Spatiotemporal characteristics of air pollutants in Seoul: How seasonal variation shapes weekly pollution cycles

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ABSTRACT

Air pollution in temperate cities changes regularly with seasons and human activities. Previous studies have explored seasonal patterns and weekday–weekend differences in Seoul's air quality. However, most studies discuss seasonal changes and weekly pollution trends separately, without focusing on their interactive effects. This study aims to analyze how weekday–weekend pollution differences vary in cold and warm seasons. It also explores the seasonal changes in correlations among major air pollutants in Seoul. This research uses three years (2017–2019) of hourly data from 25 monitoring stations in Seoul. It applies tidy data processing and visual analysis to compare the diurnal variation, weekly patterns and relationships of $PM_{2.5}$, PM_{10}, NO_2 and O_3 in different seasons. The results show that seasons strongly influence weekly pollution characteristics. $PM_{2.5}$, PM_{10} and NO_2 present higher concentrations in the cold season, whereas O_3 is higher in the warm season. Traffic-related pollutants have clearer weekday-weekend differences in cold seasons. Ozone levels in warm seasons may be related to active photochemical reactions. The correlations between particulate matter and ozone also change obviously across different seasons. This study proves that single-dimensional analysis cannot fully reflect urban air pollution features. By combining seasonal and weekly comparison, this research provides useful references for seasonal and targeted air quality management in temperate metropolitan cities.

Keywords: Seoul; Air pollutants; Seasonal variation; Weekday-weekend difference; Temporal heterogeneity

1. INTRODUCTION

Urban air pollutants including $PM_{2.5}$, PM_{10}, NO_2 and O_3 threaten public health, urban living environments and sustainable urban development [1]. They are mainly emitted by vehicles, municipal energy consumption, industrial activities and cross-border pollutant transport [1, 2]. Investigating the patterns of those times will help improve the target pollution. In Seoul, where many people live and the seasons change obviously, the freshness of the air depends on the seasonal weather and people's activity patterns [3]. The cold continental monsoon will bring tiny things from the outside and increase the concentration of particles [2]; In the warm season, the humid sea breeze will help the pollutant disperse, but the strong sunshine will lead to many ozone [4]. Because people move and work in the same cycle every week, there will be obvious differences in the amount of pollutant between working days and rest days [5].

Up to now, many paper have analyzed the characteristics of dirt in Seoul in each season and every day. Scholars have always acknowledged that automobile exhaust will cause the pollution difference between working days and weekends. Studies in more areas show that in cold and warm weather, the weekly difference will change greatly [5].

However, most existing studies treat seasonal weather and weekly exhaust cycle separately [4]. There are few quantitative studies on the interaction between them. There is little analysis on how seasons change the pollution on weekdays and weekends. In addition, in Seoul's field research, the relationship between particles and the seasonal variation of ozone is rarely measured by charts or figures, which hinders the overall understanding of the mechanism of urban composite pollution [6].

In order to solve the above shortcomings, the study uses clean data processing and multi-group charts, and based on the hourly data collected from 25 observation stations in Seoul city and suburbs for three years (2017-2019) to analyze the temporal features of $PM_{2.5}$, PM_{10}, NO_2 and O_3, this work finds out the daily and weekly differences of pollution on weekdays and weekends, clarifies how the seasons change the size of the differences, and also captures the changes of the relationship between particulate pollutants and ozone with the seasons. This paper summarizes the hourly pollution patterns of temperate cities, and gives targeted air management suggestions according to seasons and activities for Seoul and similar metropolitan areas.

2. METHODOLOGY

2.1 Dataset

This dataset is the measurement data of air quality collected by monitoring stations in 25 places in Seoul every hour from 2017 to 2019. The pollutants detected are $PM_{2.5}$, PM_{10}, NO_2, O_3, etc. Each record has a time stamp and a static identification code. Summarize the observation data of all station and calculate the average concentration of pollutants per hour in the whole city. Eliminate spatial differences and only analyze the characteristics of time changes.

2.2 Data Preprocessing

According to the rules of tidy data principles, we made Data cleaning and restructuring. Incorrect negative values of sensors and data without values have been deleted. In order to eliminate the larger erroneous observation values, a 1%–99% quantile truncation was used to eliminate each pollutant. For comparative analysis later, we made two categorical grouping variables. The first variable separates all records according to the period of one-week activities, and separates the samples collected on weekdays from those collected on weekends. The second variable is to divide the dataset by calendar month to distinguish the seasonal background: the observed values recorded from November to March are put into the cold season group, and the samples collected from April to October are put into the warm season group. Combining these two methods, all dataset can be divided into four non-overlapping groups for statistical comparison. It is cold season weekday samples, cold season weekend samples, warm season weekday samples and warm season weekend samples.

2.3 Experiment Setting

Multi-dimensional visual analysis, statistical significance testing and correlation analysis were adopted in this study. Diurnal variation line charts were plotted to compare 24-hour pollutant trends across different seasonal and weekly groups, while boxplots were applied to contrast pollutant concentration distributions between weekdays and weekends under different seasonal backgrounds. To further explore seasonal regulatory mechanisms, Pearson correlation matrices and corresponding heatmaps were constructed for the full dataset, cold-season subset and warm-season subset respectively, so as to identify seasonal discrepancies in the interactive relationships among pollutants. Two-level Wilcoxon rank-sum tests at the significance level of $\alpha = 0.05$ were implemented, including overall tests for weekly and seasonal disparities as well as season-stratified examinations on weekly cycles, which quantitatively verified the modulation effect of seasons on the weekly periodicity of pollutant concentrations. Besides, STL time series decomposition was conducted on daily $PM_{2.5}$ concentrations to clarify its long-term temporal variation patterns.

3. RESULTS

3.1 Data Preprocessing and Descriptive Statistics

After removing outliers and missing values from the three-year hourly air pollutant dataset, four core pollutants ($PM_{2.5}$, PM_{10}, O_3 and NO_2) were retained for subsequent analysis. The cleaned dataset was divided by two independent classification standards: weekday vs. weekend, and cold seasons vs. warm seasons. Here, cold seasons refer to November to March of the following year, while warm seasons cover April to October.

Descriptive statistics including mean concentration and standard deviation were calculated separately under the two grouping schemes, forming two independent summary tables.

Table 1. Descriptive statistics of four air pollutants grouped by weekday and weekend

Group	$PM_{2.5}$ mean	$PM_{2.5}$ SD	PM_{10} mean	PM_{10} SD	O_3 mean	O_3 SD	NO_2 mean	NO_2 SD
Weekday	22.28	15.98	39.07	24.77	0.02	0.02	0.03	0.02
Weekend	23.50	17.40	39.38	25.08	0.02	0.02	0.03	0.02

Table 1 lists descriptive statistics of $PM_{2.5}$, PM_{10}, O_3 and NO_2 grouped by weekday and weekend. Slight weekend increases of $PM_{2.5}$ (23.50 vs. 22.28 $\mu g/m^3$) and PM10 (39.38 vs. 39.07 $\mu g/m^3$) represent a detectable weekly signal despite small effect size. Mean O_3 and NO_2 concentrations barely differed between weekdays and weekends. Larger standard deviations for weekend particulate pollutants indicate higher temporal variability. Since the dataset pools cold and warm season observations, this overall comparison provides limited insight into weekly pollution patterns: seasonal meteorological backgrounds may substantially amplify or suppress weekday-weekend disparities. Hence, stratification by season is necessary to explore seasonal modulation on weekly pollution cycles.

Table 2. Descriptive statistics of four air pollutants grouped by cold and warm seasons

Group	$PM_{2.5}$ mean	$PM_{2.5}$ SD	PM_{10} mean	PM_{10} SD	O_3 mean	O_3 SD	NO_2 mean	NO_2 SD
Cold seasons	28.78	18.69	48.07	25.58	0.02	0.01	0.03	0.02
Warm seasons	18.39	13.03	33.02	22.37	0.03	0.02	0.02	0.01

Table 2 shows clear seasonal baselines for all pollutants. $PM_{2.5}$, PM_{10} and NO_2 presented higher concentrations in cold seasons, with average values of 28.78 μg/m³, 48.07 μg/m³ and 0.03 ppm respectively, compared with 18.39 μ、μg/m³, 33.02 μg/m³ and 0.02 ppm in warm seasons. By contrast, O_3 was higher in warm seasons (0.03 vs. 0.02 ppm). Larger standard deviations in cold seasons suggest more unstable winter pollution conditions. These consistent seasonal baseline changes underpin further interpretation of how seasons alter the magnitude of inherent weekday-weekend concentration gaps.

3.2 Diurnal Concentration Variation Based on Single Classification Dimension

We first compared the hourly diurnal fluctuation patterns of pollutants under the two grouping criteria respectively.

Figure 1 illustrates the intraday variation curves of four pollutants on weekdays and weekends. NO_2 presents distinct morning and evening traffic-induced concentration peaks on weekdays; $PM_{2.5}$ maintains a higher background concentration throughout weekends, while the daily peak of O_3 appears later on weekends; Figure 2 further visualizes the overall distribution differences of pollutant concentrations between weekdays and weekends.

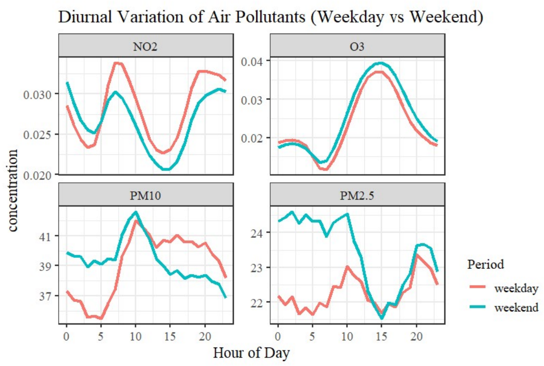

Figure 1. Diurnal Variation of Air Pollutants (Weekday vs Weekend)

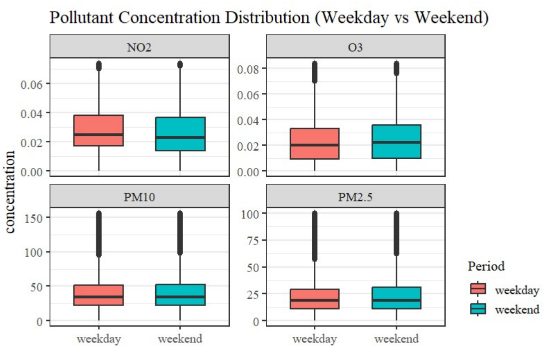

Figure 2. Pollutant Concentration Distribution (Weekday vs Weekend)

Figure 3 compares hourly pollutant cycles in cold and warm seasons. $PM_{2.5}$, PM_{10} and NO_2 are higher in the cold season, whereas O_3 is higher in the warm season. Particulate matter shows more prominent morning peaks in cold seasons; Figure 4 quantifies the overall concentration gap across seasons. Wilcoxon rank-sum tests demonstrate that seasonal differences of all four pollutants are statistically significant ($p < 0.001$).

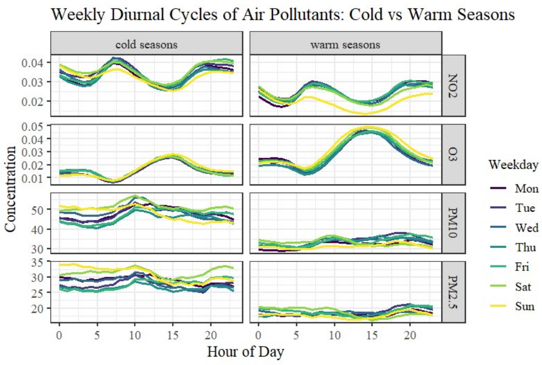

Figure 3. Weekly Diurnal Cycles of Air Pollutants: Cold vs Warm Seasons

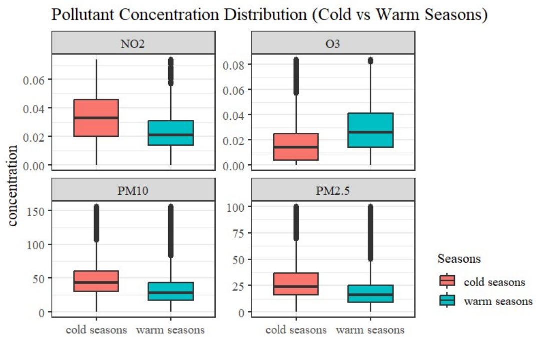

Figure 4. Pollutant Concentration Distribution (Cold vs Warm Seasons)

3.3 Long-term Temporal Trend Decomposition via STL Method

To identify the annual seasonal periodicity of air pollution, daily averaged $PM_{2.5}$ concentrations were decomposed by the STL time-series decomposition algorithm. The raw time series was separated into three components: long-term trend, stable seasonal cycle, and random residual noise.

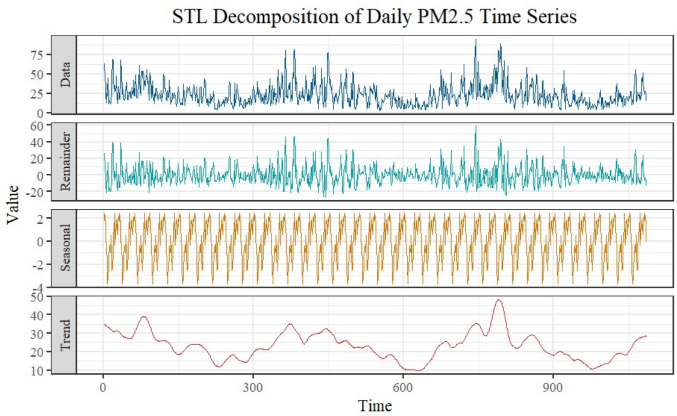

Figure 5. STL Decomposition of Daily PM2.5 Time Series

STL time series decomposition divides daily $PM_{2.5}$ records into raw data, remainder noise, seasonal cycle and long term trend (Figure 5). Seasonal component shows the same swing every year, and the value of $PM_{2.5}$ becomes higher in cold period, which is consistent with the content of Table 2. Irregular short-term swing enters the remainder component, and the trend shows a non-linear change in units of several months during the investigation. This decomposition process confirms that the seasonal background of $PM_{2.5}$ pollution is stable, and supports the analysis of the subsequent weekly pollution cycle by seasonal modulation.

3.4 Weekly Cycle Characteristics of Pollutant Concentrations

Taking $PM_{2.5}$ as the representative pollutant, a heatmap was drawn to visualize hourly concentration distribution across a complete weekly cycle (Figure 6). $PM_{2.5}$ concentration rises sharply on Friday evening and remains at a high level during weekends, forming obvious weekly periodic fluctuations.

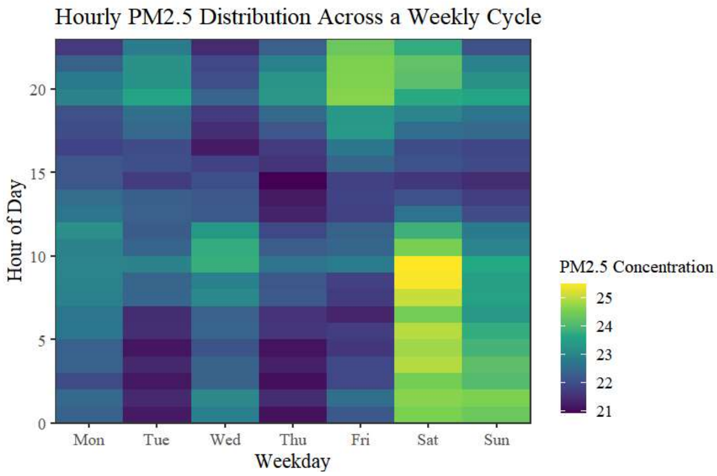

Figure 6. Hourly PM2.5 Distribution Across a Weekly Cycle

Global Wilcoxon tests between weekdays and weekends show that $PM_{2.5}$, O_3 and NO_2 have significant weekly concentration differences ($p < 0.001$). In contrast, PM_{10} shows no statistically significant disparity between weekdays and weekends ($p = 0.2907$), indicating PM_{10} lacks an evident weekly cycle pattern.

3.5 Interactive Effect Between Seasonal Background and Weekly Cycle

To verify whether seasonal temperature could eliminate or adjust weekly pollution cycles, hourly $PM_{2.5}$ weekly patterns were split into cold and warm subgroups for comparative visualization (Figure 7). Stratified Wilcoxon rank-sum tests were implemented for each season separately.

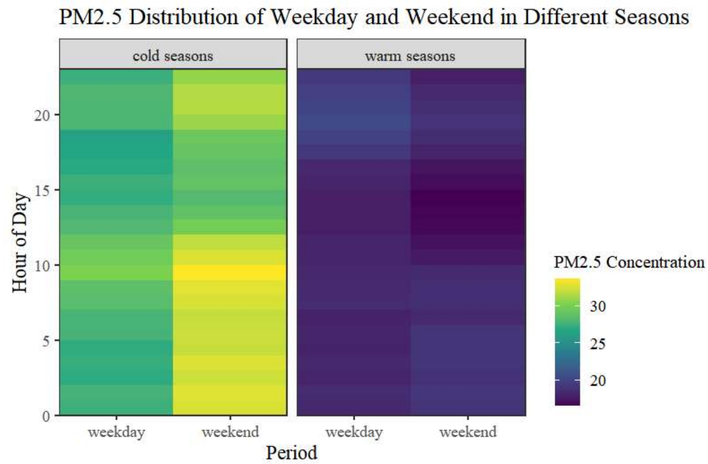

Figure 7. Weekly Hourly PM2.5 Patterns in Cold and Warm Seasons

Stratified test results reveal that significant weekday-weekend differences exist for all four pollutants in both cold and warm seasons (all stratified $p < 0.05$). It can be concluded that seasonal variation cannot eliminate the weekly pollution cycle, but modulates its fluctuation intensity: the concentration gap between weekdays and weekends is larger in cold seasons, while the amplitude of weekly fluctuation weakens in warm seasons.

3.6 Seasonal Variation of Pairwise Pollutant Correlations

Pairwise correlation coefficients of the four pollutants were calculated for the full study period, cold seasons and warm seasons respectively, visualized via three correlation heatmaps (Figure 8, Figure 9, Figure 10), to interpret the internal mechanism of seasonal modulation on weekly cycle intensity.

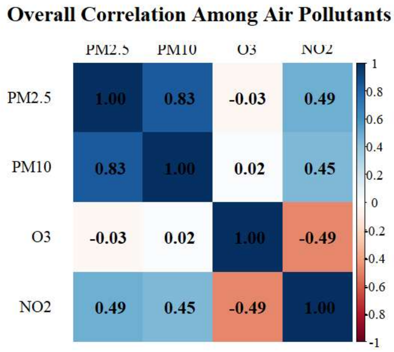

Figure 8. Overall Correlation Among Air Pollutants

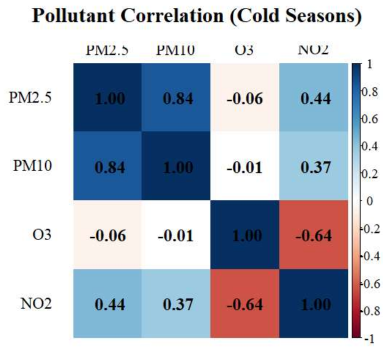

Figure 9. Pollutant Correlation (Cold Seasons)

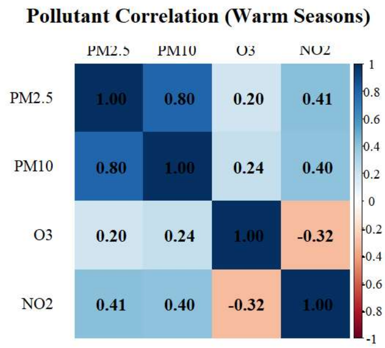

Figure 10. Pollutant Correlation (Warm Seasons)

$PM_{2.5}$ and PM_{10} maintain strong positive correlation under all scenarios, yet the correlation between gaseous pollutants and particulate matter changes drastically across seasons. The negative correlation between O_3 and NO_2 is much stronger in cold seasons ($r = -0.64$) than in warm seasons ($r = -0.32$); weak positive correlations between O_3 and particulate matter are only observed in warm seasons. This seasonal divergence in pollutant covariation is consistent with differences in photochemical reaction intensity and atmospheric diffusion conditions. It may help to interpret why the intensity of weekly pollution cycles differs between cold and warm seasons. Note that these pairwise correlation analyses were not statistically controlled for temporal and seasonal confounding factors.

4. DISCUSSION

This study shows that seasonal changes cannot eliminate the weekly pollution cycles but greatly change their fluctuation ranges. Cold seasons feature frequent temperature inversions; heating and traffic emissions may trap pollutants, which is consistent with widened weekday-weekend gaps [7, 8]. The strong negative correlation between NO_2 and O_3 may be related to such seasonal disparities. Warm seasons are characterised by active air convection and photochemical reactions; diffusion and rainfall may be associated with narrower weekly pollution gaps. PM10 has no obvious weekly variations, which might be because cross-border dust transport overwhelms local human activity signals [5, 9]. It should be noted that the pollutant correlation results reported in this work are observational covariations rather than direct causal relationships, and the analyses were not adjusted for seasonal and temporal confounders. Unlike past single-dimensional analysis focusing solely on seasonal or weekly patterns [10, 11, 12], this paper quantifies the joint modulation effect of seasonal meteorology and weekly anthropogenic emissions. Its findings align with research on temperate East Asian megacities, while differing from European and American urban results due to divergent weekend activity patterns [3, 13].

Seoul can adopt seasonal target pollution control: limit traffic peaks and heating emissions in cold seasons, and reduce substances that cause ozone in warm seasons. For PM10[9], regional cooperation is needed, and vehicles in commercial and sightseeing places on weekends need to be more strictly managed. This study only uses the urban average data from 2017 to 2019, without the analysis of meteorological quantity, the comparison of functional areas and the data of VOCs. In the future, research will use longer dataset, meteorological indicators and VOCs monitoring to investigate the relationship between seasons and weekly pollution patterns in more detail. In the future, work will also carry out correlation analysis of covariates with adjusted seasons and time to further clarify the causal relationship between pollutants.

5. CONCLUSION

The study analyzed the hourly air quality data of $PM_{2.5}$, PM_{10}, no and O throughout Seoul for three years. We investigated in detail how the atmospheric state in each season affects the changes of pollutants in a day. As can be seen from the results, even if the seasons change, the original pattern of different pollution modes between working days and weekends will not disappear, but it will obviously change the pollution difference between working days and rest days. The concentrations of pm., pm and no become higher in cold season and O becomes higher in warm season. In the cold season, the atmospheric movement is weak, pollutants are difficult to spread, and the difference between working days and weekends will become larger. On the contrary, in warm seasons, the air flows well, the pollutants produced by human beings become lighter, and the weekly gap becomes smaller. Especially PM10, dust often moves across regions, which will eliminate the influence of local human activities, so the weekly change is not obvious. These results make up for the deficiency of the previous survey with only one factor, and show how to reduce the air pollution suitable for the season in Seoul's urban policy. However, there is something wrong with this study. The time to collect data is only three years, which is very short, and it is impossible to capture long-term changes. Moreover, there are no meteorological values and VOCs observation records in our analysis. In the future research, we should extend the observation time, add various meteorological related data and compare them in different regions, so as to have a better understanding of the complex rules of urban air pollution changing with time.

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