Proceedings of the 6th International Conference on Biological Engineering and Medical Science
DOI: 10.54254/2753-8818/2026.36808

Temporal Evolution and Correlation Analysis of PM2.5 and O_3 Concentrations in Wuhan (2016-2020)

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Abstract. As a major industrial and transportation hub in central China, Wuhan has long been challenged by the compound air pollution of wintertime PM2.5 episodes and summertime O_3 pollution. This study analyzed daily air quality monitoring data from 2016 to 2020 using time-series and seasonal correlation analyses to systematically investigate the evolutionary patterns and correlation characteristics of the two pollutants. The results showed that the annual mean PM2.5 concentration decreased by 18.1%, indicating significant mitigation effectiveness, while O_3 exhibited no declining trend, remaining a persistent concern. The two pollutants displayed a clear seasonal complementarity pattern: PM2.5 peaked in winter and bottomed in summer, whereas O_3 showed the opposite pattern. At the daily scale, the overall correlation was weakly negative ($r = -0.147$). However, after seasonal stratification, summer exhibited a significant positive correlation ($r = 0.384$), winter showed a weak positive correlation, and spring/autumn correlations were not significant, revealing a classic Simpson's paradox. The findings suggest that a PM2.5-focused control strategy alone is insufficient for synergistic O_3 reduction. It is recommended to strengthen VOCs control in summer and intensify primary particle emission reductions in winter, thereby establishing a seasonally differentiated management framework to provide scientific support for precise governance of complex air pollution in central China's urban agglomerations.

Keywords: Wuhan, PM2.5, O_3, air pollution, seasonal variation, correlation

1. Introduction

Air pollution is a critical environmental issue in rapidly urbanizing Chinese cities [1]. Wuhan, a major industrial and transportation hub in central China, frequently experiences severe winter haze and increasing summer ozone episodes. Long-term exposure to PM2.5 and O_3 is associated with increased respiratory and cardiovascular hospital admissions [2], highlighting the need for effective control.

PM2.5 is primarily emitted from combustion sources and formed through secondary formation, while O_3 is a secondary photochemical pollutant formed from NOx and VOCs under sunlight. These pollutants interact through complex mechanisms including aerosol radiation feedback [3]. Previous studies in Wuhan have documented seasonal reversals between PM2.5 and O_3 [3, 4], but systematic seasonal correlation analyses using recent complete datasets remains limited [5]. This

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study uses a consistent 5-year dataset (2016-2020) to: (1) characterize interannual trends of PM2.5 and O_3; (2) examine their seasonal patterns; and (3) quantify their correlation at annual and seasonal scales, with particular attention to distinguishing between inter-seasonal and intra-seasonal relationships. By revealing the Simpson's paradox between PM2.5 and O_3 at the daily scale in Wuhan, this study provides critical data support and a theoretical basis for developing season-specific and precursor-differentiated collaborative control strategies.

2. Data and methods

2.1. Data source

Daily PM2.5 and O_3 data were obtained from Wuhan Municipal Ecology and Environment Bureau monitoring records (January 1, 2016-December 31, 2020). O_3 values represent daily maximum 8-hour averages, consistent with Chinese national standard GB 3095-2012 [3, 6]. After removing missing values, a total of 1,630 valid daily observations were retained for correlation analysis.

2.2. Data processing

Preprocessing used Python (pandas). Monthly means were calculated by averaging valid daily values per calendar month. Seasons were defined as: spring (Mar-May), summer (Jun-Aug), autumn (Sep-Nov), winter (Dec-Feb) [3].

2.3. Statistical methods

Descriptive statistics, time-series plots, Pearson correlation, and linear regression were applied. Significance was set at $p < 0.05$. Analyses used Python with numpy, scipy.stats, matplotlib, and seaborn.

3. Results

3.1. Interannual trends

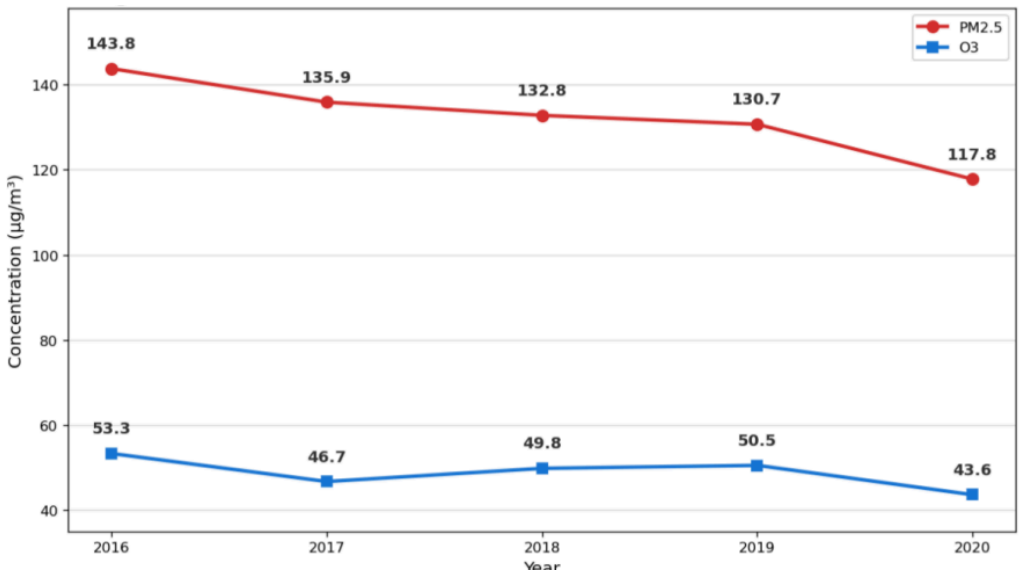

Figure 1. Annual mean concentrations of PM2.5 and O_3 in Wuhan (2016-2020)

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Figure 1 presents the annual mean concentrations of PM2.5 and O_3 in Wuhan from 2016 to 2020. PM2.5 declined consistently from 143.8 μg/m³ in 2016 to 117.8 μg/m³ in 2020, representing a total reduction of 18.1%. The largest drop occurred between 2019 and 2020 (from 130.7 to 117.8 μg/m³), likely attributable to the strict lockdown measures in early 2020 as well as cumulative effects of clean air policies implemented in previous years. This aligns with Chen et al. [3] and Ma et al. [7].

O_3 fluctuated over the study period: with values of 53.3 μg/m³ (2016), 46.7 μg/m³ (2017), 49.8 μg/m³ (2018), 50.5 μg/m³ (2019), and 43.6 μg/m³ (2020), showing no clear monotonic trend. The notably lower value in 2020 may reflect reduced precursor emissions during lockdowns. Overall, the absence of a significant declining trend for O_3, despite substantial PM2.5 reduction, suggests that O_3 formation is governed by different photochemical and precursor-driven processes [7].

3.2. Seasonal characteristics

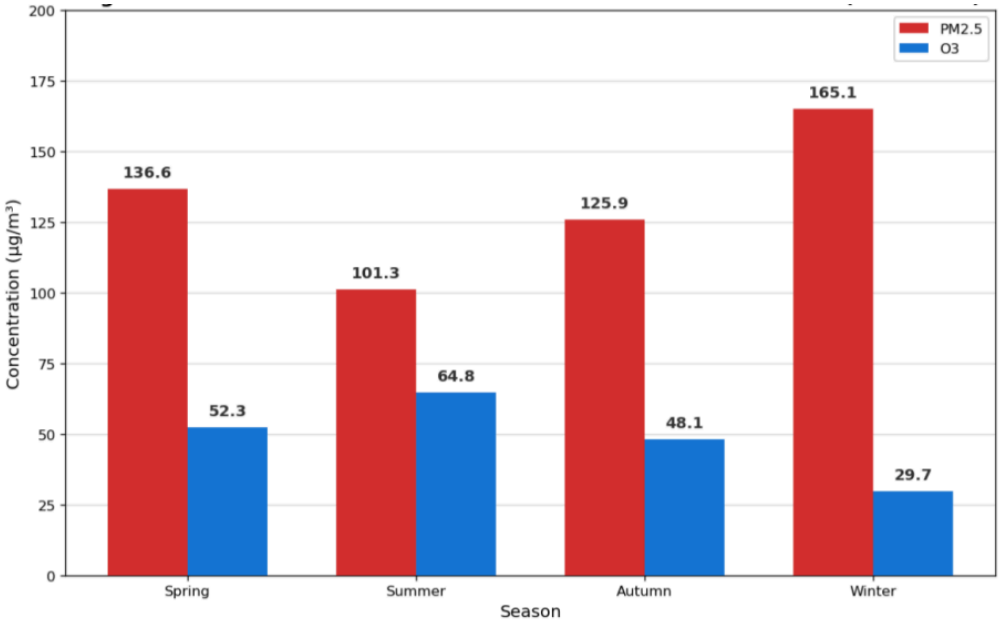

Figure 2. Seasonal mean concentrations of PM2.5 and O_3 in Wuhan (2016-2020)

The seasonal patterns of PM2.5 and O_3 in Wuhan are shown in Figure 2. PM2.5 exhibited a distinct seasonal cycle: highest in winter (mean: 165.1 μg/m³), lowest in summer (mean: 101.3 μg/m³), with spring and autumn at intermediate levels (136.6 and 125.9 μg/m³, respectively). This pattern reflects increased winter combustion for heating, reduced atmospheric mixing height, and frequent temperature inversions that trap pollutants near the surface, which is consistent with Chen et al. [3] and Wang et al. [4].

O_3 followed the opposite seasonal pattern: peak in summer (mean: 64.8 μg/m³), minimum in winter (mean: 29.7 μg/m³), with spring and autumn at moderate levels (52.3 and 48.1 μg/m³, respectively). This seasonal reversal is driven by photochemical formation requiring strong solar radiation and high temperatures—conditions most favorable during summer months, as confirmed by Chen et al. [3] and Weng et al. [8].

In summary, PM2.5 and O_3 exhibited strong seasonal complementarity: winter months show high PM2.5 with low O_3, while summer months show the opposite pattern (low PM2.5 with high O_3).

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3.3. Correlation analysis

The overall Pearson correlation between daily PM2.5 and O_3 concentrations (n = 1,630) was r = -0.147 ($p < 0.001$, $R^2 = 0.022$), indicating a weak but statistically significant negative correlation. This suggests that, on average, days with higher PM2.5 tend to have lower O_3 concentrations.

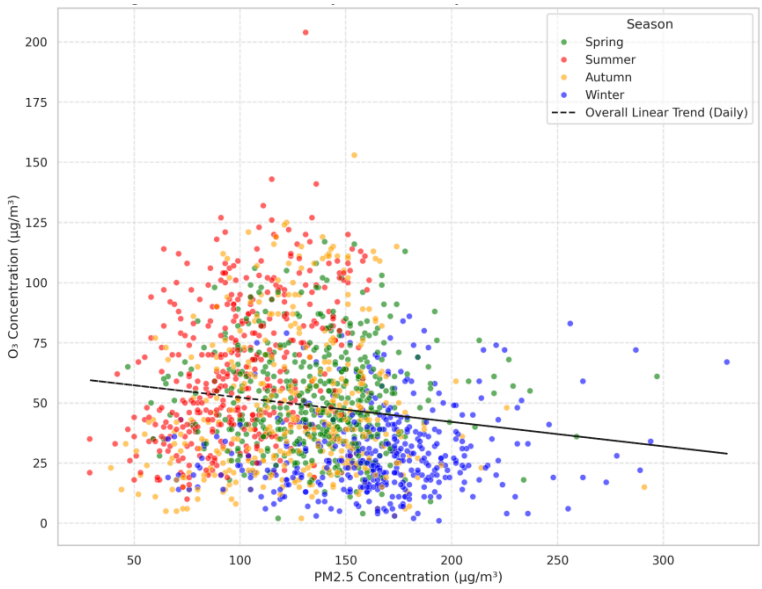

Figure 3. Scatter plot of daily PM2.5 vs. O_3 by season in Wuhan (2016-2020)

However, this overall negative correlation requires careful interpretation. As shown in Figure 3 (scatter plot color-coded by season), winter days are predominantly located in the upper-left region (high PM2.5, low O_3), while summer days occupy the lower-right region (low PM2.5, high O_3). This distinct seasonal separation is the primary driver of the apparent negative correlation. In other words, the negative relationship largely reflects inter-seasonal differences rather than a direct causal trade-off within the same season.

To disentangle inter-seasonal from intra-seasonal relationships, this study further calculated Pearson correlations within each individual season by using daily observation data.

Table 1. Seasonal Pearson correlation coefficients between daily PM2.5 and O_3 concentrations in Wuhan (2016-2020)

Season	Sample Size (days)	Correlation (r)	R^2	p-value	Regression Equation
Spring	457	–0.036	0.001	0.4443 (n.s.)	$O_3 = 55.60 – 0.024 \times PM2.5$
Summer	401	+0.384	0.148	< 0.001	$O_3 = 22.66 + 0.417 \times PM2.5$
Autumn	378	+0.069	0.005	0.1832 (n.s.)	$O_3 = 40.39 + 0.060 \times PM2.5$
Winter	394	+0.151	0.023	0.0027	$O_3 = 18.74 + 0.067 \times PM2.5$

Table 1 presents the Pearson correlation coefficients, coefficients of determination (R^2), p-values, and linear regression equations for PM2.5 versus O_3 within each season, based on daily observation data.

Critically, in summer—when photochemical activity is strongest—PM2.5 and O_3 exhibited a significant positive correlation ($r = 0.384$, $p < 0.001$, $R^2 = 0.148$). The linear regression equation was

DOI: 10.54254/2753-8818/2026.36808

quantified as $O_3 = 22.66 + 0.417 \times PM2.5$, confirming that a 1 μg/m³ increase in PM2.5 corresponds to a 0.417 μg/m³ increase in O_3 during summer days. This indicates that on hot, sunny summer days, the two pollutants tend to increase or decrease synchronously, rather than suppressing each other.

Winter also showed a weak but statistically significant positive correlation ($r = 0.151$, $p = 0.0027$, $R^2 = 0.023$), with the regression equation $O_3 = 18.74 + 0.067 \times PM2.5$. Spring and autumn correlations were not statistically significant ($p > 0.05$).

These findings reveal a classic case of Simpson's paradox: the overall negative correlation at the aggregated daily scale is reversed (to positive) when the data are stratified by season. The apparent negative relationship is therefore a statistical artifact of seasonal separation, and not evidence of a direct negative causal relationship between PM2.5 and O_3 at the daily scale.

4. Discussion

4.1. Interpretation of findings

The seasonal complementarity observed in seasonal means (winter: high PM2.5/low O_3; summer: low PM2.5/high O_3) can be explained by well-established mechanisms. First, strong summer solar radiation promotes photochemical O_3 formation, while active vertical mixing and frequent precipitation disperse PM2.5. Second, PM2.5 particles scatter solar radiation, reducing photolysis rates and potentially suppressing O_3 formation—the "aerosol radiation feedback effect" [9]. Third, heterogeneous reactions on particle surfaces can consume O_3 and its precursors. These mechanisms collectively drive the seasonal seesaw pattern.

More importantly, the significant positive correlation within summer ($r = 0.384$, $R^2 = 0.148$) suggests that on day-to-day timescales, PM2.5 and O_3 respond to shared meteorological and chemical drivers rather than competing with each other. Possible explanations include: (1) both pollutants are enhanced under stagnant high-pressure systems with strong solar radiation and high temperatures, which simultaneously accelerate photochemical O_3 production and secondary PM2.5 formation (e.g., sulfate and nitrate); (2) common precursor sources, such as vehicular NOx and VOCs, contribute to both pollutants; and (3) the aerosol inhibition effect is relatively weaker in summer when solar radiation is already intense, which allows both pollutants to rise together.

The weak positive correlation in winter ($r = 0.151$, $R^2 = 0.023$) may reflect the dominance of stable weather conditions: during winter high-pressure systems with low boundary layers and weak winds, primary PM2.5 emissions and anthropogenic VOCs/NOx accumulate concurrently, producing a modest synchronous increase despite low temperatures limiting O_3 photochemistry.

4.2. Comparison with previous studies

Our findings align with Chen et al. [3], who reported opposite monthly trends and significant negative monthly correlations for PM2.5 and O_3 in Wuhan. They are also consistent with Ma et al. [7], who found a weak negative overall relationship and identified Wuhan as a VOCs-controlled area for O_3 generation [10]. Crucially, the seasonal divergence we observed at the daily scale—specifically the positive summer correlation—is consistent with Weng et al. [8], who noted that PM2.5 and O_3 can exhibit positive correlations on shorter time scales despite negative broad-scale relationships. This reinforces the importance of temporal resolution in interpreting pollutant interactions.

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4.3. Policy implications

The divergent trends of PM2.5 and O_3, combined with their seasonal complementarity and positive within-summer correlation, have clear policy implications. First, given that PM2.5 has declined significantly while O_3 has not, PM2.5-focused strategies alone are insufficient for O_3 control. Second, since Wuhan is identified as a VOCs-controlled region [10], targeted VOC emission reductions—particularly during summer and transition seasons—are recommended for effective O_3 mitigation. Third, the positive summer correlation ($r = 0.384$) does not imply causality, but rather indicates that PM2.5 and O_3 respond to shared meteorological drivers and common precursor sources. Therefore, summer control strategies should prioritize reductions of their common precursors—particularly VOCs, as Wuhan is VOCs-limited [10]—rather than focusing solely on primary PM2.5. Fourth, winter strategies should continue to prioritize primary PM2.5 emission reductions and to address stagnant meteorological conditions. A one-size-fits-all approach is suboptimal; flexible, season-specific strategies that account for the different formation mechanisms of PM2.5 and O_3 are essential for sustained air quality improvement.

It should be emphasized that all correlations reported herein are statistical associations, not causal effects. The positive summer correlation may be confounded by meteorological variables (temperature, solar radiation) and co-emitted precursors. The modest R^2 values (≤ 0.148) further indicate that PM2.5 explains only a small fraction of O_3 variability, and future mechanistic modeling is needed to validate causal pathways.

5. Conclusion

This study analyzed 5-year daily air quality data in Wuhan (2016-2020). The main conclusions are:

First, PM2.5 decreased from 143.8 μg/m³ in 2016 to 117.8 μg/m³ in 2020 (18.1% total reduction), indicating that control policies have been effective for particulate matter.

Second, O_3 showed no clear directional trend over the study period (43.6–53.3 μg/m³), remaining a persistent environmental concern not alleviated by PM2.5-focused measures.

Third, the two pollutants exhibited strong seasonal complementarity: PM2.5 peaked in winter (165.1 μg/m³) and minimized in summer (101.3 μg/m³), while O_3 peaked in summer (64.8 μg/m³) and minimized in winter (29.7 μg/m³).

Fourth, the apparent overall negative correlation at the daily scale ($r = -0.147$, $p < 0.001$, $R^2 = 0.022$) is largely a statistical artifact of seasonal separation (Simpson's paradox), rather than evidence of a direct causal trade-off. After controlling for seasonal effects using daily data, summer revealed a significant positive correlation ($r = 0.384$, $p < 0.001$, $R^2 = 0.148$), with the linear relationship $O_3 = 22.66 + 0.417 \times PM2.5$. This statistical association is consistent with shared sensitivity to meteorological conditions, but causal mechanisms require future verification.

Several limitations of this study should be acknowledged. First, the analysis relied on publicly available monitoring data without considering spatial heterogeneity across different monitoring stations in Wuhan. Second, the study focused on statistical correlations without incorporating detailed meteorological or emission source data, which would help elucidate the causal mechanisms. Future research should integrate meteorological variables (temperature, solar radiation, wind speed) and precursor emissions (NOx, VOCs) in order to develop more comprehensive mechanistic models of PM2.5-O_3 interactions.

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