, further improvement in air quality requires not only
60 continued PM control, but also a more precise understanding of the drivers of O₃
61 increases.

62 Despite a large body of research, important knowledge gaps remain. PM_{2.5} and O₃
63 are increasingly regarded as interconnected air-quality problems requiring coordinated
64 control, because the decline in PM_{2.5} in China has been accompanied by worsening O₃



pollution and changes in the health-related air-pollution burden (Zhao et al., 2021; Xiao et al., 2022). However, many studies have focused either on national trends and health burden or on the chemical mechanisms of O₃ increases, whereas the joint city-level evolution of PM_{2.5}, PM₁₀, SO₂, NO₂, CO and O₃ within a unified multipollutant system has been less systematically examined (Chu et al., 2020; Liu et al., 2023). In addition, regional heterogeneity has often been analyzed at the level of individual pollutants or individual urban agglomerations, which makes it difficult to compare regions with different emission sources, climate, topography and photochemical conditions (Qiao et al., 2019; Dai et al., 2021; Wang et al., 2021; Wang et al., 2022b; Zhang et al., 2022; Qian et al., 2024; Xu et al., 2024). Finally, it remains insufficiently clear why cities with comparable reductions in conventional pollutants can exhibit different trajectories of O₃ response. This city-level divergence is a key limitation for moving from national air-quality assessment toward more precise city-specific control strategies.

Seasonality further complicates the interpretation of O₃ response. In spring and summer, high solar radiation and temperature can enhance photochemical O₃ formation, whereas in winter weak photochemistry and NO titration can lead to opposite relationships between O₃ and primary pollutants (Sillman, 1999; Li et al., 2021). Therefore, long-term changes in O₃ cannot be explained only by annual trends or by reductions in individual pollutants. An analysis is needed that simultaneously considers national trends, regional heterogeneity, seasonal multipollutant relationships and city-level divergence between conventional pollutant reductions and O₃ response.

In this study, we analyze the multipollutant evolution of air quality in Chinese cities during 2015–2025 using ground-based observations from the China National Environmental Monitoring Centre (CNEMC) for six major pollutants, namely PM_{2.5}, PM₁₀, SO₂, NO₂, CO and O₃. The main objectives of this study are to: (1) quantify national long-term changes in the six pollutants; (2) identify regional differences in multipollutant evolution; (3) characterize seasonal O₃-centred relationships among pollutants; and (4) develop a city-level divergence framework to assess how reductions in conventional pollutants are associated with changes in O₃ across individual cities.

2. Materials and methods

2.1. Air-quality data and preprocessing

This study used ground-based air-quality observations from the national monitoring network of the China National Environmental Monitoring Centre (CNEMC) for the



98 period from 1 January 2015 to 31 December 2025. The original data had hourly
99 resolution and covered six major air pollutants: PM_{2.5}, PM₁₀, SO₂, NO₂, CO and O₃. All
100 measurements were conducted in accordance with the national ambient air-quality
101 standard (GB3095-2012). For subsequent analysis, hourly observations were converted
102 into daily values. Daily mean concentrations were calculated for PM_{2.5}, PM₁₀, SO₂, NO₂
103 and CO, whereas O₃ was represented by the maximum daily 8-hour mean (MDA8).

104 For the annual analysis, daily data were aggregated into annual mean values
105 separately for each city, year and pollutant. An annual value was included in the
106 analysis only when at least 274 valid daily observations were available in the
107 corresponding year, corresponding to approximately 75% annual coverage. The same
108 principle was applied to the seasonal analysis: a seasonal value for a given city and year
109 was retained only when at least 68 valid daily observations were available in the
110 corresponding season.

111 **2.2. Regional classification of cities**

112 To analyze spatial heterogeneity, cities were divided into eight regions: Beijing–
113 Tianjin–Hebei (BTH), Yangtze River Delta (YRD), Pearl River Delta (PRD), Fenwei
114 Plain, Sichuan Basin, Northeast China, Northwest China and Other China. This
115 classification accounted for the major air-pollution regions of China, city location,
116 climatic conditions, topography and characteristic pollution sources. Cities belonging
117 to well-known polluted regions were assigned to the corresponding groups based on
118 predefined city lists. The remaining cities were assigned to Northeast China, Northwest
119 China or Other China according to their geographical location. Regional mean values
120 were calculated as averages across cities within each region.

121 **2.3. Estimation of national trends**

122 Long-term pollutant trends were evaluated using annual city-level concentrations for
123 2015–2025. For each city and pollutant, the trend magnitude was calculated using Sen’s
124 slope estimator. Only cities with at least eight valid annual values over the 11-year
125 period were included in the trend analysis. The statistical significance of monotonic
126 trends was assessed using the Mann–Kendall test. Trends were considered statistically
127 significant at $p < 0.05$.

128 National annual mean concentrations were calculated as averages across all available
129 cities in each year. For the national summary assessment, pollutant changes were



determined between 2015 and 2025. For the regional and city-level analyses, two multi-year periods were used: the early period of 2015–2017 and the late period of 2023–2025. This approach reduces the influence of individual anomalous years and allows a more robust assessment of changes between the beginning and the end of the study period.

2.4. Regional changes and O₃ penalty ratio

For each region, relative changes in PM_{2.5}, PM₁₀, SO₂, NO₂, CO and O₃ were calculated between the early period (2015–2017) and the late period (2023–2025). A change was considered valid only when at least two annual values were available in each of the two periods. These calculations were used to assess how consistently conventional pollutants decreased and how O₃ changed against this background.

To quantify the increase in O₃ relative to the reduction of each conventional pollutant, an O₃ penalty ratio was calculated. This indicator reflects the increase in O₃ per 10% reduction in a given pollutant. For example, if PM_{2.5} decreased while O₃ increased simultaneously, the penalty ratio indicates how strongly the increase in O₃ “offset” the reduction in PM_{2.5}. The calculation was performed as follows:

$$Penalty\ ratio_p = 10 \times \frac{\Delta O_3}{R_p}$$

where ΔO_3 is the relative change in O₃ between 2015–2017 and 2023–2025, expressed as a percentage, and R_p is the reduction of the corresponding pollutant (p), expressed as a positive value. For example, if PM_{2.5} changed by –40%, then $R_{2.5} = 40\%$. Positive penalty-ratio values indicate that O₃ increased against the background of a reduction in the given pollutant; negative values indicate that O₃ decreased despite a reduction in the conventional pollutant.

2.5. Seasonal correlation analysis

Seasonal relationships among pollutants were analyzed using city-season-year mean values. Four seasons were defined: spring (March–May), summer (June–August), autumn (September–November) and winter (December–February). For each season, pairwise Spearman rank correlations were calculated among PM_{2.5}, PM₁₀, SO₂, NO₂, CO and O₃. Spearman correlation was used because relationships among pollutants may be nonlinear and sensitive to seasonal and regional differences.



160 To control for multiple testing, p-values were adjusted using the Benjamini–
161 Hochberg false discovery rate procedure. Associations were considered statistically
162 significant at $q < 0.05$. This analysis was used only to evaluate statistical associations
163 among pollutants and was not interpreted as direct evidence of causal relationships.

164 2.6. City-level divergence framework

165 To assess the divergence between reductions in conventional pollutants and the O₃
166 response, a city-level divergence framework was developed. For each city, relative
167 changes in PM_{2.5}, PM₁₀, SO₂, NO₂, CO and O₃ were calculated between the early period
168 (2015–2017) and the late period (2023–2025).

169 Based on these changes, a five-pollutant reduction index (R5) was calculated for
170 each city, representing the mean reduction of the five conventional pollutants:

$$171 \quad R5 = \text{mean}(R_{PM2.5}, R_{PM10}, R_{SO2}, R_{NO2}, R_{CO})$$

172 where R_p is the reduction of each pollutant expressed as a positive value. For
173 example, a 40% reduction in PM_{2.5} corresponds to $R_{PM2.5} = 40\%$. Higher R5 values
174 therefore indicate stronger overall reductions in conventional pollutants in a given city.

175 The O₃ response was assessed separately as the relative change in O₃ between the
176 early and late periods (ΔO_3). Cities were then classified into four types based on the
177 median values of R5 and ΔO_3 .

178 Type I represents strong reductions in conventional pollutants ($R5 \geq \text{median}$) and a
179 weak O₃ response ($\Delta O_3 < \text{median}$). Type II represents strong reductions in conventional
180 pollutants ($R5 \geq \text{median}$) and a strong O₃ increase ($\Delta O_3 \geq \text{median}$). Type III represents
181 weaker reductions in conventional pollutants ($R5 < \text{median}$) and a strong O₃ increase
182 ($\Delta O_3 \geq \text{median}$). Type IV represents weaker reductions in conventional pollutants ($R5$
183 $< \text{median}$) and a weak O₃ response ($\Delta O_3 < \text{median}$).

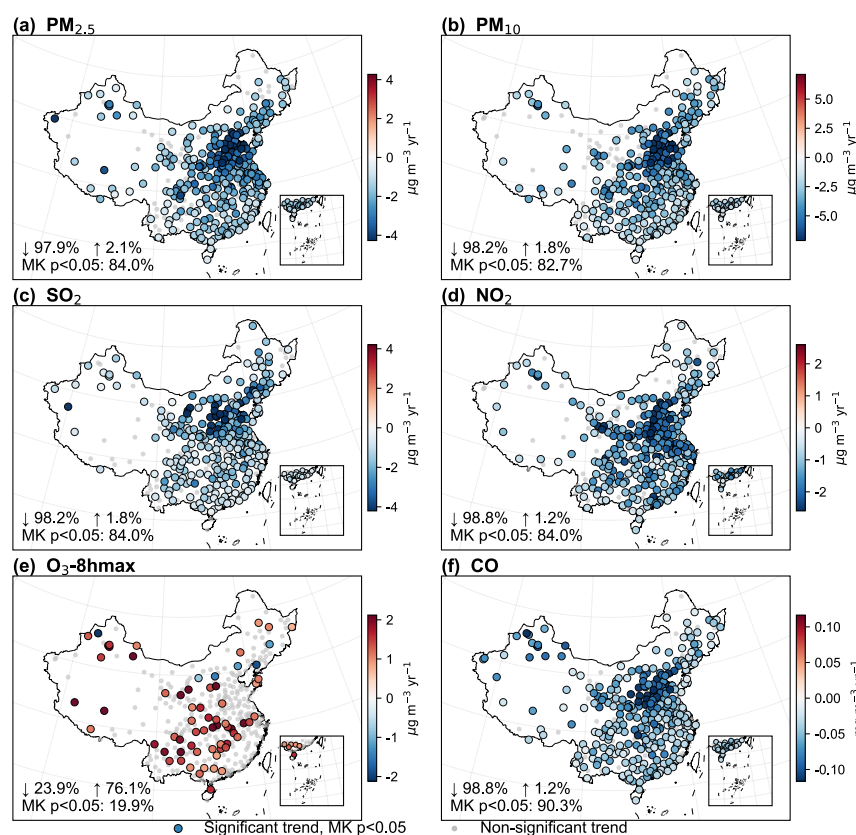
184 The relationship between R5 and ΔO_3 was additionally evaluated using Spearman's
185 rank correlation coefficient. This typology was interpreted as an empirical city-level
186 classification rather than a direct diagnosis of O₃ chemical regimes, because the
187 available data do not allow direct determination of NO_x–VOC sensitivity or aerosol
188 radiative effects.

189 3. Results and discussion

190 3.1 National spatiotemporal evolution of six pollutants



191 National trends of the six major pollutants reveal substantial but uneven changes in
192 urban air quality across China during 2015–2025 (**Figure 1**). According to Table 1, the
193 annual mean concentration of PM_{2.5} decreased from 50.4 to 29.8 $\mu\text{g}/\text{m}^3$ (–40.8%), while
194 PM₁₀ declined from 88.8 to 57.5 $\mu\text{g}/\text{m}^3$ (–35.3%). Among gaseous pollutants, the
195 strongest relative decrease was observed for SO₂, from 25.7 to 7.6 $\mu\text{g}/\text{m}^3$ (–70.3%),
196 whereas CO and NO₂ decreased by 45.0% and 36.2%, respectively. These results
197 indicate a substantial weakening of particulate and primary gaseous pollution in
198 Chinese cities, consistent with previous studies (Zheng et al., 2018; Zhai et al., 2019;
199 Silver et al., 2020).



200

201 **Figure 1.** Long-term trends of six major air pollutants across Chinese cities during
202 2015–2025.

203 The spatial distribution of Sen's slope shows that decreases in PM_{2.5}, PM₁₀, SO₂,
204 NO₂ and CO were widespread across the country (**Figure 1a–d, f**). For these five
205 pollutants, more than 97% of cities exhibited negative trends, and most of these trends



206 were statistically significant ($p < 0.05$): 84.0% for PM_{2.5}, SO₂ and NO₂, 82.7% for PM₁₀,
207 and 90.3% for CO. This spatial coherence indicates that the decline in concentrations
208 represented a robust national trend rather than a result of local changes (Li et al., 2020;
209 Geng et al., 2024; Zheng et al., 2024).

210 The decreases in SO₂, CO and NO₂ reflect an overall reduction in combustion-
211 related and primary emission sources. SO₂ and CO are closely associated with fuel
212 combustion, whereas NO₂ largely reflects contributions from transport, industry and
213 power generation. Their simultaneous decline indicates a weakening of primary
214 pollution burden. The decrease in PM_{2.5} is consistent with this pattern, because fine
215 particulate matter depends on both direct emissions and gaseous precursors of
216 secondary aerosols, including SO₂ and NO₂. Median Sen's slope values for PM_{2.5}, PM₁₀,
217 SO₂, NO₂ and CO were -1.83, -2.97, -1.11, -1.19 and -0.042, respectively,
218 confirming the persistent nature of these decreases.

219 In contrast to the other pollutants, O₃ showed the opposite pattern: its annual mean
220 concentration increased from 83.6 to 92.1 $\mu\text{g}/\text{m}^3$ (+10.3%). Positive O₃ trends were
221 observed in 76.1% of cities, whereas negative trends occurred in only 23.9% (Figure
222 1e). The median Sen's slope for O₃ was +0.54 $\mu\text{g}/\text{m}^3/\text{yr}^{-1}$, and its range was the widest
223 among all pollutants, from -2.14 to +5.36 $\mu\text{g}/\text{m}^3/\text{yr}^{-1}$. This indicates that air-quality
224 improvement in China was not characterized by a uniform decline in all pollutants:
225 reductions in PM_{2.5}, PM₁₀, SO₂, NO₂ and CO were accompanied by increasing O₃ in
226 most cities.

227 This contrast can be explained by differences in the nature of these pollutants. PM_{2.5},
228 PM₁₀, SO₂, NO₂ and CO are more directly linked to primary emissions or relatively
229 direct secondary processes, and therefore respond more strongly to reductions in
230 emission intensity. O₃ is a secondary photochemical pollutant whose formation depends
231 on nonlinear interactions among NO_x, VOCs, solar radiation, temperature and aerosol
232 loading (Li et al., 2019a; Xie et al., 2023). Therefore, reductions in primary pollutants
233 do not necessarily translate into lower O₃; on the contrary, reduced aerosol loading and
234 changes in NO_x chemistry may create conditions favorable for O₃ increases (Ivatt et al.,
235 2022).

236 Importantly, O₃ displayed a more heterogeneous statistical pattern: the share of cities
237 with significant trends was only 19.9%, compared with 82.7–90.3% for the other
238 pollutants. This suggests that the decline in primary and particulate pollutants was



239 spatially more coherent, whereas O₃ dynamics were more strongly dependent on
240 regional differences in photochemical conditions, meteorology and chemical regime.

241 Overall, over more than a decade, air quality in Chinese cities improved substantially
242 for most pollutants, but O₃ evolved in the opposite direction. This highlights the need
243 to move from single-pollutant control toward more coordinated multipollutant
244 management, especially given the increasing role of O₃ in urban air pollution.

245

246 **Table 1.** National mean changes in six major air pollutants across Chinese cities, 2015–
247 2025.

Pollutant	Mean 2015	Mean 2025	Absolute change	Relative change	Median Sen's slope	n cities
PM _{2.5}	50.4 µg/m ³	29.8 µg/m ³	-20.6 µg/m ³	-40.8%	-1.83 µg/m ³ yr ⁻¹	331
PM ₁₀	88.8 µg/m ³	57.5 µg/m ³	-31.3 µg/m ³	-35.3%	-2.97 µg/m ³ yr ⁻¹	329
SO ₂	25.7 µg/m ³	7.6 µg/m ³	-18.1 µg/m ³	-70.3%	-1.11 µg/m ³ yr ⁻¹	331
NO ₂	30.0 µg/m ³	19.2 µg/m ³	-10.9 µg/m ³	-36.2%	-1.19 µg/m ³ yr ⁻¹	331
O ₃	83.6 µg/m ³	92.1 µg/m ³	+8.6 µg/m ³	+10.3%	+0.54 µg/m ³ yr ⁻¹	331
CO	1.08 mg/m ³	0.60 mg/m ³	-0.49 mg/m ³	-45.0%	-0.042 mg/m ³ yr ⁻¹	331

248 3.2 Regional differences in pollutant evolution

249 Regional analysis shows that the national pattern of air-quality change manifested
250 unevenly across different regions of China (Figure 2). PM_{2.5}, PM₁₀, SO₂, NO₂ and CO
251 decreased in all regions, but the magnitude of these changes varied substantially,
252 reflecting differences in baseline pollution levels, source structure and local conditions
253 controlling pollutant formation.

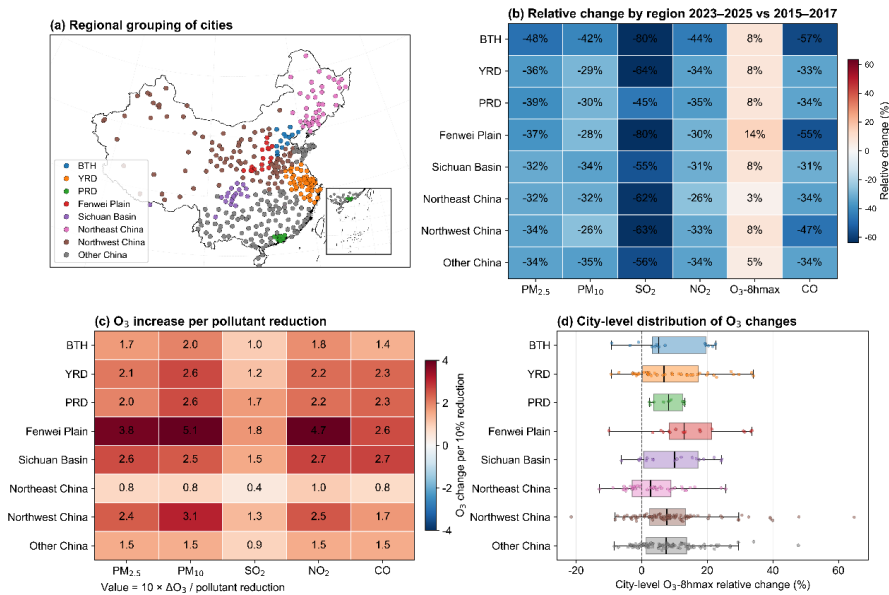


Figure 2. Regional heterogeneity in multipollutant evolution across Chinese cities.

The most pronounced decrease in PM_{2.5} was observed in BTH (−47.6%). In the other regions, the reduction was within a narrower range, from 32.2% in the Sichuan Basin to 39.1% in PRD, while in Northwest China it reached 33.7% (Figure 2b). Late-period PM_{2.5} concentrations remained high in BTH (37.0 µg/m³) and the Fenwei Plain (39.9 µg/m³), regions with basin-like terrain that limits dispersion, and low in PRD (20.6 µg/m³), where sea breezes provide effective ventilation.

PM₁₀ decreased from 41.6% in BTH to 26.5% in Northwest China (Figure 2b). This difference can be explained by the fact that PM₁₀ includes coarse particles associated with road dust, resuspension and natural sources. In Northwest China, the arid climate and extensive deserts, including the Taklamakan and Gobi deserts, determine a high contribution of natural dust; therefore, the anthropogenic reduction in PM₁₀ is less pronounced there (Mu et al., 2023; Filonchik et al., 2019, 2024). The highest late-period PM₁₀ concentrations remained in the Fenwei Plain (83.0 µg/m³) and Northwest China (77.3 µg/m³).

SO₂ showed the strongest decrease among all pollutants: −80.5% in the Fenwei Plain and −79.7% in BTH, with reductions exceeding 55% in most other regions (Figure 2b). This reflects targeted reductions in coal-related emissions, which were especially effective in regions with historically high shares of coal-based energy, including the Fenwei Plain, the coal belt of Shanxi–Shaanxi, and BTH (Zheng et al., 2018; Zhang et



275 [al., 2019; Tong et al., 2020](#)). The lowest late-period SO₂ concentrations were observed
276 in PRD (6.5 µg/m³) and YRD (6.9 µg/m³). CO decreased by 31–57% across different
277 regions, further confirming a broad reduction in combustion-related pollution.

278 NO₂ decreased in all regions, but its reduction was more moderate than that of SO₂.
279 The largest decrease was observed in BTH (−44.3%), whereas the smallest decrease
280 occurred in Northeast China (−25.9%; [Figure 2b](#)). This difference can be explained by
281 the fact that NO₂ is associated not only with industry and power generation, but also
282 with transport, where emission reductions occur more gradually. In Northeast China,
283 extremely cold winters and widespread coal-based heating maintain a persistent NO₂
284 contribution even under an overall decline in emissions.

285 In contrast to the other pollutants, O₃ increased in all regions, but with different
286 intensities. The strongest increase was observed in the Fenwei Plain (+14.3%), whereas
287 in most regions it ranged from 7% to 9%, and was minimal in Northeast China (+2.7%;
288 [Figure 2b](#)). This difference has a physicochemical explanation. In the Fenwei Plain, the
289 sharp reduction in aerosol loading (SO₂ −80.5%, PM_{2.5} −37.4%) may have contributed
290 to more favorable photochemical conditions for O₃ increases ([Lou et al., 2014; Li et al.,](#)
291 [2019b; Ivatt et al., 2022](#)). In Northeast China, by contrast, low solar radiation during
292 the cold season limits photochemistry, while high NO concentrations may additionally
293 titrate O₃ through the reaction NO+O₃→NO₂+O₂, explaining the minimal O₃ increase
294 ([Sillman, 1999; Li et al., 2021](#)).

295 [Figure 2c](#) shows that the O₃ increase was not uniformly related to reductions in
296 different pollutants. The highest O₃ penalty ratios were observed in the Fenwei Plain,
297 reaching 5.1 for PM₁₀, 3.8 for PM_{2.5} and 4.7 for NO₂, whereas values in Northeast China
298 and PRD were much lower (0.8–2.4). This indicates that in the Fenwei Plain, the
299 relationship between conventional pollutant reductions and O₃ increase was strongest
300 precisely where primary emissions declined most sharply and photochemical
301 conditions became most favorable for O₃ formation.

302 The city-level distribution of O₃ changes shows substantial intra-regional
303 heterogeneity ([Figure 2d](#)). The largest spread was observed in Northwest China, with a
304 standard deviation of 12.7% and a range from −21.5% to +64.8%, reflecting the
305 heterogeneity of cities in the arid zone, including the combined influence of natural dust
306 sources, local industry and differences in photochemical conditions. The broad spread
307 in Other China, with a standard deviation of 9.4% and a range from −8.4% to +47.8%,
308 partly reflects the heterogeneous composition of this residual group. In contrast, PRD



309 (4.4%) and Northeast China (8.7%) showed more compact distributions, indicating a
310 more homogeneous regional O₃ response.

311 Overall, the regional evolution of air pollution in China was characterized by two
312 main features. First, PM_{2.5}, PM₁₀, SO₂, NO₂ and CO decreased in all regions, although
313 the magnitude of these reductions varied depending on source structure and climatic
314 conditions. Second, O₃ increased almost everywhere, but the strongest increase
315 occurred in regions where the reduction in aerosol loading was most pronounced,
316 particularly the Fenwei Plain, and was minimal where photochemical activity is
317 climatically limited, such as Northeast China. This points to a fundamental difference
318 between controlling primary and particulate pollution and managing secondary
319 photochemical pollution.

320 **3.3. Seasonal O₃-centred multipollutant relationships**

321 Seasonal correlation analysis shows that relationships among pollutants changed
322 substantially throughout the year (Figure 3). Unlike PM_{2.5} and PM₁₀, which exhibited
323 consistently strong correlations across all seasons ($\rho = 0.85\text{--}0.91$), the relationships
324 between O₃ and other pollutants were strongly season-dependent. This indicates that O₃
325 is not a simple component of the overall pollution burden; rather, its behavior is linked
326 to other pollutants through seasonally varying photochemical and meteorological
327 conditions (Liao et al., 2024; Yang et al., 2024). However, it should be emphasized that
328 the correlation analysis does not establish causal relationships. The results presented
329 here describe statistical associations, which may reflect both common sources and
330 indirect chemical interactions.

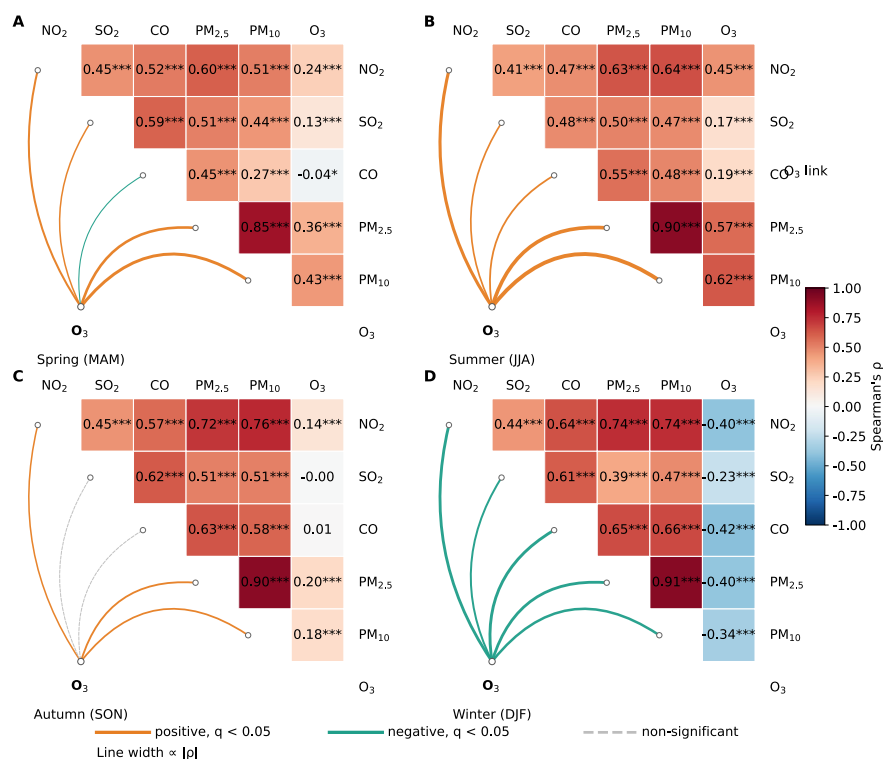


Figure 3. Seasonal relationships between O₃ and other air pollutants across Chinese cities.

As shown in Figure 3, O₃ was positively associated with most pollutants in spring. The strongest relationships were observed with PM₁₀ ($\rho = 0.43$, $q < 0.001$) and PM_{2.5} ($\rho = 0.36$, $q < 0.001$), whereas the relationship with NO₂ was more moderate ($\rho = 0.24$, $q < 0.001$). The relationship with SO₂ was weak but statistically significant ($\rho = 0.13$, $q < 0.001$), while the relationship with CO was statistically significant but practically very weak ($\rho = -0.04$, $q = 0.014$). At the same time, PM_{2.5} and PM₁₀ showed a very strong mutual correlation ($\rho = 0.85$, $q < 0.001$), indicating common sources and processes. This pattern is consistent with the view that, during spring, O₃ remains partly linked to the overall pollution burden, especially particulate pollution, although the direction of this relationship requires further investigation.

In summer, positive relationships between O₃ and other pollutants became stronger. The highest coefficients were observed for PM₁₀ ($\rho = 0.62$, $q < 0.001$), PM_{2.5} ($\rho = 0.57$, $q < 0.001$) and NO₂ ($\rho = 0.45$, $q < 0.001$). Relationships with CO and SO₂ were also positive but weaker, with $\rho = 0.19$ and $\rho = 0.17$, respectively. The correlation between



348 PM_{2.5} and PM₁₀ remained very high ($\rho = 0.90$). This pattern is consistent with the
349 expected enhancement of photochemical activity during summer, when high solar
350 radiation and temperature may promote both O₃ formation and secondary aerosol
351 production (Wang et al., 2016; Chen et al., 2024), creating conditions for the joint
352 variability of these pollutants.

353 In autumn, relationships between O₃ and other pollutants weakened markedly. O₃
354 retained weak positive relationships with PM_{2.5} ($\rho = 0.20$, $q < 0.001$), PM₁₀ ($\rho = 0.18$,
355 $q < 0.001$) and NO₂ ($\rho = 0.14$, $q < 0.001$), whereas its relationships with SO₂ and CO
356 became statistically insignificant. The correlation between PM_{2.5} and PM₁₀ remained
357 high ($\rho = 0.90$). This indicates that, during autumn, O₃ was less closely associated with
358 combustion-related pollutants, which may reflect changes in photochemical conditions
359 and reduced solar radiation.

360 The most pronounced contrast was observed in winter. During this season,
361 relationships between O₃ and all conventional pollutants became negative and
362 statistically significant. The strongest negative correlations were observed with CO (ρ
363 $= -0.42$, $q < 0.001$), NO₂ ($\rho = -0.40$, $q < 0.001$) and PM_{2.5} ($\rho = -0.40$, $q < 0.001$).
364 Relationships with PM₁₀ and SO₂ were also negative, with $\rho = -0.34$ and $\rho = -0.23$,
365 respectively. The correlation between PM_{2.5} and PM₁₀ remained high ($\rho = 0.91$). This
366 winter structure indicates opposite behavior of O₃ and primary/particulate pollutants
367 during the cold season. It is consistent with the known mechanism of NO titration, in
368 which high NO concentrations associated with NO₂ can destroy O₃, as well as with
369 weakened photochemical O₃ formation under low solar radiation (Sillman, 1999; Li et
370 al., 2021).

371 Overall, Figure 3 shows a clear seasonal reversal in pollutant relationships: from
372 positive relationships between O₃ and other pollutants in spring and summer, to weaker
373 relationships in autumn and negative relationships in winter. At the same time,
374 relationships between PM_{2.5} and PM₁₀ remained consistently strong across all seasons,
375 confirming their common nature. The seasonal dynamics of O₃ partly explain why its
376 increase, identified at the national and regional levels, does not follow the dynamics of
377 PM_{2.5}, PM₁₀, SO₂, NO₂ and CO. Although correlation analysis cannot establish causal
378 relationships, the observed pattern is consistent with the idea that seasonal
379 photochemical and meteorological conditions substantially modify the relationship
380 between O₃ and primary and particulate pollutants. This highlights that O₃ management



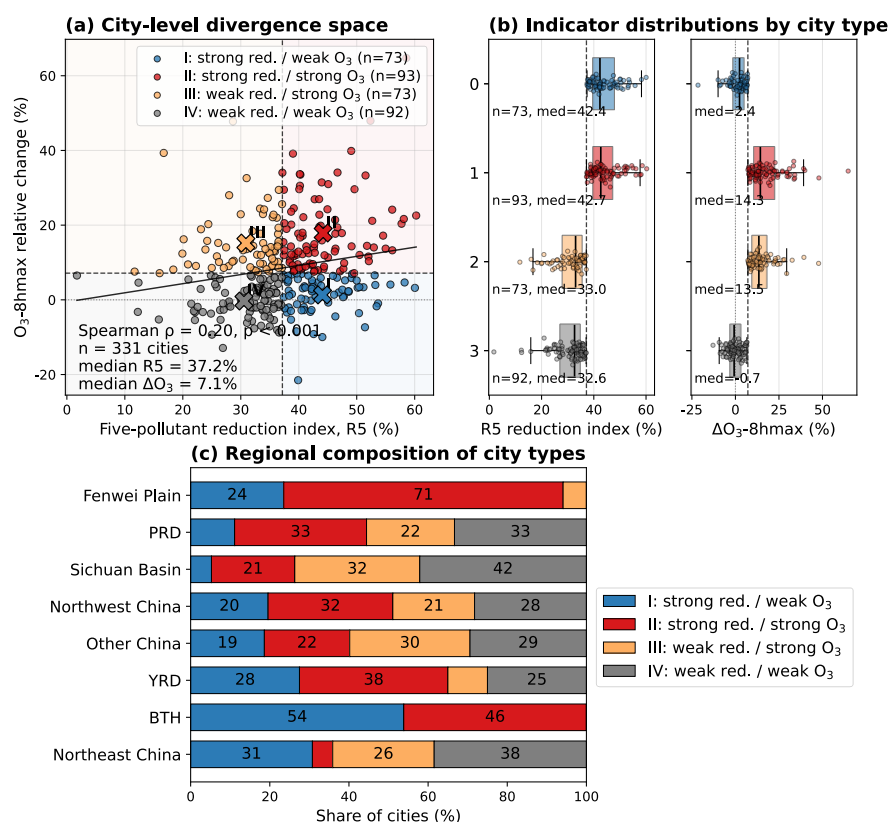
381 requires a separate approach and cannot be reduced to the control of particulate and
382 primary gaseous pollution.

383 **3.4. City-level divergence between conventional pollutant reduction and O₃**
384 **response**

385 The use of the city-level divergence framework shows that reductions in
386 conventional pollutants were not accompanied by a uniform O₃ response at the level of
387 individual cities (Figure 4). For 331 cities with sufficient observations in the early and
388 late periods, the relationship between the five-pollutant reduction index and the change
389 in O₃ was positive but weak (Spearman's $\rho = 0.197$, $p = 0.0003$; Figure 4a). The spread
390 of values was substantial: cities with comparable reductions in PM_{2.5}, PM₁₀, SO₂, NO₂
391 and CO could exhibit either weak O₃ changes or pronounced O₃ increases. This
392 indicates that the magnitude of conventional pollutant reduction alone does not explain
393 the city-level O₃ response.

394 Based on the median values of the five-pollutant reduction index (37.2%) and O₃
395 change (7.1%), cities were divided into four types (Figure 4b). Type I cities (22.1% of
396 cities) showed strong reductions in conventional pollutants, with a median reduction of
397 42.4%, and a weak O₃ response, with a median O₃ change of -2.4%. Type II cities
398 (28.1%) also showed strong reductions, with a median reduction of 42.7%, but
399 experienced strong O₃ increases, with a median change of 14.3%. Type III cities (22.1%)
400 showed weaker reductions in conventional pollutants, with a median reduction of
401 33.0%, but strong O₃ increases, with a median change of 13.5%. Type IV cities (27.8%)
402 showed weaker reductions, with a median reduction of 32.6%, and a weak O₃ response,
403 with a median change of -0.7%. The key difference among the types was not the
404 magnitude of conventional pollutant reduction, since Type I and Type II were nearly
405 identical in their reduction index, but rather the O₃ response under comparable
406 improvements in PM and primary gaseous pollutants.

407



408

409 **Figure 4.** City-level divergence between conventional pollutant reduction and O₃
 410 response.

411 The physicochemical interpretation of these types should be regarded as hypothetical,
 412 because the available data do not allow direct diagnosis of the chemical regime of O₃
 413 formation (Jin and Holloway, 2015; Jin et al., 2017). Type I may represent cities where
 414 strong reductions in conventional pollutants were not accompanied by enhanced O₃
 415 increases, which may be related to more effective ventilation, lower photochemical
 416 sensitivity or more balanced changes in precursor-related pollution (Ivatt et al., 2022).
 417 Type II characterizes cities where strong reductions in PM, SO₂ and other conventional
 418 pollutants were accompanied by pronounced O₃ increases; this pattern may be related
 419 to reduced aerosol-related attenuation of solar radiation and enhanced photochemical
 420 conditions (Verstraeten et al., 2015; Wang et al., 2022), although the role of NO_x–VOC
 421 sensitivity cannot be established without additional data. Type III shows that strong O₃
 422 increases can occur even under more moderate reductions in conventional pollutants,
 423 which may indicate the importance of local meteorological conditions, insolation,



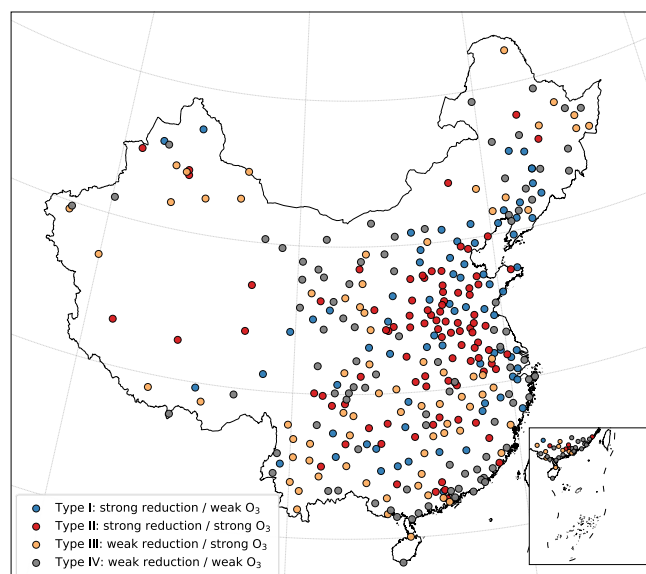
424 ventilation and regional transport (Qu et al., 2021). Type IV, by contrast, includes cities
425 with weaker reductions in conventional pollutants and a weak O₃ response, which may
426 reflect more limited photochemical activity, different baseline pollution levels or less
427 pronounced changes in precursor conditions (Yang et al., 2025). Therefore, these types
428 should not be interpreted as a direct diagnosis of O₃ chemical regimes, but rather as an
429 empirical city-level typology indicating different trajectories of O₃ response under
430 reductions in conventional pollutants. Confirmation of the underlying mechanisms
431 requires additional data on VOCs, emissions, meteorology and satellite-based
432 indicators of chemical regime, such as HCHO/NO₂.

433 The regional composition of the types shows pronounced spatial heterogeneity
434 (Figure 4c). The Fenwei Plain was most clearly skewed toward Type II. Here, strong
435 reductions in conventional pollutants were often accompanied by strong O₃ increases.
436 This is consistent with the regional analysis in Section 3.2, where the sharp reduction
437 in aerosol loading in the coal belt may have contributed to enhanced photochemical
438 conditions under basin-like topography (Lin et al., 2023). BTH also showed a high
439 share of Type II cities, although Type I remained slightly more common. Northeast
440 China, by contrast, was more strongly represented by Type IV and Type I, indicating
441 weak O₃ increases under different levels of conventional pollutant reduction, likely
442 reflecting limited photochemical activity in a cold climate and NO titration (Li et al.,
443 2021). Northwest China and Other China showed a more mixed structure, including
444 notable shares of both ozone-increase types and weak-response types, reflecting the
445 heterogeneity of cities within these large regions.

446 The spatial distribution of city-level divergence types further shows that the
447 identified types were not randomly distributed across China (Figure 5). Type II cities,
448 where strong reductions in conventional pollutants were accompanied by strong O₃
449 increases, formed the most pronounced cluster in the North China and central-eastern
450 belt, including BTH, the Fenwei Plain and adjacent inland areas. Individual Type II
451 cities also occurred in Northwest China and some inland southern regions. Type I cities,
452 characterized by strong reductions in conventional pollutants and a weak O₃ response,
453 were more common in eastern and coastal China and also accounted for a substantial
454 share of BTH cities. Type III cities, where strong O₃ increases occurred under weaker
455 reductions in conventional pollutants, were more spatially mosaic and occurred in
456 Northwest China, southern regions and inland areas. Type IV cities, characterized by
457 weaker reductions in conventional pollutants and a weak O₃ response, were more



458 frequently observed in Northeast China, western regions and other peripheral cities.
459 Importantly, different types often coexisted within the same broad regions, indicating
460 that the city-level O₃ response was determined not only by regional background
461 conditions but also by local factors.



462
463 **Figure 5.** Spatial distribution of city-level divergence types across Chinese cities.

464 This analysis complements the seasonal results in Section 3.3. Seasonal correlations
465 show that relationships between O₃ and other pollutants vary substantially throughout
466 the year, whereas the city-level divergence analysis identifies the cities and conditions
467 under which O₃ increased despite the overall decline in conventional pollutants.
468 Together, these results indicate that air-quality improvement in Chinese cities was not
469 a single coherent process: in many cities, reductions in PM_{2.5}, PM₁₀, SO₂, NO₂ and CO
470 diverged from the O₃ response.

471 The results show that reductions in conventional pollutants were not necessarily
472 accompanied by weak changes in O₃. Some cities exhibited relatively balanced
473 improvement, whereas others experienced strong O₃ increases under comparable
474 reductions in PM and primary gaseous pollutants. This highlights the need to move
475 beyond assessing air quality only through reductions in particulate and primary gaseous
476 pollution toward city-specific and regionally differentiated multipollutant control
477 strategies that account for the risk of O₃ enhancement.

478 **4. Conclusions**



479 This study analyzed the multipollutant evolution of air quality in Chinese cities
480 during 2015–2025 based on long-term observations of PM_{2.5}, PM₁₀, SO₂, NO₂, CO and
481 O₃. The results show that substantial air-quality improvement occurred in Chinese cities
482 over the study period. Annual mean concentrations of PM_{2.5}, PM₁₀, SO₂, NO₂ and CO
483 decreased by 40.8%, 35.3%, 70.3%, 36.2% and 45.0%, respectively. These changes
484 were spatially coherent and statistically significant in most cities, indicating a persistent
485 national decline in particulate and primary gaseous pollution.

486 However, this improvement was not accompanied by a simultaneous decrease in O₃.
487 In contrast to the other pollutants, O₃ increased by 10.3% at the national level, and
488 positive O₃ trends were observed in 76.1% of cities. This shows that air-quality
489 improvement in China was not a uniform decline of all pollutants. Instead, reductions
490 in PM and primary gaseous pollutants were accompanied by an intensification of
491 secondary photochemical pollution.

492 Regional analysis showed that ozone divergence exhibited pronounced spatial
493 heterogeneity. The Fenwei Plain experienced the strongest O₃ increase despite
494 substantial decreases in SO₂, CO and PM, whereas Northeast China showed the
495 smallest O₃ increase. Seasonal analysis further showed that relationships between O₃
496 and other pollutants varied substantially throughout the year: in spring and summer, O₃
497 was positively associated with PM and NO₂-related pollution, whereas these
498 relationships weakened in autumn and became negative in winter. This highlights the
499 seasonal dependence of O₃ response and its distinction from conventional pollutants.

500 At the city level, the proposed city-level divergence typology showed that
501 comparable reductions in conventional pollutants can be accompanied by
502 fundamentally different O₃ responses. Type I and Type II cities had nearly identical
503 median values of the five-pollutant reduction index but differed sharply in O₃ change:
504 weak decrease or almost no increase in Type I, and strong increase in Type II. The
505 spatial distribution of the types showed that ozone-divergent cities were more
506 frequently concentrated in northern and inland regions, whereas balanced-improvement
507 and weak-response types were more common in eastern, northeastern and peripheral
508 areas. This confirms that O₃ divergence is not only a national or regional issue, but also
509 a city-specific problem.

510 Overall, the results show that reductions in PM_{2.5}, PM₁₀, SO₂, NO₂ and CO do not
511 guarantee mitigation of O₃ pollution. The next stage of air-quality management in China
512 should move beyond single-pollutant or PM-focused control and shift toward city-



specific and regionally differentiated multipollutant management. Particular attention should be paid to the coordinated management of PM, NO_x and VOC precursors, seasonal photochemical conditions and local meteorological constraints. Because this study is based on observational data, future work should incorporate VOC measurements, emission inventories, radiation data and chemical-regime indicators, such as HCHO/NO₂, to more precisely identify the mechanisms underlying city-level O₃ divergence.

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Conflicts of interest

The author declares no competing interests.

Author contributions.

V.H: Formal analysis, Investigation, Writing-Original Draft. M.F: Conceptualization, Methodology, Funding Acquisition, Writing-Review & Editing, Project administration. T.T: Methodology, Writing-Review & Editing. L.Z: Conceptualization, Writing-Review & Editing, Supervisor. All authors discussed the results, contributed to the final manuscript, and approved the submitted version.

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