Long-Term Variability of PM$_{2.5}$ and PM$_{10}$ in Seoul:

Impacts of Asian Dust Events and Synoptic Circulation

3   **Abstract**

4   This study utilized $PM_{2.5}$ data from two stations in Seoul, South Korea, providing a long record from

5   2000 to the present, during winter (DJF) and spring (MAM) seasons. Both $PM_{2.5}$ and PM_{10} exhibited a decreasing

6   trend in both seasons, with a slower decline in the last decade (2011-2020) compared to the earlier decade (2000-

7   2010). Concerning the correlation between $PM_{2.5}$ and PM_{10}, the winter season exhibited a complex behavior with

8   the last decade showing a stronger correspondence. By contrast, the spring season showed a robust interannual

9   correlation throughout the whole period. It appears that Asian dust events reduced the correlation between $PM_{2.5}$

10   and PM_{10} concentrations. Regarding daily variation, $PM_{2.5}$ and PM_{10} generally fluctuated together during winter

11   corresponding to migratory synoptic systems originating from northwest China. Such systems can remain

12   stationary over Korea for multiple days, alternating PM behaviors. These features persisted into the spring season,

13   with a spatial pattern similar to winter but with weaker intensity. The results offer insights into $PM_{2.5}$ variability

14   across different time scales and its correlation with PM_{10} over an extended period, with potential implications for

15   $PM_{2.5}$ mitigating planning.

Plain language summary

This study looked at air pollution in Seoul, South Korea, focusing on smaller particles ($PM_{2.5}$) and larger particles (PM_{10}) during winter and spring from 2000 to now. We found that both $PM_{2.5}$ and PM_{10} levels have been going down over time, but the decrease slowed in the last 10 years (2011-2020) compared to the previous 10 years (2000-2010). In winter, the connection between $PM_{2.5}$ and PM_{10} was more complex, with a stronger link in the recent decade. In spring, this connection stayed strong throughout the whole period. We also found that natural dust storms from China and Mongolia (Asian dust events) weakened the link between $PM_{2.5}$ and PM_{10} levels. Daily changes in $PM_{2.5}$ and PM_{10} levels were usually similar during winter, influenced by synoptic sale weather systems from northwest China that can stay over Korea for several days and affect pollution levels. This pattern continued into spring but was less strong. These findings help us understand how $PM_{2.5}$ levels change over time and how they relate to PM_{10} levels based on unique long-term records. This information is useful for planning ways to reduce $PM_{2.5}$ pollution and improve air quality in the future.

Key Points

1. Both $PM_{2.5}$ and PM_{10} exhibit a decreasing trend from 2000 in Seoul, South Korea. The decline is more pronounced in the earlier decade compared to the last decade, indicating changes in air quality over time and likely reflecting enhanced air quality regulation.

2. In general, $PM_{2.5}$ and PM_{10} display comparable interannual variability. Winter exhibits intricate behavior, with the correlation being significantly weaker in the earlier decade compared to the last decade. Nevertheless, a robust correlation between the two PM types can be observed in spring, regardless of the period.

3. The daily variations of $PM_{2.5}$ and PM_{10} during winter are closely linked to a migratory synoptic anticyclone circulation system originating from northwest China. This system also influences PM concentrations in spring, albeit with reduced intensity.

4. The impact of Asian dust events on the correlation between $PM_{2.5}$ and PM_{10} has been demonstrated to be detrimental, affecting both interannual variability and daily fluctuations.

1. Introduction

Particulate matter (PM) pollution significantly impacts human health and the environment. Concerns about air pollution, particularly the high concentrations of PM during winter and spring seasons, have intensified in South Korea due to rapid economic growth in recent decades. Public concern about PM has surged, driven by the daily discomfort it causes. Since regular measurements began in 1995, the concentration of PM_{10} has gradually declined, thanks to government-led policies focused on reducing anthropogenic emissions. However, PM concentrations in South Korea are also influenced by Asian dust, a natural phenomenon (Chun et al., 2001). Asian dust transports coarse particles to South Korea, consequently increasing the proportion of PM_{10} (Kim & Kim, 2003). Moreover, frequent Asian dust events significantly affect the annual average concentration of PM_{10} (Ghim et al., 2015). To enhance prediction accuracy, linking PM levels to meteorological conditions is crucial. In response, the Ministry of Environment initiated nationwide forecasts for PM_{10} and $PM_{2.5}$ in 2014 and 2015, respectively.

Meteorological conditions near South Korea manifest synoptic scale patterns, significantly influencing both pollutant transport and local air quality (Kim et al., 2016). These patterns affect PM_{10} concentrations by either facilitating transport from external sources or causing stagnation from internal sources (Lee et al., 2022; Lee et al., 2011). The number of high PM_{10} events in Seoul corresponds to the seasonality of Asian dust, and a characteristic synoptic scale condition favorable for high PM_{10} events has been identified (Jung et al., 2019). Long-range transport of emissions from east-central China heavily influences South Korea's air quality, with domestic emissions also playing a role (Lee et al., 2019). Atmospheric blocking (Oh et al., 2015; Yun & Yoo, 2019) and large-scale circulation patterns resembling wave trains in the upper troposphere (Ku et al., 2021) also affect PM_{10} concentrations. Based on these associations, there have been attempts to predict PM10 levels using related atmospheric factors.

Previous studies have identified that temperature, wind, and pressure could be potential predictors of PM_{10} concentrations (Callahan et al., 2019; Lee et al., 2022; Lee et al., 2018; Lee et al., 2011). They have examined PM_{10} concentrations and meteorological conditions at different time scales. Lee et al. (2018) developed an index representing atmospheric conditions during high PM_{10} cases by performing regression analysis of daily PM_{10} concentrations and weather conditions. Jeong et al. (2022) also used statistical and dynamical models to develop a prediction model for the winter mean PM_{10} concentration. The model demonstrated significant forecasting abilities, validating the feasibility of seasonal air quality forecasting based on climate conditions. Climate conditions are underscored by their physical linkage with PM_{10} and their reliable

72   predictability through climate models.

73   This study is timely because we now have the extended $PM_{2.5}$ data from two long-term, reliable

74   observation stations in Seoul. Although $PM_{2.5}$ has historically received less attention than PM_{10} due to its shorter

75   observation period, we can overcome this limitation by using the longer dataset available. We comprehensively

76   analyze $PM_{2.5}$ concentration characteristics during winter and spring and their associated meteorological

77   conditions on a multi-time scale. We also analyze the long-term trend of $PM_{2.5}$ and establish the relationship

78   between $PM_{2.5}$ and PM_{10} concentrations from daily to interannual variability. Additionally, we characterize the

79   meteorological conditions associated with their daily relationship. Understanding the intricate dynamics

80   dictating Seoul's air quality is crucial for future research directions and policy strategies aimed at maintaining

81   and improving air quality standards.

2. Data and Methods

2.1. $PM_{2.5}$ and PM_{10} concentration data sources and processing

We obtained daily mean PM_{10} concentrations from 2000 to 2021 by averaging data from 25 observation stations in Seoul, provided by the National Institute of Environmental Research (NIER) (available at https://www.airkorea.or.kr/). Due to the relatively short period of available $PM_{2.5}$ data from NIER, starting only after 2015, we extended the data period for $PM_{2.5}$ back to December 2000 using hourly $PM_{2.5}$ observations from the Seoul Research Institute of Public Health and Environment (SRIPHE) (available at https://data.seoul.go.kr/dataList/OA-15526/S/1/datasetView.do#), which offers the longest $PM_{2.5}$ observation record in South Korea (Chang et al., 2021; Jeong et al., 2023).

Among the 25 monitoring stations in Seoul, two stations (Seongdong-gu and Gwangjin-gu) have data from December 2000 (Supplementary Figure 1). However, the dataset lacked calibration and contained outliers due to various factors such as calibration errors, power disconnections, maintenance activities, and data abnormalities. Additionally, in December 2018, the Seongdong-gu Observatory was relocated from Seoul Forest to the Seongsu 1-ga 1-dong Residents' Center. To obtain reliable daily data, we implemented the following steps:

1. Outlier removal for hourly data: We removed outliers from the hourly data collected at each station to exclude abnormal values.

2. Daily mean calculation: After eliminating outliers, we computed the daily mean by aggregating the remaining hourly data points to smooth out irregularities.

3. Outlier removal for daily mean: We excluded any day with more than 25% outliers to maintain data integrity, following NIER's data screening approach.

4. Data combination from two stations: To maximize data coverage, we combined daily data from two stations. If one station lacked data for a specific day, we imputed it using the data from the other station, extending the dataset's temporal coverage.

These steps improved data quality and reliability by systematically addressing calibration issues and outliers. The $PM_{2.5}$ daily data resulting from our study showed a total of 8 missing values during the winter season (DJF) from 2000 to 2020 over 1895 days and 14 missing values during the spring season (MAM) from 2001 to 2020 over 1840 days. Most missing data instances occurred in the earlier decade (2000-2010) for both seasons. These dates are listed in Supplementary Table 1.

This data is suitable for use in the study as a representation of $PM_{2.5}$ because it closely matches NIER

PM$_{2.5}$ data, as shown in Supplementary Figure 2. During the common winter (spring) period of 2015-2020, we compared the average NIER PM$_{2.5}$ data from the same two stations with the SRIPHE PM$_{2.5}$ data produced in this study and found a high correlation of 0.99 (0.99), indicating a close match. Although we used the same stations, discrepancies in certain values likely result from NIER's additional data screening processes. However, the data's reliability is supported by the high correlation for both seasons and the lack of any cases where PM$_{2.5}$ concentrations exceeded PM$_{10}$. Furthermore, PM$_{10}$ concentrations, widely used as a proxy for PM$_{2.5}$ in air quality studies, also showed a high correlation of 0.84 (0.83) over a common period during winter (spring) for the same two stations (Supplementary Figure 3). Thus, we used the daily PM$_{2.5}$ data for the winter months of 2000 to 2020 and the spring months of 2001 to 2020, generated as described above.

2.2. Definition of Asian dust events

Since Asian dust primarily affects larger particulate matter, we accounted for its more pronounced impact on PM$_{10}$ levels than PM$_{2.5}$ (Kim & Kim, 2003). We excluded Asian dust events from the analysis to discern their influence on the variability and concentration levels of both PM$_{10}$ and PM$_{2.5}$. We identified days designated as Asian dust events based on records reported by the Korea Meteorological Administration (available at https://www.weather.go.kr). Throughout the winters (springs) of 2000-2020 (2001-2020), a total of 33 (138) Asian dust events were recorded.

Asian dust is a natural occurrence that results in high PM episodes, which also occur during non-Asian dust conditions. To compare the meteorological background fields, we conducted a composite analysis. During winter (spring), we defined 251 (216) high PM$_{2.5}$ cases as days with concentrations exceeding 1 standard deviation of the winter (spring) mean for 2000-2020, 57.98 μg/m³ (2001-2020, 52.78 μg/m³).

2.3. Meteorological data

To examine the relationship between fluctuations in PM levels and weather patterns, we utilized the 6-hourly Japanese 55-year Reanalysis (JRA-55) as the meteorological dataset. JRA-55 has a horizontal resolution of 1.25° x 1.25° with 37 vertical levels (Kobayashi et al., 2015). Previous studies (Jung et al., 2019; Ku et al., 2021; Lee et al., 2022; Lee et al., 2018; Lee et al., 2011; Oh et al., 2015) have found the relationship between PM$_{10}$ levels and meteorological conditions in Korea, specifically pressure, temperature, and wind. We used the winter and spring daily mean geopotential height (Z), air temperature (T), and horizontal winds (U and V) from 2000 to 2020, considering the local time of Seoul. We calculated daily anomalies by subtracting the

142   corresponding daily climatologies.

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144   **2.4. Methods for analyzing trends, variability, and correlations**

145   To understand the relationship between the interannual variability of $PM_{2.5}$ and PM_{10}, it is necessary

146   to remove trends. The winter mean of $PM_{2.5}$ and PM_{10} between 2000 and 2020 displayed marked trends

147   attributed to government policies aimed at emission reduction (Heo et al., 2017). However, the linear trend

148   derived through the least-squares method was insufficient to capture the nuanced trends observed in winter

149   mean PM levels across the study period (Supplementary Table 2). Distinct differences in trends were apparent

150   between the initial and final decades. Therefore, we omitted the second-order polynomial regression curve for

151   the winter mean trends to depict the trend spanning the entire timeframe accurately. On the other hand, we

152   successfully detrended the trends in spring mean PM using the least-squares method.

153   We evaluated the interannual and daily relationship between $PM_{2.5}$ and PM_{10} using Pearson

154   correlation coefficients with a two-tailed Student's t-test to assess statistical significance. To examine the

155   association between weather conditions and $PM_{2.5}$ concentrations in space and time, we performed lead-lag

156   correlation analysis with weather conditions using a time lag of 7 days before and after.

3. Results and Discussions

3.1. Decreasing long-term trends of $PM_{2.5}$ and PM_{10} with recent decadal weakening

The long-term variation in winter mean $PM_{2.5}$ and PM_{10} shows a notable downward trend from 2000 to 2020 (Figure 1(a) and Table 1). Both $PM_{2.5}$ and PM_{10} exhibit significant decreasing trends, reflecting the efficacy of Korean government policies in reducing PM levels. The spring season shows similar characteristics. Both $PM_{2.5}$ and PM_{10} display steadily decreasing long-term trends in spring as well (Figure 1(b) and Table 2). However, among the similar trends, there is a marked disparity between the trends in the earlier decade (2000-2010, P1) and the recent decade (2011-2020, P2). During P2, the trends for both $PM_{2.5}$ and PM_{10} weaken compared to P1. Specifically, $PM_{2.5}$ shows an almost flattened trend (-2.476 μg/m³/decade) compared to PM_{10} (-10.33 μg/m³/decade). In spring, the trends for P1 are steeper compared to P2 and both $PM_{2.5}$ and PM_{10} exhibit similar decreasing trends (Table 1 and Table 2). Yeo and Kim (2019) observed fluctuations of the decreasing trend in the annual mean concentrations from 2001, and this pattern is even more pronounced in the winter and spring means observed in this study. Excluding Asian dust events does not result in a significant difference in trend compared to the original trends. This demonstrates that Asian dust does not impact the long-term decrease driven by pollution-reduction policies.

The observed long-term decreasing trends in $PM_{2.5}$ and PM_{10} from 2000 to 2020 indicate the success of South Korea's air quality management policies. These policies appear particularly effective in the earlier decade, as evidenced by the steeper decline in PM concentrations during this period compared to the recent decade. This suggests that initial policy measures had a strong impact, but the effectiveness may have diminished over time, possibly due to changes in emission sources or saturation of policy impact.

The more pronounced weakening in the $PM_{2.5}$ trend compared to PM_{10} in the recent decade raises concerns. $PM_{2.5}$, being finer and more harmful to human health, requires continued and possibly more strict control measures. Furthermore, the seasonal analysis highlights that the policy impacts vary by season, with winter and spring showing different degrees of trend reductions. This seasonal variability suggests that policies may need to be tailored to address specific seasonal emission sources and meteorological conditions.

182   **Table 1. DJF mean trends of PM$_{10}$ and PM$_{2.5}$ concentrations (brackets: excluding Asian dust events).**

DJF mean trend (μg/m³/decade)	2000-2020	P1 (2000-2010)	P2 (2011-2020)
PM$_{10}$	-14.21* (-14.28*)	-13.27 (-16.21*)	-10.33 (-9.014)
PM$_{2.5}$	-14.07* (-14.01*)	-30.90* (-31.16*)	-2.476 (-2.719)

183   *: significant at a 95% significance level.

184

185   **Table 2. MAM mean trends of PM$_{10}$ and PM$_{2.5}$ concentrations (brackets: excluding Asian dust**

186   **events).**

MAM mean trend (μg/m³/decade)	2001-2020	P1 (2001-2010)	P2 (2011-2020)
PM$_{10}$	-24.32* (-15.88*)	-46.93* (-28.49*)	-12.0 (-6.513)
PM$_{2.5}$	-15.38* (-12.42*)	-42.26* (-33.22*)	3.352 (4.096)

187   *: significant at a 95% significance level.

188

189 **3.2. Seasonal differences in the interannual relationship between PM$_{2.5}$ and PM$_{10}$**

190   Table 3 shows that Asian dust disrupts the interannual relationship between PM$_{2.5}$ and PM$_{10}$. Without

191 Asian dust events, PM$_{2.5}$ and PM$_{10}$ show similar long-term interannual variabilities, with a correlation coefficient

192 of 0.50 over the 2000-2020 period during winter. However, disparities emerge between the earlier decade (2000-

193 2010, P1) and the recent decade (2011-2020, P2): P1 has a lower coefficient of 0.45 compared to a stronger 0.66

194 correlation in P2. Here, the separation of these periods is solely determined by the mid-point. The statistically

195 significant correlations in P2 emphasize the yet similar complex nature of interannual variability between PM$_{2.5}$

196 and PM$_{10}$. In spring, PM$_{2.5}$ and PM$_{10}$ exhibit highly similar interannual variability (Table 4). During P1, spring

197 maintains a high correlation throughout both periods, whereas the winter correlation is significantly lower. By

198 removing Asian dust events, the correlation between PM$_{2.5}$ and PM$_{10}$ concentrations increases, particularly in

199 winter. By contrast, the spring season maintains a strong correlation throughout the study period, with or without

200 Asian dust events. These findings highlight the modulation of Asian dust events on the year-to-year variability of

201 PM$_{2.5}$ and PM$_{10}$ in winter when cold-air outbreaks are frequent and more widespread.

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The interannual variability analysis reveals that Asian dust events significantly disrupt the correlation between $PM_{2.5}$ and PM_{10}, particularly in winter. The higher correlation in the recent decade (2011-2020) suggests that, despite overall decreasing trends, episodic events like Asian dust storms still play a critical role in PM variability. By comparison, the weaker interannual correlation in 2000-2010 (P1) may be influenced by heightened variability in PM levels due to the pronounced effects of emission reduction policies. The GEOS-Chem (Goddard Earth Observing System-Chemistry) experiment with fixed emissions shows no significant trends. However, it reveals consistent correlations in both P1 and P2. Specifically, monthly $PM_{2.5}$ and PM_{10} data from this model (Jeong et al., 2018) indicate nearly flat trends over the same period. They also show a high interannual correlation of 0.91 (Supplementary Figure 4).

Furthermore, the declining $PM_{2.5}/PM_{10}$ fraction in P1 supports this result (Supplementary Figure 5). A stable fraction indicates a strong correlation, while P2, with a higher interannual correlation, exhibits a less pronounced fraction variation than P1. The reduction in policy influence suggests that the proportion of the impact of other factors may increase in the relationship between the two PM types. These findings indicate that underlying meteorological conditions continue to drive PM levels even as emissions decrease. This points to the importance of integrating meteorological considerations into air quality management strategies.

Table 3. Correlation coefficients between winter mean $PM_{2.5}$ and PM_{10} concentrations.

DJF mean correlation	With Asian dust	Without Asian dust
2000-2020	0.34	0.50[*]
2000-2010 (P1)	0.38	0.45
2011-2020 (P2)	0.32	0.66[*]

*: significant at a 95% significance level.

Table 4. Correlation coefficients between spring mean $PM_{2.5}$ and PM_{10} concentrations.

MAM mean correlation	With Asian dust	Without Asian dust
2000-2020	0.77[*]	0.80[*]
2001-2010 (P1)	0.77[*]	0.75[*]
2011-2020 (P2)	0.79[*]	0.87[*]

*: significant at a 95% significance level.

3.3. Daily variation of PM$_{2.5}$ and PM$_{10}$ under the synoptic-scale circulation system

PM$_{2.5}$ and PM$_{10}$ show a robust correlation in their daily variations, with an expected influence from Asian dust events. During winter from 2000 to 2020, PM$_{2.5}$ and PM$_{10}$ exhibit similar daily variabilities, with a correlation coefficient of 0.80 when including Asian dust events, and 0.91 without. Figure 2(a) confirms this influence, showing weaker correlations during winters with Asian dust events included and stronger correlations when dust days are excluded. In spring, PM$_{2.5}$ and PM$_{10}$ display highly similar daily variations (Figure 2(b)), especially when excluding Asian dust events, resulting in a correlation coefficient of 0.89. Including these events reduces the correlation coefficient to 0.85. This further confirms that Asian dust events disrupt the relationship between PM$_{2.5}$ and PM$_{10}$ in both daily and interannual variability.

The impact of emissions-driven long-term trend differences in winter mean PM levels, which previously caused interannual correlation disparities, appears minimal on a daily scale. This is evident in the significant and relatively consistent daily correlation observed in P1 and P2. Comparing these periods reveals consistent correlations, albeit higher when excluding Asian dust events (winter P1: 0.84 and P2: 0.71; spring P1: 0.87 and P2: 0.72 when including Asian dust events; winter P1: 0.90 and P2: 0.88; spring P1: 0.89 and P2: 0.87 when excluding Asian dust events). Hence, the daily variability appears less affected by fluctuations in emission trends.

We analyzed the covarying patterns between PM$_{2.5}$ and meteorological conditions to understand the role of synoptic circulation patterns in winter and spring. Correlation maps between PM$_{2.5}$ and Z500, T850, U500, and V850 illustrate the synoptic-scale circulation system over Korea (Figure 3(A)(a), (c), (e), and (g)). This system is characterized by several features. First, mid-tropospheric positive pressure anomalies (Z500) are centered over Korea. Second, low-tropospheric northerly winds (V850) are weakened. Third, positive temperature anomalies (T850) occur due to reduced cold air inflow. Mid-tropospheric zonal wind patterns (U500) exhibit north-south symmetry, further reducing northerlies and impeding the removal of PM$_{2.5}$. Considering the reduced role of government policies in the recent decade as discussed in section 3.2, the influence of synoptic patterns may have become more pronounced compared to the previous decade. Their relationship remains significant throughout the period, although some years exhibit lower correlations (Figure 3(A)(b), (d), (f), and (h)). The spring patterns are similar to winter patterns but differ in intensity and location, and the relationship shows more year-to-year variability than the winter (Figure 3(B)).

The synoptic patterns align with the study on PM$_{2.5}$ in Beijing, approximately 1000 km from Seoul (Cai et al., 2017). Furthermore, the similarity to synoptic patterns associated with pollutant transport underscores the relationship with the meteorological conditions (Kim et al., 2016; Lee et al., 2011). This indicates that similar

synoptic patterns affect PM levels across East Asia. Therefore, understanding these patterns is crucial for predicting high PM events and developing responsive air quality management measures.

The temporal evolution of the synoptic circulation system is shown in Figure 4 through time lead-lag correlation maps. During winter, a migratory anticyclone originating from northwest China shows significant positive correlation patterns with $PM_{2.5}$, beginning two days prior and persisting over the Korean peninsula for two additional days due to blocking by low pressure over the Northern Pacific. This system brings warm temperature anomalies and weakened northerlies in the low troposphere over Korea, leading to high $PM_{2.5}$ levels. The migratory system might be associated with the propagating wave train pattern observed in high PM_{10} cases (Ku et al., 2021), and the stagnation could be linked to atmospheric blocking, which impacts PM_{10} concentrations (Yun & Yoo, 2019). The significant relationship with $PM_{2.5}$ concentrations persists for approximately five days (Figure 4(A)(i)). While spring spatial patterns resemble those of winter, their intensity is weaker. Consistent durations of covariability are observed in pressure and other meteorological factors such as U500, T850, and V850 (not shown). The result suggests that forecasting these patterns could provide a few days' lead time for implementing mitigative actions. This highlights the potential for using synoptic-scale forecasts in operational air quality management.

3.4. Contrasting meteorological conditions during Asian dust events

We conducted a composite analysis to identify the background conditions when Asian dust events occur. In Figure 5, high $PM_{2.5}$ cases without Asian dust events are associated with mid-tropospheric positive pressure anomalies centered over Korea, weakened low-tropospheric northerly winds, and positive temperature anomalies for both seasons. The patterns are similar to the correlation maps in Figure 3 showing the stagnant high-pressure system. This emphasizes the critical role of synoptic circulation systems in the variation of $PM_{2.5}$ concentrations.

In contrast, the composite maps of Asian dust events reveal contrasting features. Negative Z500 and intensified V850 are shown, and these conditions are known to facilitate the transportation of Asian dust from its source region in arid northern China (Jung et al., 2019). The low T850 extends from continental Asia to the Korean Peninsula, diverging from the positive T850 patterns observed in high $PM_{2.5}$ cases. These temperature anomaly patterns resemble cold surge patterns over Korea, aligning with negative pressure patterns associated with the cold surge phenomenon. The negative Z500 pattern extending toward the Korean Peninsula resembles the migratory anticyclone patterns from the Siberian High to the Korean Peninsula (Jeong et al., 2006; Ryoo et al., 2005). Thus, the contrasting conditions highlight how Asian dust events disrupt the relationship between $PM_{2.5}$ and PM_{10}

284   variability. They also emphasize the complexity of managing PM levels, requiring different strategies for different

285   types of high PM events. For example, reducing local emissions might be more effective for non-dust high PM

286   events, while regional cooperation is essential for addressing transboundary dust transport.

4. Conclusion

This study reports an extended analysis of the long-term trends and interannual variability of $PM_{2.5}$ and PM_{10} in Seoul, considering the impact of Asian dust events and synoptic circulation patterns. Both $PM_{2.5}$ and PM_{10} exhibit significant declining trends from 2000 to 2020, reflecting the effectiveness of emission reduction policies. Excluding Asian dust events shows that while they significantly affect PM_{10} levels, they do not alter the overall declining trend of $PM_{2.5}$ and PM_{10}. However, the correlation between $PM_{2.5}$ and PM_{10} is influenced by Asian dust events, which disrupt their relationships on both daily and interannual scales.

The study also reveals that the interannual correlation during winter between $PM_{2.5}$ and PM_{10} is stronger in the recent decade (2011-2020) compared to the earlier decade (2000-2010), likely due to the variability in PM levels caused by emission reduction policies. During spring, the relationship remains very stable throughout the study period. On a daily scale, $PM_{2.5}$ and PM_{10} show robust correlations, but these are weakened by the presence of Asian dust events. The findings emphasize the role of synoptic-scale circulation patterns in the daily and seasonal variability of PM concentrations.

The results highlight the importance of considering Asian dust events in air quality management strategies. Although policies aimed at reducing emissions have effectively decreased PM levels over the past two decades, the presence of Asian dust can obscure these improvements. Transport of dust also implies PM from remote sources. Understanding the synoptic meteorological conditions that influence PM variability can enhance the accuracy of PM forecasts and aid in developing more effective mitigation strategies. This study underscores the need for integrated air quality management that addresses both local emissions and transboundary pollution events to protect public health.

Future research should focus on the detailed mechanisms through which meteorological factors influence PM variability. There is a need to explore the seasonal differences in the impact of synoptic circulation patterns on PM levels. Additionally, further studies should investigate the potential impacts of future policy interventions on PM trends, considering both local and regional sources of pollution. Enhanced monitoring and modeling efforts are necessary to improve the accuracy of PM forecasts and to develop effective mitigation strategies.

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