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RESEARCH ARTICLE

Meteorological Factors Associated with Elevated Levels of Daily $PM_{2.5}$ Concentrations in Seoul, South Korea, in 2019

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ABSTRACT: Studies have revealed the adverse health impact of particulate matter 2.5 ($PM_{2.5}$). Elevated $PM_{2.5}$ levels are often observed in cities with abundant sources of emissions of pollutants. In addition to emissions, $PM_{2.5}$ concentrations can vary with meteorological conditions. This study aimed to identify meteorological variables associated with high levels of $PM_{2.5}$ in Seoul, South Korea. An analysis was conducted using data associated with daily meteorological variables in Seoul from 2019, downloaded from the Korea Meteorological Administration (KMA) and Air Korea webpages. These variables included daily precipitation duration and amount, maximum and average wind speed, dominant and prevailing wind direction, relative humidity, vapor pressure, and temperature. The relationship between these variables and $PM_{2.5}$ concentrations was analyzed using two datasets: one containing data from the entire year of 2019 and the other from January, February, and March when $PM_{2.5}$ levels were relatively high. Daily average $PM_{2.5}$ concentrations were categorized into two groups: acceptable ($PM_{2.5} \le 25$ μg/m³) and poor ($PM_{2.5} > 25$ μg/m³) air quality. When analyzing data from the entire year, it was observed that the median $PM_{2.5}$ concentration was statistically higher when westerly winds were observed [Probability value (P-value) <0.001]. By contrast, the three-month sub-analysis did not show any statistically significant differences in median $PM_{2.5}$ levels between westerly and non-westerly winds (P =0.390 for dominant wind direction, P =0.846 for prevailing wind direction). Although average wind speed, vapor pressure, and a prevailing westerly wind direction showed a significant correlation with $PM_{2.5}$ levels in data for the whole year, interpretations of the link between these meteorological variables and high levels of $PM_{2.5}$ were limited, partly due to seasonal variation. Further sub-analysis of the three-month dataset, corresponding with winter and early spring, showed that maximum wind speed and vapor pressure are significant factors associated with poor air quality. The results of this study can be used to predict $PM_{2.5}$ levels in Seoul, South Korea.

KEYWORDS: Earth and Environmental Sciences; Atmosphere Science; $PM_{2.5}$; Meteorological Conditions; Air Quality.

Introduction

Elevated levels of particulate matter (PM) degrade visibility and threaten public health.[1-3] Concentrations of PM are affected by various factors, including emissions of air pollutants, meteorological conditions, and wind-transported air pollution from foreign countries.[4,5] Recently, emissions in Seoul, South Korea, have slowly decreased; thus, polluted air from foreign sources has gained increasing attention.[6-8] Investigators have asserted that air pollutants are transported from China by westerly winds, particularly during winter and early spring, resulting in frequent and severe haze episodes in western South Korea and other East Asian countries.[9,10] Previous studies have analyzed ground-level PM concentrations using satellite-based data,[11] satellite observations, and process-based models,[12] and conducted simulations using a regional air quality modeling system.[1] A large number of studies recently investigated the impact of meteorological conditions such as surface temperature, pressure, humidity, and wind speed on PM variability.[1,13] Among different PMs, $PM_{2.5}$ is known to be especially harmful to the human body; because of its smaller size compared to PM_{10}, it can infiltrate the lungs and bloodstream when breathing.[14] Therefore, this study aimed to investigate the meteorological factors related to high levels of $PM_{2.5}$ in Seoul.

Methods

Daily meteorological and air pollution data in Seoul from 2019 were downloaded from the Korea Meteorological Administration (KMA) (https://data.kma.go.kr) and Air Korea webpages (https://www.airkorea.or.kr).[15,16] The variables analyzed included daily precipitation duration and amount, maximum and average wind speed, dominant and prevailing wind direction, relative humidity, vapor pressure, and temperature. Dominant wind direction was defined as the direction of the wind with the highest speed over a particular point, and prevailing wind direction was defined as the direction that the wind blows most often in a location. Wind direction was categorized into eight directions: north, northeast, east, southeast, south, southwest, west, and northwest. The daily average $PM_{2.5}$ concentration in Seoul was categorized into two groups: acceptable air quality ($PM_{2.5} \le 25$ μg/m3) and poor air quality ($PM_{2.5} > 25$ μg/m³). The threshold of 25 μg/m³ was selected instead of 35 μg/m³, which is the daily air quality standard for $PM_{2.5}$ in Korea because exposure to $PM_{2.5} > 25$ μg/m3 is known to be harmful to sensitive groups, including people with heart or lung disease, older adults, children, and teenagers.[17]

The statistical analysis was conducted using two datasets: one containing the annual data for 2019 and the other

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comprising data for January, February, and March, when relatively high levels of $PM_{2.5}$ were observed. The three-month sub-analysis was performed to minimize the effects of seasonal variations in data. Levels of $PM_{2.5}$ were analyzed in relation to eight dominant and prevailing wind directions using a Kruskal-Wallis test, which is used to find the difference between medians of three or more groups.[18] *Post-hoc* analysis was performed for multiple comparisons using the Dunnett C test, often used to compare one group with others.[19] Furthermore, the difference in $PM_{2.5}$ levels was compared between the westerly and non-westerly dominant and prevailing wind directions to specifically investigate the effect of westerly winds on $PM_{2.5}$ levels using Wilcoxon rank-sum test.

Univariate and multivariate analyses were performed to identify the meteorological factors associated with high levels of air pollution in Seoul. Meteorological variables were compared between the acceptable and poor air quality groups using Fisher's exact test for categorical variables and the Wilcoxon rank-sum test for continuous variables.[20,21] Variables with probability values (P-values)< 0.1 obtained through univariate analysis were selected to perform the multivariate logistic regression analysis,[22] for which a forward stepwise selection mode was used; this mode allowed an iterative entry of variables based on test score P-values< 0.05 and achieved the removal of variables with a probability of 0.10. All statistical analyses were performed using the SPSS version 23.0 software (IBM Corp., Armonk, NY, USA). Statistical significance was set at P< 0.05.

Results and Discussion

The monthly average $PM_{2.5}$ and PM_{10} concentrations showed an apparent seasonal variation in particle levels. Particle concentrations were relatively high in winter and early spring (January, February, and March) (Figure 1). Thus, additional analyses were conducted for the three-month period.

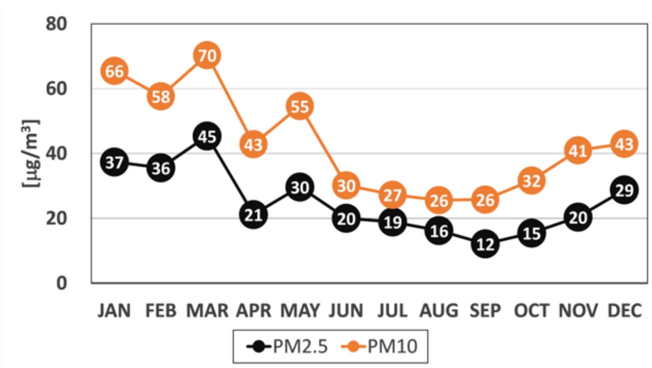

Figure 1: Monthly average $PM_{2.5}$ concentrations in Seoul, Korea, in 2019. Particle concentrations were relatively high in winter and early spring (January, February, and March).

Differences in $PM_{2.5}$ Levels between Wind Directions:

The median $PM_{2.5}$ concentrations of the eight wind directions were compared (Table 1). The Kruskal-Wallis test showed that $PM_{2.5}$ levels varied significantly between different dominant wind directions (P< 0.001). Multiple further post hoc comparisons were made using the Dunnett C test. The results showed that the differences were particularly significant between northerly and southerly, northerly and northwesterly, and easterly and westerly winds (P< 0.05). An identical analysis was conducted for the difference in $PM_{2.5}$ levels between prevailing wind directions using the Kruskal-Wallis test, the results of which also showed that $PM_{2.5}$ levels vary significantly between different prevailing wind directions (P< 0.001). Dunnett's *post hoc* multiple comparisons showed that the difference in $PM_{2.5}$ was significant between northerly and westerly winds as well as southeasterly and westerly winds
(P< 0.001).

Table 1: Median $PM_{2.5}$ levels in relation to wind direction in 2019. Westerly winds were observed most frequently and associated with higher $PM_{2.5}$.

Wind direction	Dominant wind direction		Prevailing wind direction	
	No.	$PM_{2.5}$ [μg/m³] [Median (25th, 75th)]	No.	$PM_{2.5}$ [μg/m³] [Median (25th, 75th)]
N	37	14.0 (6.6, 19.6)	47	12.8 (7.2, 21.5)
NE	4	34.2 (28.6, 37.4)	35	19.7 (15.9, 27.0)
E	41	18.7 (10.8, 25.0)	46	19.5 (11.5, 27.4)
SE	5	22.6 (13.53, 24.0)	2	13.9 (13.7, 14.2)
S	49	20.3 (16.1, 28.0)	21	20.4 (13.7, 25.2)
SW	17	20.4 (12.9, 25.2)	18	17.6 (12.0, 26.1)
W	161	23.4 (16.9, 35.5)	180	23.4 (17.5, 34.1)
NW	51	21.1 (16.2, 31.0)	16	21.0 (15.1, 25.9)

Among the eight wind types, westerly winds were observed most frequently (Table 1), during which $PM_{2.5}$ levels were relatively high. Thus, further analysis was conducted to compare the differences in $PM_{2.5}$ levels between westerly and non-westerly winds. When analyzing the 2019 dataset, the median $PM_{2.5}$ level was significantly higher when westerly winds were observed (P< 0.001) (Table 2). However, when analyzing the January–March dataset, the difference in median $PM_{2.5}$ levels between wind directions was not statistically significant (P= 0.390 for dominant wind direction, P= 0.846 for prevailing wind direction). The results indicated that in addition to meteorological variables, other variables could affect $PM_{2.5}$ levels in Seoul.[4,5] Given that emissions emitted from South Korea or those transported from other countries would affect the air quality; those data should have been included in variables to reach a solid conclusion. Unfortunately, this issue may be beyond the scope of this study because the data were not accessible from any online site in this study. One thing to point out is that temperature inversions would also affect the air quality in the winter season in Seoul. As cooler air is entrapped below the inversion layer where warmer air is located, air stagnation would be aggravated in the winter, resulting in horrible air pollution in Seoul, especially in the winter.

Table 2: The difference in $PM_{2.5}$ levels between westerly and non-westerly winds in 2019. $PM_{2.5}$ levels were higher in the westerly wind than non-westerly wind in the entire 2019 year, whereas they were not when sub-analyzed in the winter and early spring.

Overall (365 days in 2019)	West		Non-west		P-value
	No.	PM2.5 [μg/m³] [Median (25th, 75th)]	No.	PM2.5 [μg/m³] [Median (25th, 75th)]	
Dominant wind direction	161	23.4 (16.9, 35.5)	204	19.4 (12.0, 26.2)	< 0.001
Prevailing wind direction	180	23.4 (17.5, 34.1)	185	18.7 (11.2, 25.7)	< 0.001
Winter and Early Spring (114 days in 2019)	**West**		**Non-west**		**P-value**
	No.	PM2.5 [μg/m³] [Median (25th, 75th)]		PM2.5 [μg/m³] [Median (25th, 75th)]	
Dominant wind direction	51	32.9 (23.0, 53.5)	39	31.8 (22.2, 39.5)	0.390
Prevailing wind direction	63	23.4 (22.9, 48.0)	27	34.4 (21.2, 47.3)	0.846

Meteorological Factors Associated with Poor Air Quality:

Because the prevailing wind direction in South Korea is westerly, particles originating from neighboring countries to the west, such as China, could influence ambient air pollution levels.[10] Furthermore, the relatively high $PM_{2.5}$ and PM_{10} levels observed in winter (Figure 1) could be attributed to increased air pollution due to burning fossil fuels for heating.[14,23]

The statistical difference between meteorological variables associated with $PM_{2.5}$> 25 μg/m³ and $PM_{2.5}$≤ 25 μg/m³ was investigated through univariate analysis using the 2019 dataset (Table 3). The Wilcoxon rank-sum test was used for precipitation duration and amount, maximum and average wind speed, average relative humidity, vapor pressure, and temperature. Fisher's exact test was used to determine the dominant and prevailing wind directions. The test resulted in P-values< 0.1 for the precipitation amount, maximum wind speed, average wind speed, average vapor pressure, average temperature, dominant wind direction, and prevailing wind direction. Using variables with P-values< 0.1, a multiple logistic regression was subsequently conducted to identify factors linked to elevated $PM_{2.5}$ levels. This resulted in P-values< 0.05 for average wind speed, average vapor pressure, and prevailing wind direction. Lower wind speed, lower vapor pressure, and westerly prevailing wind direction were significantly associated with elevated $PM_{2.5}$ levels.

Table 3: Univariate and multivariate analysis of meteorological factors affecting air quality in 2019. Average wind speed, average vapor pressure, and prevailing wind direction were independent factors associated with poor air quality in the entire 2019 year.

	$PM_{2.5}$ ≤25 μg/m³ (n=238)	$PM_{2.5}$ >25 μg/m³ (n=127)	P-value	Multiple logistic regression		
				P-value	Odds ratio	95% CI
Precip. duration (hr)	0.0 (0.0, 2.8) 2.5 ± 4.7*	0.0 (0, 1.25) 1.5 ± 3.5*	0.156¹			
Precipitation (mm)	0.0 (0.0, 0.6) 3.3 ± 9.8*	0.0 (0.0, 0.0) 0.8 ± 2.6*	0.053¹			
Max. wind speed (m/s)	4.3 (3.6, 4.9)	4.1 (3.5, 4.7)	0.062¹			
Avg. wind speed (m/s)	1.9 (1.6, 2.4)	1.7 (1.4, 2.1)	< 0.001¹	**<0.001**	0.33	(0.20, 0.53)
Avg. relative humidity (%)	57.5 (45, 67)	56.1 (46, 66)	0.618¹			
Avg. vapor press. (hPa)	10.9 (4.7, 19)	5.9 (4.0, 11)	< 0.001¹	**<0.001**	0.92	(0.89, 0.96)
Avg. temperature (°C)	17.5 (7.3, 24)	7.8 (2.7, 20)	< 0.001¹			
Dominant wind direction			0.006²			
Non-west	146 (61.3%)	58 (45.7%)				
West	92 (38.7%)	69 (54.3%)				
Prevailing wind direction			0.002²	**0.017**	1.80	(1.11, 2.92)
Non-west	135 (56.7%)	50 (39.4%)				
West	103 (43.3%)	77(60.6%)				

Note-Data are presented as median (interquartile range) for continuous variables and number (percentage) for categorical variables. *indicates mean ± standard deviations. ¹ P-value based on Wilcoxon rank-sum test;² P-value based on Fisher's exact test

To identify the meteorological factors affecting $PM_{2.5}$levels, it is desirable to analyze data from one season or similar climatic conditions. Thus, an identical analysis to that described above was conducted using data from the January–March period (Table 4). The Wilcoxon rank-sum test and Fisher's exact test statistics showed that the P-values for precipitation, maximum wind speed, average wind speed, relative humidity, vapor pressure, and temperature were less than 0.1. A multiple logistic regression was subsequently conducted using variables with a P-value< 0.1. This resulted in P-values< 0.05 for maximum wind speed and vapor pressure.

Table 4: Univariate and multivariate analysis of meteorological factors affecting air quality between January and March 2019. Maximum wind speed and vapor pressure were independent factors associated with poor air quality.

	$PM_{2.5}$ ≤25 μg/m³ (n=32)	$PM_{2.5}$ >25 μg/m³ (n=58)	P-value	Multiple logistic regression		
				P-value	Odds ratio	95% CI
Precip. duration (hr)	0.0 (0.0, 0.6) 1.0 ± 2.7*	0.0 (0.0, 0.5) 1.5 ± 3.8*	0.996¹			
Precipitation (mm)	0.0 (0.0, 0.0) 0.1 ± 0.4*	0.0 (0.0, 0.0) 0.8 ± 3.1*	0.477¹			
Max. wind speed (m/s)	4.7 (3.6, 5.8)	4.2 (3.2, 5.2)	0.064¹	**0.015**	0.49	(0.28, 0.87)
Avg. wind speed (m/s)	2.1 (1.7, 2.5)	1.7 (1.3, 2.1)	0.009¹			
Avg. relative humidity (%)	39.6 (32, 46)	51.6 (41, 60)	< 0.001¹			
Avg. vapor press. (hPa)	2.1 (1.6, 3.3)	4.1 (3.2, 5.2)	< 0.001¹	**<0.001**	2.81	(1.74, 4.55)
Avg. temperature (°C)	-1.5(-3.5, 3.3)	4.0 (1.3, 7.1)	< 0.001¹			
Dominant wind direction						
Non-west	13 (40.6%)	26 (44.8%)	0.871²			
West	19 (59.4%)	32 (55.2%)				
Prevailing wind direction						
Non-west	8 (25.0%)	19 (32.8%)	0.597²			
West	24 (75.0%)	39 (67.2%)				

Note-Data are presented as median (interquartile range) for continuous variables and number (percentage) for categorical variables. *indicates mean ± standard deviations. ¹ P-value based on Wilcoxon rank-sum test;² P-value based on Fisher's exact test

The results of the above test indicated that maximum wind speed was one of the crucial factors affecting the elevated $PM_{2.5}$ levels. The maximum wind speed was slower on days with relatively high $PM_{2.5}$ levels. This result is closely related to that of a previous study, in which severe air pollution episodes were often observed alongside stagnant air conditions.[24] This phenomenon is exacerbated in winter when the low planetary boundary layer inhibits air pollution dispersion.[1,25] The Wilcoxon rank-sum test showed that temperature is also related to PM levels (P< 0.001). High-pressure systems in Siberia often result in cold surges, which rapidly decrease temperature and blow PM away. Elevated $PM_{2.5}$ levels are also correlated with high vapor pressure, which tends to increase with temperature. However, despite this correlation, the temperature was not a statistically significant variable in the multiple logistic regression (Table 4).

Nevertheless, this research has several limitations. Firstly, this study focused on meteorological data to evaluate factors linked with $PM_{2.5}$ without considering emissions from South Korea or those transported from other countries. Secondly, the link between $PM_{2.5}$ levels and meteorological variables could not be supported scientifically with statistical significance. For example, although wind direction was not among the statistically significant variables, it should have been included, given the significant emissions originating west of South Korea. To overcome these limitations, emissions of air pollutants and meteorological variables in both South Korea and surrounding countries should be analyzed together in the future. Trajectory or factor analysis (e.g., positive matrix factorization, chemical mass balance, etc.) with a speciated particulate concentration should also be used to improve the accuracy of the analysis. In addition, data analysis, including many cumulative years, is needed to gather sufficient samples for future studies from January to March.

■ Conclusion

The relationship between meteorological variables (precipitation duration and amount, maximum and average wind speed, dominant and prevailing wind direction, relative humidity, vapor pressure, and temperature) and elevated $PM_{2.5}$ levels in Seoul were evaluated using an annual dataset for 2019 and a dataset for January, February, and March when $PM_{2.5}$ levels were relatively high. The analysis of the 2019 dataset revealed that the most common dominant wind direction was westerly and was associated with elevated $PM_{2.5}$ levels. In contrast, the three-month sub-analysis did not show any statistically significant differences in median $PM_{2.5}$ levels between westerly and non-westerly winds. The multiple logistic regression conducted during the January–March dataset analysis demonstrated that maximum wind speed and vapor pressure were significant independent predictors of elevated $PM_{2.5}$ levels.

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