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An Analysis on the Concentration Characteristics of PM2.5 in Seoul, Korea from 2005 to 2012

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Abstract: PM2.5 is a big issue as it is considerably more harmful than other sizes of particulate matter. World Health Organization (WHO) recommends 25 μg m^{-3} as the daily average concentration, and 10 μg m^{-3} per day as an annual average. To keep up with global trends, it is first necessary to understand the current status and characteristics of PM2.5 concentrations in Korea. Using the PM2.5 data measured by Seoul Metropolitan City from November 2005 to March 2012, the author analyzed its statistical characteristics and correlations with other air pollutants. For the time period from 2005 to 2012, the annual average concentration of PM2.5 was 27 μg m^{-3}, three times the WHO standard. Also, the daily average PM2.5 concentration of 215 days per year also exceeded the WHO standard. However, the number days exceeding the Korean daily average standard of 50 μg m^{-3} to be enacted in 2014 was only three. PM2.5 concentration had a high correlation (r = 0.84) with PM10, and also showed high correlations with gaseous pollutants, such as SO_2, NO_2, and CO, but not O_3. This study suggests that the Korean government should strengthen their standard to match the criteria used by WHO.

Key words: Particulate matter 2.5, statistical analysis, correlation, Seoul

1. Introduction

Particulate matter, whether solid or liquid, is an important indicator of air quality. Its size, varying from 0.001 to 500 μm, affects the particles impact on health because it influences the particles' penetration into, deposition in and elimination from the respiratory organs (Yoon *et al*., 2003). PM10 is particulate matter of less than about 10 μm in diameter, and it penetrates the gas exchange (respiratory) surfaces of the lungs. At PM2.5, less than 2.5 μm in diameter, particulate matter reaches deeper into the alveolar region. PM2.5 is of particular research interest when investigating the health impacts and effects of air pollution because its harmfulness is considerably greater than particulate matter of other sizes (Hossain *et al*., 2012; Fan *et al*., 2013; Shimadera *et al*., 2013; Chung *et al*., 2014; Park *et al*., 2014). It has been reported that PM2.5 can easily penetrate into other organs, is removed more slowly, and has increased reactivity within the cell (WHO 2003).

Because of increasing awareness that PM2.5 has a different way of penetrating into and being eliminated from the human body and can cause serious health damage to health, it has been studied actively. In the early 2000s, the majority of studies analyzed PM2.5 concentrations in countries and cities around the world. In Europe, particularly Switzerland, Spain, and Milano in Italy, PM2.5 concentration and correlation analyses were carried out (Marcazzan *et al*., 2001; Gehrig and Buchmann, 2003; Querol *et al*., 2004b). Nanjing and Guangzhou of China, famous for serious particulate matter pollution, were also studied (Wang *et al*., 2002, 2006). Since the end of the 2000s, various approaches to analyzing health damage have been applied to PM2.5. For example, indices related to diseases and death, such as the rate of emergency room visits and hospital admissions have been analyzed on days of high PM2.5 concentration (Dominici *et al*., 2006; Franklin *et al*., 2006; Zeger *et al*., 2008).

In addition, some studies analyzed the relationships between PM2.5 concentration and infant mortality rates or pediatric hospitalization, as infants and children tend to react more sensitively to particulate pollution (Woodruff *et al*., 2006; Ostro *et al*., 2009). Through such studies, it was discovered that PM2.5 is related to health damage such as increased premature death rate, and hospitalization owing to acute or chronic respiratory/cardiovascular disease (Ostro *et al*., 2006; Eftim *et al*., 2008; Bell *et al*., 2009).

Because the adverse health impact of especially PM2.5 among particulate matter has become more apparent, the Environment Performance Index (EPI), which measures the environmental performance of each country, shifted its index for measuring outdoor air quality from PM10 to PM2.5 in 2012 (YCELP and CIESIN, 2012). In addition to such global changes, many advanced countries have studied the impact of PM2.5 on health and strengthened their air pollution control standards for PM2.5 on scientific grounds. Based on environmental epidemiology studies, the USA recommends the air pollution control standard for PM2.5 as a maximum of 35 μg m^{-3} for the a daily average and 15 μg m^{-3} for the annual average, while the World Health Organization (WHO) recommends 25 μg m^{-3} for the daily average, and 10 μg m^{-3} for the annual average. Korea is also preparing for an air pollution

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control standard for PM2.5 to be enacted in 2014. The standard proposed in the 2009 public hearing was 50 μg m^{-3} as a daily average and 30 μg m^{-3} as an annual average, which is higher than either the USA or WHO standards.

Keeping up in Korea with global trends in particulate matter research and policy necessitates firstly understanding the current status and characteristics of PM2.5 concentrations here. There are several literatures analyzing PM 2.5 concentration and its characteristics in Seoul. Kang *et al*. (2004) analyzed PM2.5 concentration by collecting samples from one monitoring station at Konkuk University in Seoul for four seasons from April 2001 to February 2002. Park and Ha (2008) focused PM2.5 characteristics inside trains and platforms on subway in Seoul for four days of January in 2008. Park *et al*. (2008) studied PM2.5 concentration by monitoring every other month for one year from April 2005 to February 2006 at the only one sampling site located in a residential area of Seoul. Heo *et al*. (2009) has similar research scope to this study, however, their PM2.5 concentration data was measured every third day from March 2003 to December 2006 at only one monitoring site. These four literatures analyzed PM2.5 concentration of Seoul, however, most of them had less than one year time period and used only one sampling site or specific place such as subway. Even though Heo *et al*. (2009) monitored longer than one year, their only one monitoring site cannot guarantee that it shows well the PM2.5 characteristics in the whole Seoul.

To overcome the limits of the above literatures and to contribute to PM2.5 control policy, it is necessary to enlarge research scope in terms of time and space. For the reason, the spatial scope of the present study was set to Seoul Metropolitan City for which PM2.5 concentration data from 25 monitoring stations has been available since November 2005. PM2.5's concentration characteristics were analyzed based on daily concentration data spanning a period from November 2005 to March 2012.

2. Data and method

In Korea, although there is no PM2.5 measurement at a national level, Seoul City, recognizing its importance, started measuring PM2.5 concentrations in November 2005. This PM2.5 concentration data has been measured at 25 air pollution-monitoring posts installed in the administrative districts of Seoul using the SPM-613D beta gauge method (Fig. 1). The PM2.5 data is measured automatically at each post and transmitted in real time to the TeleMetering System (TMS) server in the Research Institute of Public Health & Environment of Seoul and subject to quality control before fixation. The collected data is reviewed comprehensively by comparing with the data collected in previous hours and total average concentrations and checking relationships with other air pollutants and concentrations in other areas. This process takes about a month, after which the processed data is generally announced as fixed by the 10th day of the following month.

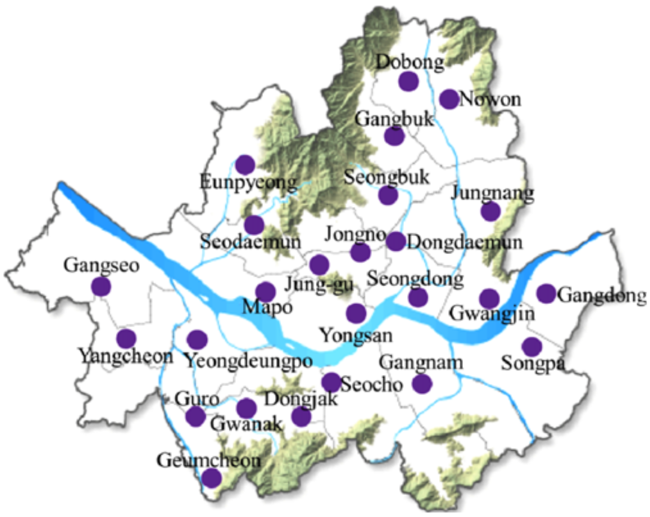

Fig. 1. 25 air pollution monitoring posts in Seoul.

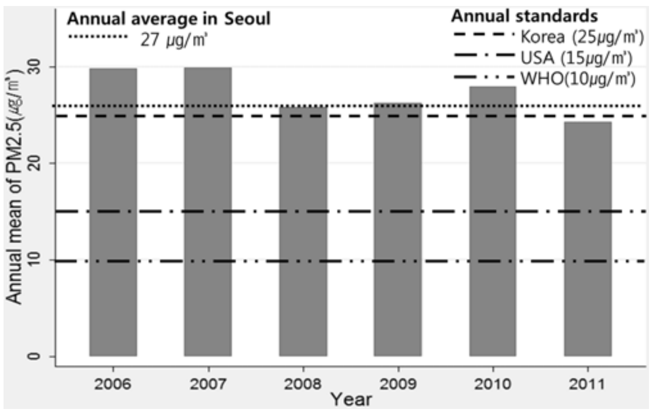

Fig. 2. Comparison of annual average PM2.5 concentrations in Seoul (2006-2011).

From this fixed data, I could secure daily average concentration data from November 2005 to March 2012, a period of 6 years and 5 months, and, excluding missing data, the final number of samples was 2,336.

These Seoul-based PM2.5 measurements were analyzed statistically to obtain concentration characteristics. STATA SE Version 11 was used for technological analyses based on average values, correlation analyses with other air pollutants, specifically PM10, SO_2, NO_2, O_3, and CO, and analyses of the effect of the meteorological factors, temperature, wind speed, and precipitation.

3. Results and discussions

a. Analysis of average PM2.5 concentration

(1) Analysis of annual average PM2.5 concentrations

The annual average PM2.5 concentration in Seoul from 2006 to 2011 was calculated to be 27.3 μg m^{-3}, after the exclusion of the years 2005 and 2012 as they were represented

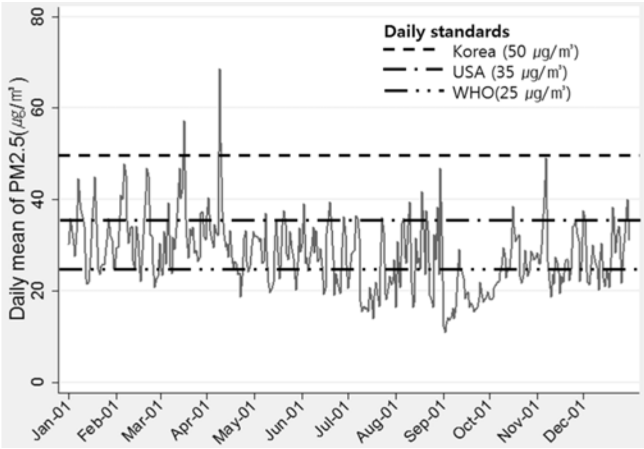

Fig. 3. Daily average PM2.5 concentrations in Seoul over the year.

by only partial data sets of less than three months (Fig. 2). Although PM2.5 concentration decreased in 2008 and 2009, it increased again in 2010. Thus, it would be difficult to say that the annual average PM2.5 concentrations in Seoul have been decreasing continuously. Furthermore, for Seoul every year's average PM2.5 concentration exceeded the annual average concentration standards of both the USA (15 μg m^{-3}) and WHO (10 μg m^{-3}), clearly indicating that fine particle pollution is a particularly serious issue for Seoul.

In contrast to the international standards, all the annual average PM2.5 concentration data points were below the Korean concentration standard of 30 μg m^{-3} to be adopted in 2015 for air pollution control. Therefore, this standard needs to be strengthened.

(2) Analysis of daily average PM2.5 concentration

Daily average PM2.5 concentration was calculated based on the 2,336 daily average PM2.5 concentration data obtained from November 2005 to March 2012. Figure 3 is a line graph showing the daily average concentrations of PM2.5.

The graph shows that daily average PM2.5 concentration increased from February to April, and decreased from May to August. The number of days exceeding the WHO daily average standard of 25 μg m^{-3} was 214 (58.6%), and exceeding the US daily average standard of 35 μg m^{-3} was 54 (14.8%). Thus, the results of the annual average PM2.5 analysis show that more than half of the year exceeded the WHO-recommended value, confirming that Seoulites, by global standards, have indeed been exposed to high levels of fine particulate pollution.

In contrast, the air pollution control standard for daily average PM2.5 concentration to be executed in 2015 for Korea is 50 μg m^{-3}, and the number of days exceeding that standard was only three per year. As of June 2012, this standard of 50 μg m^{-3} is complied with, so it is not a functional standard for the control of PM2.5 concentration. Thus, it is necessary to also strengthen the daily average standard to make it comparable to those of the USA and WHO.

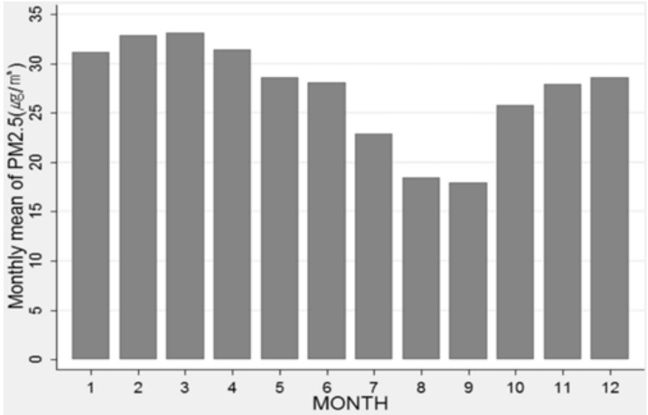

Fig. 4. Monthly average PM2.5 concentrations in Seoul.

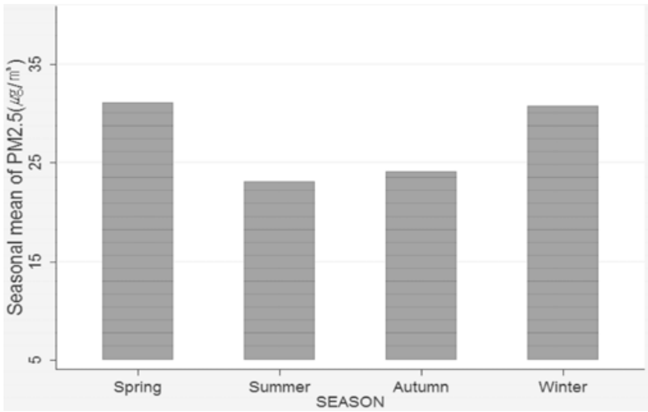

Fig. 5. Seasonal average PM2.5 concentrations in Seoul.

(3) Analysis of monthly average/seasonal PM2.5 concentrations

Monthly average PM2.5 concentration was calculated based on 2,336 daily averages in total from November 2005 to March 2012 (Fig. 4). The highest PM2.5 concentration was in March (33.1 μg m^{-3}), and the lowest was in September (17.9 μg m^{-3}).

In addition to the monthly variation of average PM2.5 concentration, seasonal fluctuations were also calculated and compared. The seasons were divided as follows: spring, March-May; summer, June-August; fall, September-November; and winter, December-February. The highest seasonal PM2.5 concentration, 31.2 μg m^{-3}, was in the spring (Fig. 5).

To check statistical variation by season, an ANOVA (analysis of variance) was conducted. The average PM2.5 concentrations in spring and winter showed no statistically significant difference, and those of summer and fall also showed no significant difference (in both cases, p-value of F-test = 1.000). However, between the two groups of spring/winter and summer/fall, the PM2.5 concentrations did show significant difference. Specifically, the average PM2.5 concentration of spring/winter was statistically significantly higher than that of summer/fall (p-value of F-test = 0.000). PM2.5 concentration was higher in spring/winter because of Asian Dusts in the spring and heating fuel consumption in winter. The reduced

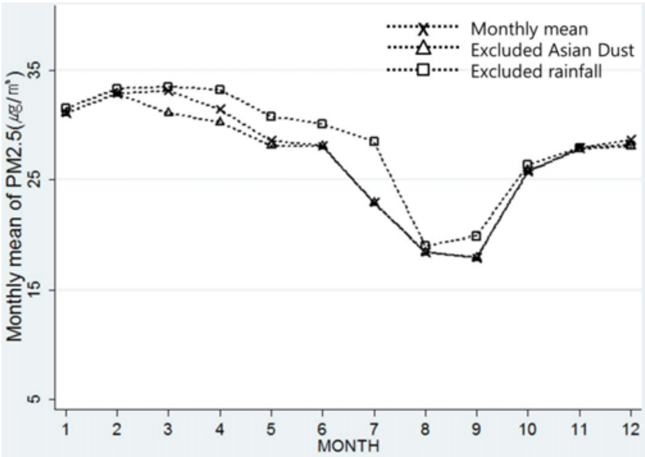

Fig. 6. Monthly average PM2.5 concentrations with and without Asian dust or rainfall in Seoul.

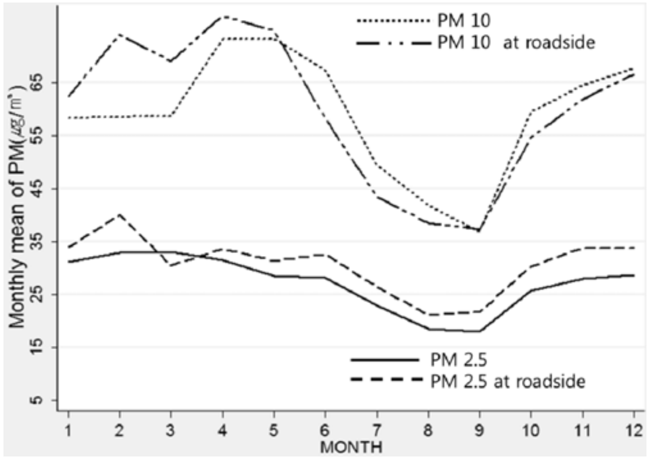

Fig. 7. Comparison of monthly average PM2.5 and PM10 concentrations between roadsides and monitoring posts.

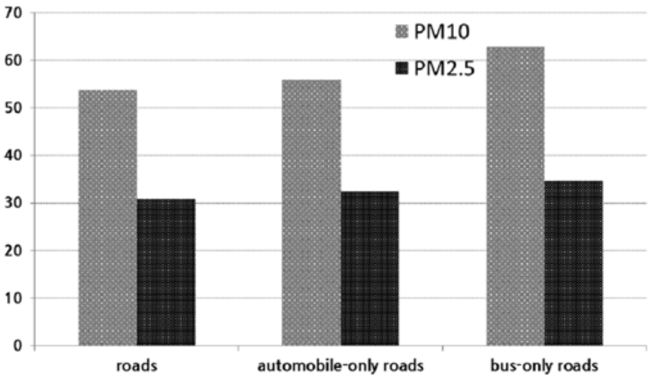

Fig. 8. PM10/PM2.5 concentrations by road type.

summer PM2.5 concentration was also contributed to by the cleansing effects of rainfall (Kim, 1999; Zhang *et al*., 2006; Tiwari *et al*., 2012).

(4) Analysis of monthly average PM2.5 fluctuation caused by rainfall and Asian dust

The results of the comparative analyses of monthly average and seasonal average PM2.5 concentrations, suggest that they were influenced by Asian Dust and rainfall. To verify this, monthly average PM2.5 measurements when Asian Dust was present were compared to those when it was absent, and likewise those when rainfall was present were compared to those when it was absent (Fig. 6).

Although monthly average PM2.5 concentrations when Asian Dust was absent, and when it was present, usually show a similar pattern, the concentration was reduced in the February-April section. However, when conducting t-tests with average values of days with Asian Dust (reflecting the influence of Asian Dust) against those without Asian Dust (excluding the influence of Asian Dust, i.e., controlled data), the p-value of the t-test was 0.0755, meaning that it is difficult to determine whether there is any significant difference. That is, although PM2.5 concentrations appeared to increase in days with Asian Dust, it was difficult to find a statistically significant difference in the measured average when the days of Asian Dust were excluded. Thus, the background PM2.5 emitted within Seoul itself dominated any contributions made by Asian Dust.

On the other hand, the plot of monthly average PM2.5 concentration excluding rainy days, was generally higher than the monthly average including rainy days. That is, it seemed that PM2.5 concentration was reduced on rainy days due to a cleansing effect. When statistically comparing the data set including the rainy days (reflecting the influence of rainfall) with the data set excluding rainy days (excluding the influence of rainfall, i.e., the control) the p-value of the t-test was 0.0171, so the difference was significant. This confirms that when rainfall occurs, PM2.5 concentration is reduced due to a cleansing effect.

(5) Analysis of monthly average PM2.5 change according to artificial influence

Seoul City also controls for artificial impacts to air pollution (e.g., vehicle emissions) by measuring the concentrations of air pollutants at the roadside. The roadside data also includes PM2.5 and PM10 concentrations, and their roadside monthly averages were also analyzed (Fig. 7).

PM10 concentrations at the monitoring posts were lower than those at the roadsides from January-May, but for the rest of the year, concentrations at the roadsides were lower than those at the monitoring posts. Thus, it was difficult to see that there was any overall difference between the concentrations at the two locations. A t-test yielded a p-value of 0.7110, showing that there is no significant difference in PM10 concentration between the roadsides and the monitoring posts and thus that vehicles did not significantly affect PM10 concentrations.

On the other hand, PM2.5 concentrations at the roadsides were higher throughout the year except for March. The t-test for differences in monthly average PM2.5 concentrations between the roadsides and the monitoring posts yielded a p-value

Table 1. Correlations between PM2.5 and other air pollutants.

	PM2.5	PM10	SO2	NO2	O3	CO
PM2.5	1.0000					
PM10	0.8386*	1.0000				
	0.0000					
SO2	0.6499*	0.5045*	1.0000			
	0.0000	0.0000				
NO2	0.6419*	0.4603*	0.6813*	1.0000		
	0.0000	0.0000	0.0000			
O3	−0.0394	0.0014	−0.2930*	−0.3756*	1.0000	
	0.0569	0.9642	0.0000	0.0000		
CO	0.6897*	0.5102*	0.7732*	0.8262*	−0.4910*	1.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	

Note: In the tables of this paper, the upper rows show correlation coefficients, and lower ones show p-values. $^*p < 0.05$

of 0.0004, indicating statistically significant difference. That is, PM2.5 concentrations at the roadsides were statistically higher than those at the monitoring posts, meaning that vehicles did cause an increase in PM2.5 concentration.

Seoul City also provides roadside air pollutant data measured by road type: general road, highway, and bus lane. Thus, it was possible to analyze whether there was any difference in PM2.5 concentration according to road type. We had already established that PM2.5 concentration was higher at the roadsides, confirming the influence of vehicles. Next, we analyzed the data broken down by road type to see if this influence was mediated by the types of vehicle using the respective road types.

Figure 8 shows the average concentrations of PM10 and PM2.5 on general roads, highways, and bus lanes. Bus lanes showed the highest concentrations of both PM10 and PM2.5 and ANOVA was used to check whether this difference was statistically significant. The p-value of the F-test was 0.3928, showing that there was in fact no significant difference. In other words, PM2.5 concentrations in the bus lanes were not meaningfully higher than those in other road types. In fact previous studies have shown that PM2.5 concentration generally increases in proportion to the number of vehicles rather than differences in vehicle or fuel type (Querol *et al*., 2004a; Charron and Harrison 2005).

b. Correlation analysis

(1) PM2.5 and other air pollutants

When analyzing correlations between concentrations of

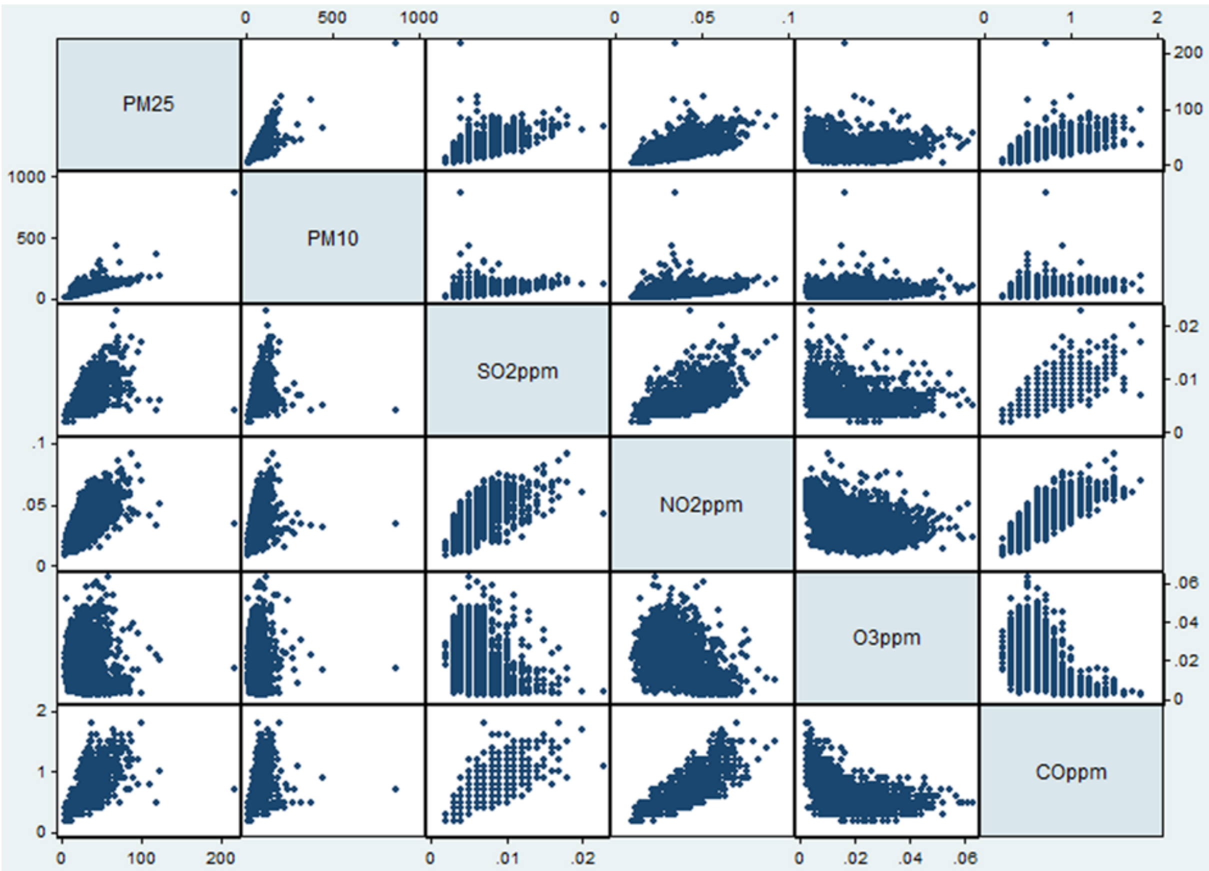

Fig. 9. Scatter diagrams showing correlations between air pollutant concentrations.

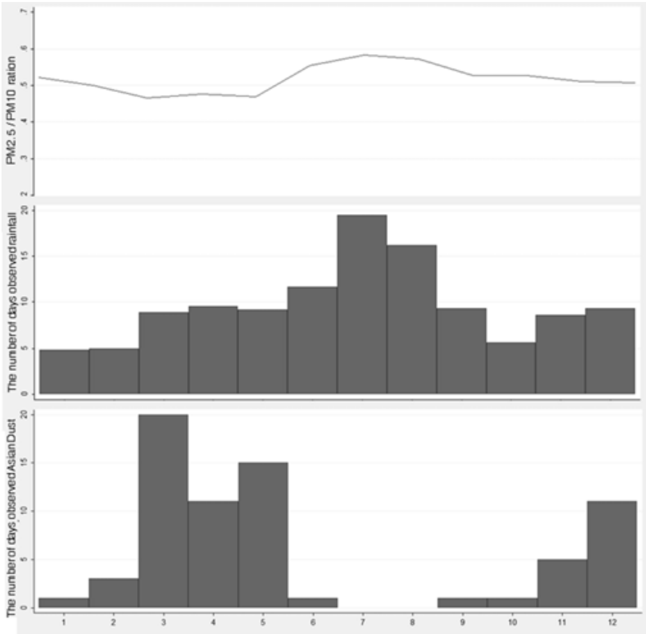

Fig. 10. Monthly average PM2.5/PM10 ratio.

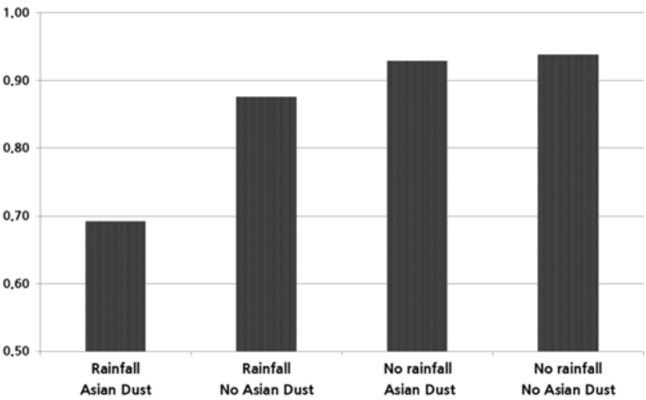

Fig. 11. Change in the correlation of PM2.5 and PM10 due to meteorological factors.

PM2.5 and other air pollutants, specifically PM10, SO_2, NO_2, O_3, and CO, it was confirmed that PM2.5 showed correlations with all the air pollutants studied except O_3 (Table 1).

In particular, PM2.5 showed a strong correlation with PM10, with a correlation coefficient of 0.8386, corroborating previous research (Marcazzan *et al*., 2001; Querol *et al*., 2004b; Wang *et al*., 2006). The highest correlation coefficient between the two pollutants, 0.94, appeared when the occurrence of Asian Dust and rainfall was controlled for. Thus, it could be conjectured that the correlation between PM2.5 and PM10 is affected by the occurrence of Asian Dust and rainfall (Fig. 9)[a)].

Average monthly values of PM2.5/PM10 ratios, frequently used as an indicator of the relations between PM2.5 and PM10, were calculated. The uppermost diagram of Fig. 10 shows the fluctuation of the monthly average PM2.5/PM10 ratio, while the middle one shows the average number of rainy days per month. These two diagrams show a similar pattern. That is, the PM2.5/PM10 ratio was relatively high from June to August, when there were many rainy days. It shows that the cleansing effects of rainfall reduced PM2.5 concentration much less than PM10 concentration. One explanation may be that the larger size of PM10 particles increases their surface area and hence their contact with raindrops which causes more elimination of PM10 particles than PM2.5 particles (Misaki *et al*., 1977; Cotton, 1995; Chaloulakou *et al*., 2005).

Table 2. T-test result of monthly average difference in the PM2.5/PM10 ratio caused by rainfall and Asian dust.

	PM2.5/PM10 Ratio	T-test (95% level)
Rainfall	0.5432235	Significant
No rainfall	0.500093	
Asian Dust	0.3228693	Significant
No Asian Dust	0.5194793	

On the other hand, the lower diagram shows the number of days with Asian Dust. This shows an inverse correlation with average monthly PM2.5/PM10 ratios. That is, during the period from March to May, in which Asian Dust occurs more frequently, the PM2.5/PM10 ratio tended to decrease, suggesting a larger influx of PM10 particles than PM2.5 particles.

The graph (Fig. 11) shows differences in the relations between PM2.5 and PM10 owing to the occurrence of Asian Dust and rainfall. To verify these differences statistically, a t-test is conducted to check for significant difference in the PM2.5/PM10 ratios (Table 2). The result shows that both rainfall and Asian Dust generated significant differences in PM2.5/PM10 ratios (p-value = 0.0000 in every case). The PM2.5/PM10 ratio of rainy days tended to be larger than those without rain, which means that PM10 particles are more easily removed by rain than PM2.5 particles. On the other hand, on a day with Asian Dust, the PM2.5/PM10 ratio reduced considerably, which means that the influx of PM10 particles due to Asian Dust is much larger than that of PM2.5 particles (Chun *et al*., 2001; Kim *et al*., 2010).

(2) PM2.5 and meteorological factors

The concentration of an air pollutant released into the air owing to diverse factors is affected by various meteorological phenomena, which diffuse and spread the pollutant. Some of these effects were analyzed by checking for correlations between air pollutants and meteorological phenomena. After reviewing preceding research, the following four meteorological factors were selected: precipitation, wind speed, tem-

[a)]Although the impact of Asian Dust on monthly average PM2.5 concentration, appeared to be statistically insignificant in the above analysis, PM10 may be affected by Asian Dust, in turn affecting the PM2.5/PM10 ratio. Thus, it is necessary to check whether there is any influence of Asian Dust on the correlation between PM2.5 and PM10.

Table 3. Correlations between meteorological factors.

	Precipitation	Temperature	Wind speed	Humidity
Precipitation	1.0000			
Temperature	0.2408* 0.0000	1.0000		
Wind speed	0.0446 0.2246	−0.1530* 0.0000	1.0000	
Humidity	0.4520* 0.0000	0.4214* 0.0000	−0.1036* 0.0047	1.0000

*$p < 0.05$

Table 4. Correlations between meteorological factors and air pollutants.

	PM2.5	PM10
Precipitation	−0.2344* 0.0000	−0.2376* 0.0000
Temperature	−0.0242 0.3406	0.4214* 0.0000
Wind speed	−0.3098* 0.0000	−0.1964* 0.0000

*$p < 0.05$

perature, and relative humidity. Before analyzing correlations between air pollutants and the meteorological factors, it was necessary to review the correlations between the meteorological factors themselves. For example, if there is a correlation between precipitation and wind speed, then it is necessary to control for the impact of wind speed when analyzing the correlation between precipitation and PM2.5. However, when analyzing the correlations between the meteorological factors, no correlation had correlation coefficients of ± 0.5 or more. Therefore, when calculating meteorological correlations with air pollutants, it was determined unnecessary to control for other meteorological factors (Table 3).

Precipitation's correlation with PM2.5 and PM10 was analyzed first. For the analysis, only the rainy days were selected. Precipitation showed negative correlations with both PM2.5 and PM10, but as both correlation coefficients were less than 0.5 in magnitude, it was difficult to determine whether they were statistically meaningful (Table 4). Above however, the decrease of PM2.5 with rainfall was confirmed statistically, but the analysis was limited to only addressing the occurrence of rainfall, and not its degree. On the other hand, the correlation coefficient between precipitation and PM2.5 concentration was −0.23, which showed that there was no correlation. Thus, it is considered that even if the precipitation increases, PM2.5 would not continue to decrease.

When calculating correlations between temperature or wind speed and PM2.5/PM10, days of rainfall and Asian Dust were excluded. With temperature, as shown in Table 4, the correlation coefficient was also low at less than 0.5. In case of wind speed, both PM2.5 and PM10 showed negative directivities, but their correlation coefficients were also less than 0.5. Thus, it was confirmed that even when the wind speed increases, the

Table 5. Correlations between PM2.5, PM10 and heavy metal content.

	PM2.5	PM10	Pb	Cd	Cr	Cu	Mn	Fe	Ni
PM2.5	1.0000								
PM10	0.7225* 0.0000	1.0000							
Pb	0.2189 0.0708	0.4731* 0.0000	1.0000						
Cd	0.2447 0.0427	0.2797* 0.0199	0.5832* 0.0000	1.0000					
Cr	0.1708 0.1607	0.4793* 0.0000	0.3857* 0.0011	0.2932* 0.0145	1.0000				
Cu	−0.1154 0.3452	0.2221 0.0666	0.1198 0.3268	−0.0123 0.9129	0.3382* 0.0045	1.0000			
Mn	0.2939* 0.0142	0.5684* 0.0000	0.7656* 0.0000	0.5900* 0.0000	0.5430* 0.0000	0.0565 0.6448	1.0000		
Fe	0.2879* 0.0164	0.6185* 0.0000	0.6930* 0.0000	0.5122* 0.0000	0.5561* 0.0000	0.1384 0.2569	0.9098* 0.0000	1.0000	
Ni	−0.0070 0.9547	0.1664 0.1717	0.2285 0.0590	0.2202 0.0691	0.3633* 0.0022	0.0243 0.8430	0.3394* 0.0043	0.3693* 0.0018	1.0000

*$p < 0.05$

Table 6. Correlations between seasonal PM2.5, PM10 and heavy metal content.

	Spring		Summer		Autumn		Winter	
	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10
Pb	0.4265	0.0352	0.4234	0.284	0.0149	0.4082	−0.3954	0.305
	0.0878	0.8934	0.08	0.2533	0.9533	0.0927	0.1295	0.2506
Cd	0.5185*	0.07	0.1422	0.1255	0.1452	0.0823	−0.2031	0.052
	0.033	0.7895	0.5735	0.6197	0.5654	0.7455	0.4506	0.8483
Cr	0.067	0.3464	0.3486	0.3736	0.0357	0.2167	−0.2973	0.3406
	0.7983	0.1732	0.1562	0.1268	0.888	0.3876	0.2635	0.1968
Cu	0.4525	0.6411*	0.0459	0.4041	−0.4062	0.0477	−0.2569	0.161
	0.0682	0.0056	0.8565	0.0963	0.0944	0.8508	0.3367	0.5513
Mn	0.2926	0.0138	0.493*	0.4674	0.1996	0.381	−0.4106	0.318
	0.2545	0.9581	0.0376	0.0505	0.4271	0.1187	0.1142	0.2301
Fe	0.3401	0.138	0.5787*	0.5638*	0.2655	0.5914*	−0.4024	0.2791
	0.1816	0.5972	0.0119	0.0148	0.2869	0.0097	0.1223	0.2951
Ni	−0.21	−0.1779	0.0282	−0.0959	−0.0636	0.1022	−0.3928	0.1947
	0.4185	0.4945	0.9116	0.7051	0.8022	0.6866	0.1323	0.47

*$p < 0.05$

concentrations of either PM2.5 or PM10 would not decrease significantly. Coinciding with this study, Marcazzan *et al.* (2001) showed that among meteorological factors including temperature, relative humidity, and wind speed, only wind speed showed a slightly higher correlation coefficient.

(3) PM2.5 and heavy metals

Seoul City also provides monthly heavy metal content data. Using the data, we conducted correlation analyses between PM2.5/PM10 concentrations and heavy metal content, and it was possible to check indirectly the inclusion and level of heavy metal particles in PM2.5.

As shown in Table 5 while no heavy metal content showed a strong correlation with PM2.5, manganese (Mn) and iron (Fe) showed relatively high correlations with PM10. Therefore, it could be conjectured that the heavy metal particles tend to larger than PM2.5 particles, and so they constitute a smaller proportion of PM2.5 than PM10. However, this is a tentative hypothesis requiring further verification.

The availability of heavy metal content data on only a monthly basis limited the possibilities for controlling for occurrences such as rainfall affecting PM2.5 or Asian Dust affecting PM10. More finely-grained data, such as daily data might produce completely different results. However, in this study correlations of PM2.5/PM10 and heavy metal content were analyzed on a seasonal basis, controlling for the occurrence of rainfall and Asian Dust indirectly (Table 6).

PM2.5 concentration had a correlation coefficient of 0.52 with cadmium (Cd) in spring and a correlation coefficient of 0.58 with Fe in summer. PM10 concentration showed relatively strong correlation with copper (Cu) in the spring (correlation coefficient = 0.64), some correlation with Fe in summer (correlation coefficient = 0.56), and a relatively high correlation with Fe in autumn (correlation coefficient = 0.59).

In summer, both PM2.5 and PM10 correlated highly positively with Fe, but in winter, both PM2.5 and PM10 showed no significant correlation. Likewise, seasonal correlation analyses, controlling for rainfall and Asian Dust indirectly, showed significant correlations of some heavy metals. However, as before, further more detailed analysis made possible by more granular data such as daily averages is desirable.

4. Conclusions

Based on daily average PM2.5 concentration data measured by Seoul City from November 2005 to March 2012, this study analyzed average changes of concentration on a daily, monthly, seasonal and annual basis, and also analyzed correlations with other air pollutants including PM10, SO_2, NO_2, O_3, and CO, and meteorological factors such as precipitation, wind speed, and temperature.

The annual average concentration of PM2.5 was 27 $\mu g\ m^{-3}$, which was three times the WHO standard of 10 $\mu g\ m^{-3}$ and two times the USA standard of 15 $\mu g\ m^{-3}$ so the quantity of fine particles inhaled into a human body would be considerable. In 2014, Korea will enact a limit on annual average PM2.5 concentration of 25 $\mu g\ m^{-3}$, but that target would have been met sufficiently even in 2012, so it should be tightened in line with the standards of WHO and the USA.

For the daily average concentration of PM2.5, 215 and 54 days per year exceeded the WHO (25 $\mu g\ m^{-3}$) and USA (54 $\mu g\ m^{-3}$) standards respectively. This contrasts the Korean standard (50 $\mu g\ m^{-3}$) to be enacted in 2015, which is only exceeded on three days of the year. Therefore, like the proposed annual standard, the daily standard should be tightened.

The occurrence of Asian Dust did not significantly affect PM2.5 concentration, though it did impact the PM2.5/PM10 ratio suggesting that Asian Dust increased PM10 rather than PM2.5 concentration.

Although rainfall exerted a significant impact on PM2.5 concentration, the correlation coefficient between precipitation and PM2.5 concentration was only −0.23. Thus, there was no suggestion of a sustained decrease in PM2.5 concentration at higher levels of precipitation.

The increased PM2.5 concentration at the roadside was highly statistically significant, so vehicle operation increased PM2.5 concentration. However there was no significant difference between the PM2.5 concentrations of different road types, namely general roads, highways, or bus lanes.

The result of the correlation analysis showed that PM2.5 had high correlations with PM10 ($r = 0.84$), and with the gaseous pollutants, SO_2, NO_2, and CO, but not O_3. On the other hand, the correlations between PM2.5 and either meteorological factors or heavy metal content was not high. However, as PM10 did show correlations with Fe and Mn, it could be interpreted that these heavy metal particles were larger than PM2.5 particles.

This study was conducted by analyzing the characteristics of PM2.5 concentration using its daily average concentration data for six years and five months across the entire Seoul area. In this regard, this study is differentiated from preceding research which had limited study areas or restricted durations of three months to one year. However, this study also has some limitations including that it couldn't control rainfall and Asian dust for analyzing PM2.5 characteristics at the roadside and PM2.5's heavy metal concentration because PM2.5 concentration data at the roadside and its heavy metal concentration data are available only for monthly data. In spite of such limitations, by analyzing the current status and characteristics of PM2.5 particles, this study meaningfully contributes to a wider discussion about the inclusion of PM2.5 in the domestic air pollution control standards and the necessity of stronger standards for PM2.5 concentration.

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