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Seasonal Variations of Fine Particulate Matter and Mortality Rate in Seoul, Korea with a Focus on the Short-Term Impact of Meteorological Extremes on Human Health

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Abstract: Rapid industrialization of Korea's economy has brought with it environmental pollution that threatens human health. Among various other pollutants, ambient fine particulate matter known to endanger human health often exceeds air quality standards in Seoul, South Korea's capital. The goal of this research is to find the impact of meteorological extremes and particle levels on human health. The analysis was conducted using hourly air pollutant concentrations, meteorological variables, and the daily mortality from cerebrovascular disease. Results show that the effect of fine particulate matter on mortality from cerebrovascular disease was more noticeable during meteorological extremes. The linkage between extreme weather conditions and mortality was more apparent in winter than in summer. Comprehensive studies of various causes of diseases should be continued to more accurately analyze the effects of fine particulate matter on human health and meteorological extremes, and to further minimize the public health impact of air pollution and meteorological conditions.

Keywords: fine particulate matter; meteorological extremes; mortality; cerebrovascular disease

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1. Introduction

The indiscriminate use of fossil fuels has aggravated air pollution over the last century [1–3]. In addition, increased greenhouse gas emissions have caused global climate change [4]. Tremendous efforts have been exerted worldwide to solve widespread environmental problems, but air quality cannot be improved in a short time [5,6]. Seoul, the capital of South Korea, occupies less than 1% of the nation's area, but is home to a fifth of the country's population—about 10 million people. If the floating population is included, the number of people in Seoul may be much larger than that number. In any case, because of this large population, elevated levels of air pollution are often present in Seoul.

Among the various kinds of air pollutants, fine particulate matter has recently received special attention. Elevated levels of fine particulate matter can block sunlight and worsen visibility [7,8]. Because of the tiny size of fine particles such as PM_{10} and $PM_{2.5}$, they can be deposited in the alveoli at the very end of the respiratory tree. Because the main function of the alveoli is the exchange of oxygen and carbon dioxide molecules to and from the bloodstream, a direct effect on health is expected when these fine particles are inhaled [9,10]. Because they are even smaller than the thickness of the capillaries, these particles can penetrate blood vessels, blocking them and causing various vascular diseases including cerebrovascular disease [11–13].

Meteorological conditions such as cold surges or heat waves, in combination with air pollution can have a direct impact on human health. Zhang et al. found that in China the annual mortality from heat waves was between 18.7 and 61.3 deaths per million people [14]. Wang et al. noted that the projected mortality because of global warming would be 48.8–67.1 per million with warming of 1.5 °C and 59.2–81.3 per million with 2.0 °C warming [15]. Cold surges are also associated with increased mortality from cardiovascular and respiratory diseases [16]. The effect of heat waves on health lasted only a few days, but the health effects of cold surges occurred over several weeks [17–20]. In addition, meteorological conditions, such as atmospheric stability or the wind direction/speed, affect ambient pollutant levels through transportation. Moreover, temperature, through photochemical reactions, is a key factor in the formation of secondary pollutants.

Our goal in this research was to find the short-term impact of meteorological extremes such as heat waves and cold surges on seasonal variations of fine particulate matter and their consequences for human health [21]. Health impact was analyzed based on the mortality rate from cerebrovascular disease, which is known to have a direct linkage with air pollution [17,22,23]. The study was conducted using data collected from Seoul between 2008 and 2018. Our findings from this study can be used to establish air pollution control strategies to reduce the adverse public health impact of air pollution.

2. Materials and Methods

Hourly pollutant concentrations and meteorological variables were collected in Seoul between 2008 and 2018 [21,24]. Air pollutant concentrations (PM_{10}, $PM_{2.5}$, NO_2, O_3, SO_2, and CO) were collected from 25 monitoring stations distributed relatively evenly around Seoul (Figure 1). Meteorological variables collected in one monitor include temperature, precipitation, wind speed, and wind direction (Figure 1). To assure the reliability of the results, daily pollutant concentrations and meteorological variables were only calculated from the hourly data when 20 or more data out of 24 data per day were valid. Daily mortality was obtained from Statistics Korea [25]. Among various causes of deaths, daily mortality from cerebrovascular disease was analyzed to determine any linkage between air pollution and human health. Codes for cerebrovascular diseases were I60–I69 of the 10th revision of the International Statistical Classification of Diseases and Related Health Problems (ICD), a list of medical classification lists by the World Health Organization [26].

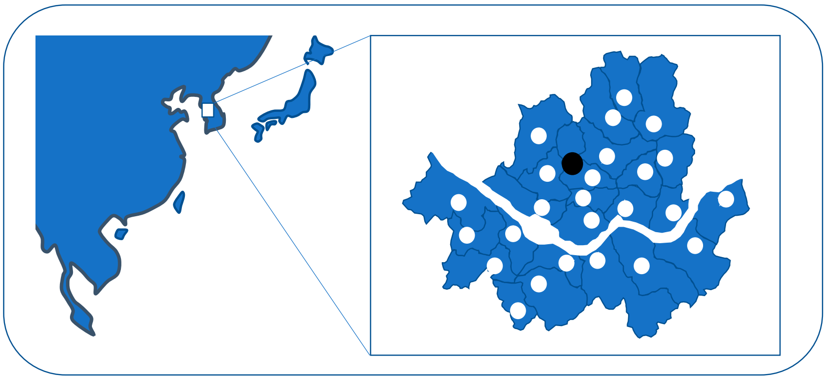


Figure 1. Location of 25 monitoring stations for air pollutant (○) and one station for meteorology (●) in Seoul, Korea.

The analysis was conducted by categorizing "H days (days of high probability of death)" and "L days (days of low probability of death)." H days and L days were based on the median number of death of persons aged 65 or older from cerebrovascular disease in Seoul between 2008 and 2018. We have focused on deaths aged 65 or older since the elderly or the weak were susceptible to elevated levels of air pollution or extreme meteorological conditions. We used eight as the median number instead of an average number because the mean was likelier to be affected by infrequent large values. Then, the monthly average pollutant levels and meteorological variables for H and L days were compared. Although elevated levels of air pollution and meteorological extreme events can directly increase the mortality rate, death may occur a few days after exposure to either cause. Thus, to investigate the lag time between the occurrence of elevated pollutant levels or meteorological extremes and subsequent deaths, pollutant levels and meteorological variables one and two days before the occurrence of death were also examined.

3. Results and Discussion

3.1. Meteorological Condition, Air Pollution, and Mortality Rate in Seoul, Korea

3.1.1. Status of Meteorological Conditions

Meteorological conditions were investigated through temperature, precipitation, wind speed, and wind direction in Seoul, Korea. Between 2008 and 2018, 101 heat-wave and 42 cold-surge days occurred (Table 1). A heat wave was classified as more than two days of maximum daily temperatures above 33 °C [21]. A cold surge in this work is when the daily minimum temperature is below −12 °C, or if the daily minimum temperature is below −3 °C and 10 °C lower than the daily minimum temperature of the previous day [21]. Heat waves occurred mostly in July and August with one in May and three in June. Cold surges occurred in January, February, and December.

Table 1. Occurrences of heat waves and cold surges in Seoul, Korea [21].

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Sum
						Heat Wave (Days)						
May	-	-	-	-	-	-	1	-	-	-	-	1
Jun	-	-	-	-	1	-	-	1	-	1	-	3
Jul	-	-	-	1	1	-	5	3	2	4	15	31
Aug	3	3	1	1	9	2	2	2	20	5	18	66
						Cold Surge (Days)						
Jan	-	-	6	3	-	3	-	-	5	-	6	23
Feb	-	-	-	-	2	3	1	1	1	-	1	9
Dec	1	-	4	-	3	-	1	-	-	-	1	10

To investigate the seasonal variations of extreme meteorological events, monthly average meteorological variables were plotted separately for heat waves, cold surges, and other days (Figure 2). Figure 2 does not contain the monthly average for meteorological variables in May for heat waves because only one heat wave was observed in that month. Average temperatures on cold-surge days were lower by as much as 8.4 °C, 8.7 °C, and 7.2 °C, respectively, than on other days in January, February, and December, respectively (Figure 2). Average temperatures on heat-wave days were higher by as much as 2.9 °C, 4.0 °C, and 4.4 °C, respectively, than on other days in June, July, and August.

Daily average precipitation was lower by as much as 0.34 mm, 0.76 mm, and 0.74 mm on cold-surge days, respectively, in January, February, and December than on other days (Figure 2). In addition, daily average precipitation on heat-wave days in June, July, and August was also lower than on other days by as much as 4.4 mm, 13.3 mm, and 8.9 mm, respectively. When precipitation occurs in summer, it often lowers the temperature because evaporation absorbs the latent heat. Conversely, winter precipitation, which includes snow as well as rain, sometimes increases temperature because it releases latent heat through the sublimation of the snow. Thus, precipitation was relatively lower on both cold-surge and heat-wave days than on other days.

Monthly average wind speed was higher by as much as 0.27 m/s, 0.92 m/s, and 1.1 m/s on cold-surge days, respectively, in January, February, and December than on other days (Figure 2). However, wind speed was lower by as much as 0.01 m/s, 0.61 m/s, and 0.48 m/s on heat-wave days, respectively, in June, July, and August (Figure 2).

The wind direction is represented using wind rose chart (Figure 2). The wind direction is divided into 16 directions in the chart. The length of each "spoke" of the wind rose in Figure 2 is proportional to the frequency that the wind blew from a particular direction. Each spoke is divided into colored bands to illustrate the ranges of wind speed. A wind speed less than 0.5 m/s is called a calm wind. The wind direction and speed of calm winds are not represented using a spoke. Instead, frequency of calm winds is designated inside a small circle in the center. Figure 2 shows that the percentage of calm wind is 3% in spring, and the westerly wind is prevalent. The wind direction during heat waves was similar to that on other days in summer, but the percentage of calm wind increased from 3% on other days during summer to 5% during heat waves. The major wind direction includes westerly and northeasterly in fall. The average wind direction in Seoul is westerly in winter, and strong northwesterly wind was particularly prevalent during cold surges (Figure 2).

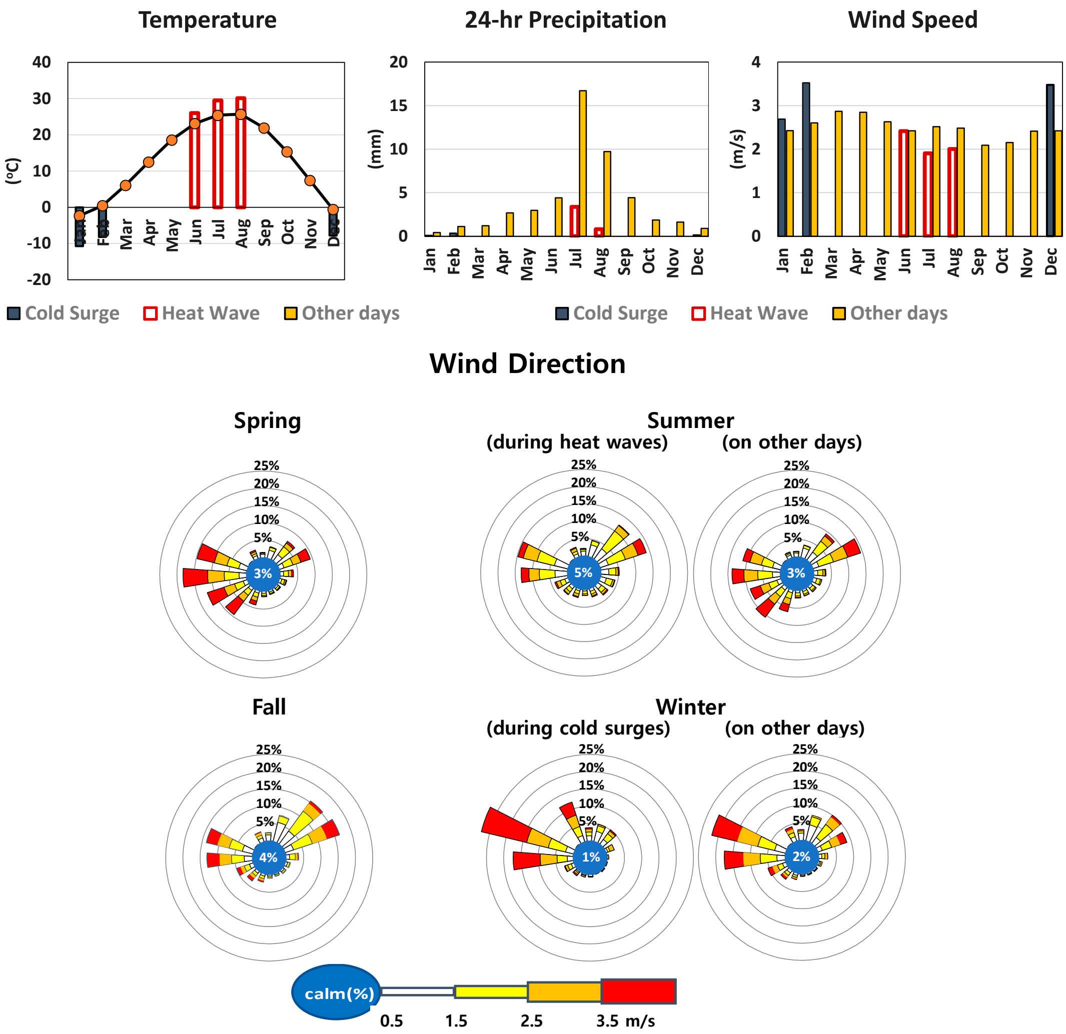


Figure 2. Monthly average temperature, precipitation, wind speed, and seasonal average wind direction.

3.1.2. Status of Air Quality

Among the various kinds of air pollutants, eight—sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_x), ozone (O_3), PM_{10}, $PM_{2.5}$, lead (Pb), and benzene (C_6H_6)—are classified as criteria pollutants in Korea. The air quality standards for lead and benzene are based on only the annual average concentrations; those of other pollutants are based on their 1-h, 8-h, or 24-h average values (Table 2).

Table 2. Air quality standard for criteria pollutants in Korea [24].

Averaging Time	PM_{10} ($\mu g{\cdot}m^{-3}$)	$PM_{2.5}$ ($\mu g{\cdot}m^{-3}$)	NO_2 (ppm)	O_3 (ppm)	SO_2 (ppm)	CO (ppm)	Pb ($\mu g{\cdot}m^{-3}$)	C_6H_6 ($\mu g{\cdot}m^{-3}$)
1 year	50	15	0.03	-	0.02	-	0.5	5
24 h	100	35	0.06	-	0.05	-	-	-
8 h	-	-	-	0.06	-	9	-	-
1 h	-	-	0.10	0.10	0.15	25	-	-

Monthly average concentrations and one standard deviation of criteria pollutants except Pb and C_6H_6, which have only annual air quality standards, were examined (Figure 3). Monthly average PM_{10} levels are relatively high in spring and have a distinct seasonal variation. The 24-h average PM_{10} concentration added by one standard deviation is higher than the air quality standard in February, indicating PM_{10} levels exceeded the standard. PM10 levels during cold surges or heat waves were compared with those on other days. Monthly average PM_{10} concentrations on days of cold surges were lower than those on other days in January, February, and December by as much as 18.2 µg/m^3, 12.6 µg/m^3, and 17.2 µg/m^3, respectively. Average PM_{10} levels on days during heat waves were higher in June and August than on other days by as much as 1.6 µg/m^3 and 3.5 µg/m^3, respectively, and lower in July than on other July days by as much as 1.0 µg/m^3. Thus, the differences were more noticeable on days during cold surges.

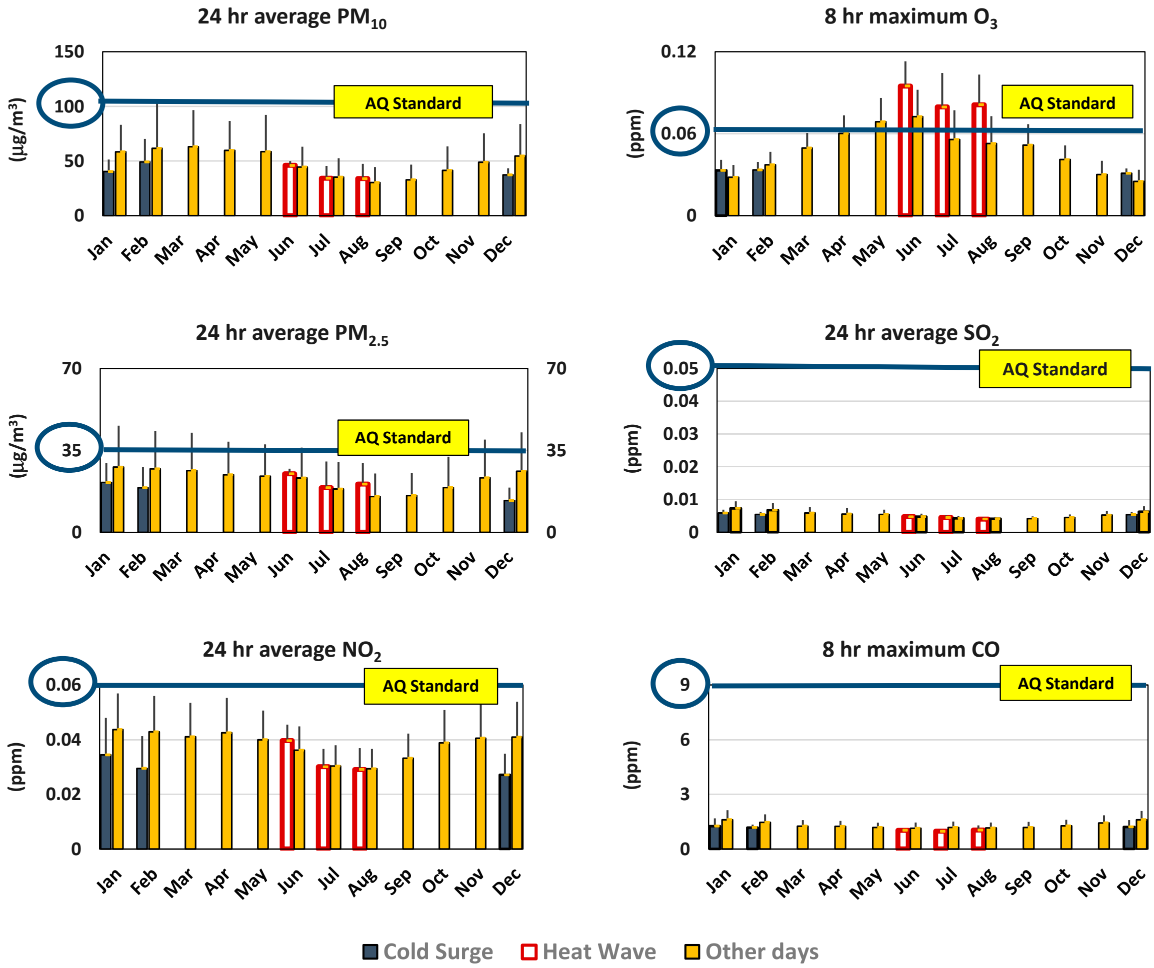


Figure 3. Monthly average (box) and one standard deviation (spike on top of the box) of pollutant concentrations in Seoul, Korea between 2008 and 2018 for PM_{10}, $PM_{2.5}$, NO_2, O_3, SO_2, and CO.

Concentrations of many types of pollutants are relatively high in winter (Figure 3). One reason is that air pollution is concentrated in the lower troposphere in winter because of a low mixing layer. Another reason is that the inversion layer, in which temperature increases with height, is often formed near the surface in winter. Then, the atmosphere becomes quite stable, and air pollution cannot be easily moved to surrounding areas. However, from time to time, cold surges originating in the Siberian area contribute to decreased pollutant concentrations in winter partly because the region has few emission sources, or relatively strong wind accompanied by cold surges wash out the air pollution [27,28]. For example, the daily average PM_{10} concentrations were 45 $\mu g \cdot m^{-3}$ on 14 January 2017, when the daily temperature dropped to −8.3 °C. Whereas, the daily average PM_{10} level was 114 $\mu g \cdot m^{-3}$ on 2 January 2017, when the daily average temperature was 5.2 °C.

The $PM_{2.5}$ concentration was also relatively high in spring, but the seasonal difference with $PM_{2.5}$ was less obvious than with PM_{10}. The length of the rods in Figure 3 signify one standard deviation. Average concentrations added by one standard deviation exceeded the air quality standard except in July, August, September, and October, indicating a need for an immediate reduction. Monthly average $PM_{2.5}$ concentrations during cold surges were lower than those on other days by as much as 6.6 $\mu g/m^3$, 8.0 $\mu g/m^3$, and 12.4 $\mu g/m^3$ in January, February, and December, respectively. Average $PM_{2.5}$ levels on days during heat waves exceeded those on other days by as much as 1.8 $\mu g/m^3$, 0.5 $\mu g/m^3$, and 5.3 $\mu g/m^3$ in June, July, and August.

Fine particle concentrations are particularly high in spring, partly because of Asian dust originating from China and the deserts of Mongolia and Kazakhstan, all located to the west of Korea (Figure 4). Because of the desertification caused by deforestation and climate change, episodes of Asian dust occur more often and last longer than in the past. Asian dust is carried to Korea by prevailing westerlies in spring as illustrated by the wind rose chart (Figure 2). Fine particle concentrations significantly decrease in summer partly because of the heavy precipitation. Average precipitation in the two summer months of July and August accounts for 547 mm of the 1006 mm of annual precipitation in Korea. Accordingly, wet scavenging significantly decreases air pollutant levels in July and in August.

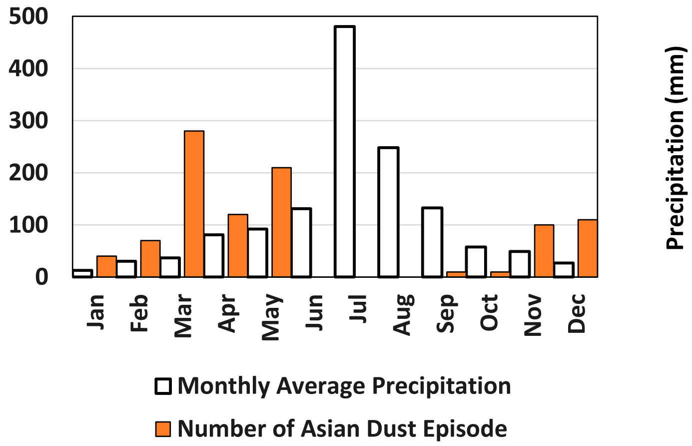


Figure 4. The number of episodes of Asian dust and monthly precipitation between 2008 and 2018 [21].

NO_2 levels, similar to those of PM_{10} and $PM_{2.5}$, were relatively higher in winter. Average NO_2 concentrations added by one standard deviation approached the air quality standard level, implying that NO_2 exceeded the standard. Monthly average NO_2 concentrations during cold surges were lower than those on other days by as much as 9.2 ppb, 13.4 ppb, and 13.8 ppb in January, February, and December, respectively. The NO_2 concentrations during heat waves differed from those on other days.

Along with NO_2 and particulate matter, O_3 is one of the important pollutants in Korea, where O_3 levels are relatively high in spring and in summer. It is a secondary pollutant, naturally formed by the photochemical dissociation of oxygen. Equilibrium concentrations of naturally formed O_3 in the troposphere are usually less than 40 ppb. However, nitrogen oxides (NOx) and volatile organic carbons (VOCs) generated by anthropogenic activities increase O_3 concentrations. As a result, high O_3 concentrations occur often in Seoul. The formation of O_3 is favored by strong solar radiation associated with high temperatures. Thus, O_3 levels are relatively higher in summer. Monthly average O_3 concentrations during heat waves were higher than on other days by as much as 22.4 ppb, 23.8 ppb, and 28.5 ppb in June, July, and August, respectively.

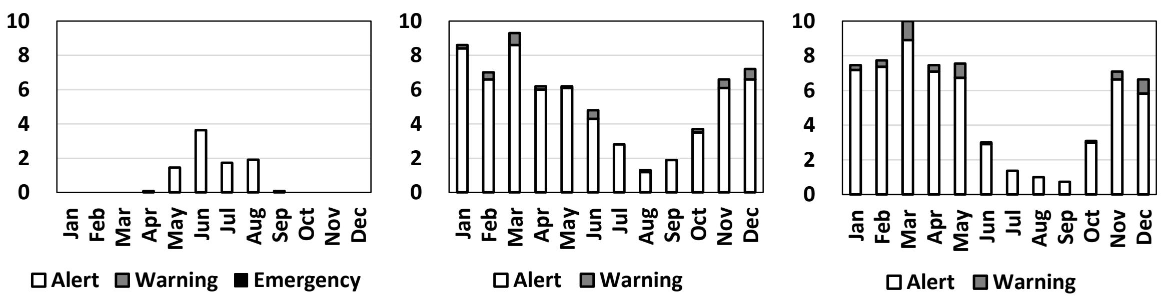
CO and SO_2 levels were much lower than the air quality standard, implying that neither has significant epidemiological effects. Pollutant concentrations of most species were relatively low in Seoul in autumn. The predominant northeast wind also helps decrease concentrations of pollutants in the city because few emission sources are located in northeastern Korea (Figure 2).

As such, PM_{10}, $PM_{2.5}$, and O_3 levels often exceed the air quality standards in Seoul. Thus, the Korean government issues air quality warnings if levels of the above pollutants are high (Table 3). Air quality alerts for O_3 are issued only in summer, but those for $PM_{2.5}$ or PM_{10} are issued throughout the year with relatively higher numbers issued in spring and winter (Figure 5). Alerts for O_3 were issued on average 8.9 times per year and none for warnings between 2008 and 2018. In contrast, annual average alerts and warnings for PM_{10} issued between 2008 and 2018 were 63.1 times and 4.4 times, respectively; the corresponding issuances for $PM_{2.5}$ were 59.6 times and 3.2 times, respectively, all indicating elevated air quality levels that threatened public health. Therefore, effective measures should be implemented to decrease the adverse health impact of air pollution.

Table 3. Thresholds for the air quality warning system in Korea.

	PM_{10} [$\mu g \cdot m^{-3}$]	$PM_{2.5}$ [$\mu g \cdot m^{-3}$]	O_3 [ppm]
Alert	150	75	0.12
Warning	300	150	0.3
Emergency	-	-	0.5

Air quality alert, warning, and emergency are effective when hourly average concentrations exceed the threshold at least two hours.



(**a**) Ozone Alert Times (**b**) PM2.5 Alert/Warning Times (**c**) PM10 Alert/Warning Times

Figure 5. Monthly average numbers for alerts, warnings, and emergency alarms in each year between 2008 and 2018 for PM_{10}, $PM_{2.5}$, and O_3 in (**a**–**c**), respectively.

3.1.3. Mortality Rate from Cerebrovascular Disease

The effect of meteorological extremes on air pollution and on human health was studied. Mortality caused by cerebrovascular disease was analyzed as part of the study of health impacts. Because the weak or elderly are susceptible to the effect of extreme weather or ambient pollutant levels, the study focused on people aged 65 or older. The number of deaths in Seoul between 2008 and 2018 was 458,012; 321,958 of these were people aged 65 or older, accounting for 70% of total mortality. Cardiovascular disease accounted for 16% of total mortality (Figure 6). Mortality from cerebrovascular disease accounted for 45% of the mortality from cardiovascular disease among persons aged 65 or older, and its seasonal variation was obvious, with relatively higher mortality occurring in winter than in summer (Figure 7).

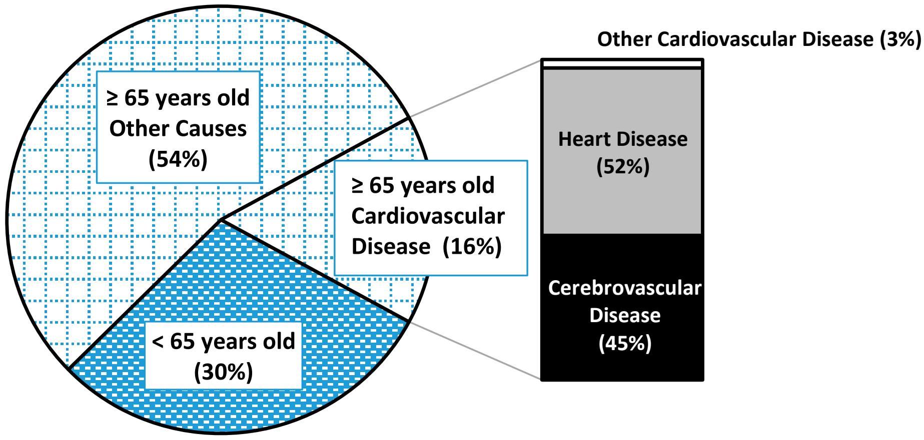


Figure 6. Specific causes of the mortality rate in Seoul from 2008 to 2018.

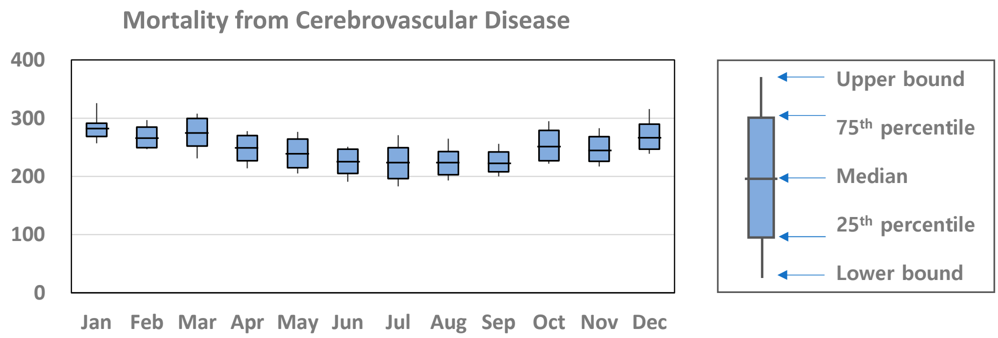


Figure 7. Monthly mortality rate per year, 2008–2018, for cerebrovascular disease for persons aged 65 or older in Seoul, Korea.

3.2. Impact of Air Pollution and Meteorological Extreme Events on Cerebrovascular Disease

Prolonged exposure to elevated levels of air pollution or extreme weather conditions may cause serious health effects. The elderly or the weak are especially vulnerable to air pollution or weather extremes. Thus, our analysis focused on those aged 65 or older who died from cerebrovascular disease. Each day was categorized as ranking "H days (days of high probability of death)" and "L days (days of low probability of death)" according to the median number of deaths of persons aged 65 or older from cerebrovascular disease in Seoul between 2008 and 2018.

Monthly average PM_{10} concentrations on H days exceeded those on L days except in February, April, and September, which is consistent with previous studies (Figure 8) [22,23]. The difference for lag time of zero day corresponds to PM_{10} on H day minus that on L day. The differences of PM_{10} for a lag time of one day in January is slightly higher than for a zero-day lag time. Although PM_{10} on H day was less than on L day for a zero-day lag time, PM_{10} levels on H day were higher than on L day for lag times of one and two days in February. The average PM_{10} levels on H days were slightly more than on L days, and the difference did not change consistently as lag time increased from zero to two days. However, PM_{10} levels on H days were obviously higher than on L days for a lag time of zero days, and the difference decreased for a lag time of one and two days in January and February when cold surges occurred (Figure 8).

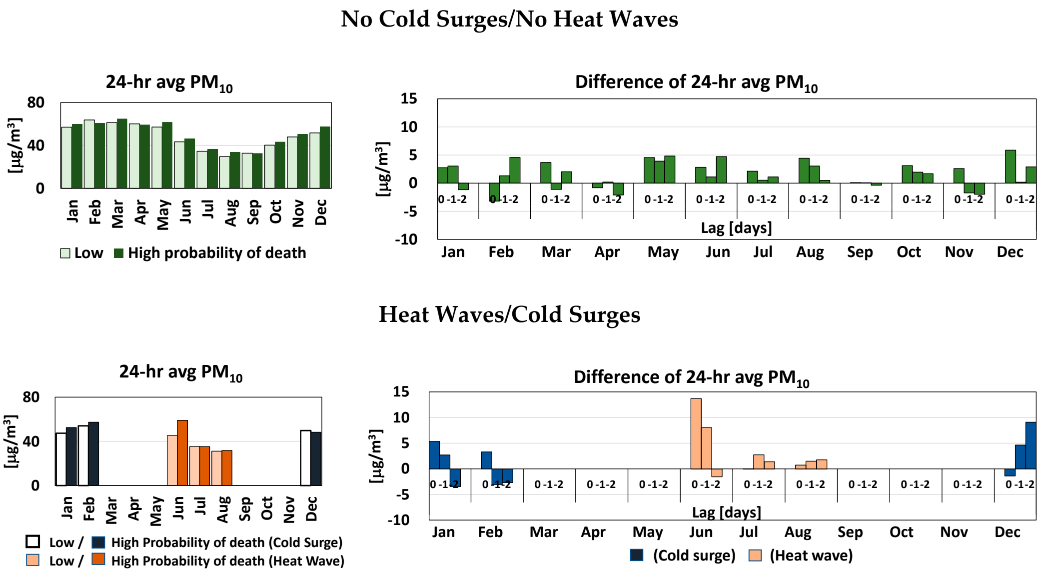


Figure 8. Comparison of monthly average PM_{10} levels on days of high and low probability of death and the differences in PM_{10} ($PM_{10\ (\text{high probability of death})}$–$PM_{10\ (\text{low probability of death})}$) from zero to two days before death.

Monthly average $PM_{2.5}$ levels on H days were higher than those on L days except in April and September (Figure 9). Differences in $PM_{2.5}$ on H days and on L days decreased as the lag time increased from zero to one day in most months, indicating that the health impact of $PM_{2.5}$ could appear no later than a few days. Studies indicated that the elevated fine particle levels were often observed a few days prior to death from cardiovascular disease [10,12]. The difference in $PM_{2.5}$ levels on H days and on L days was quite apparent when cold surges or heat waves occurred (Figure 9). The difference in $PM_{2.5}$ levels for lag times of one or two days were smaller than those for a zero-day lag time when a cold surge occurred.

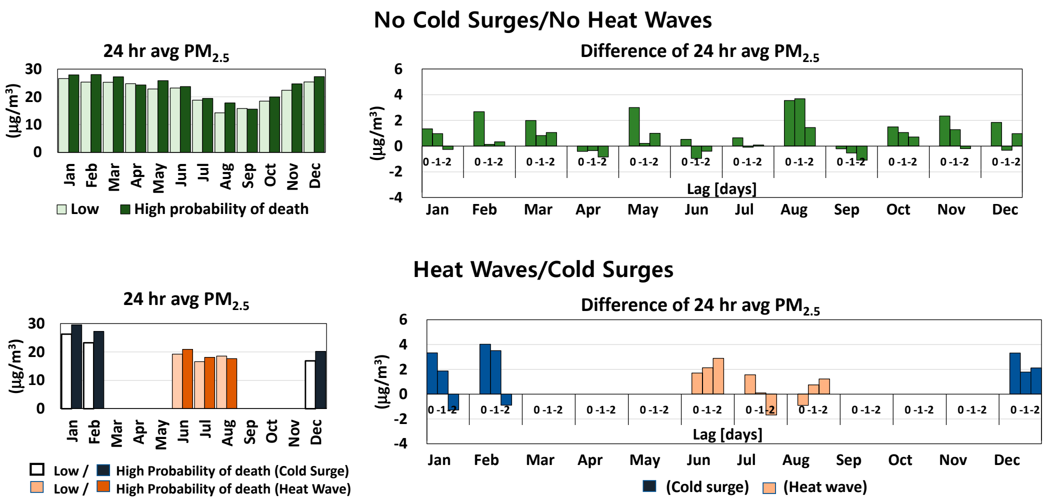


Figure 9. Comparison of monthly average $PM_{2.5}$ levels on days of high and low probability of death and the differences in $PM_{2.5}$ ($PM_{2.5\ (\text{high probability of death})}$–$PM_{2.5\ (\text{low probability of death})}$) from zero to two days before death.

Monthly average NO_2 concentrations on H days were slightly higher than those on L days in most months (Figure 10). Previous studies also illustrate the health impact of elevated NO_2 levels [29–31]. The differences in NO_2 levels decreased as the lag time increased from zero to two days. NO_2 levels were apparently higher on H days than on L days when cold surges occurred (Figure 10). The differences in NO_2 levels between H and L days was also observed with a lag time of one day.

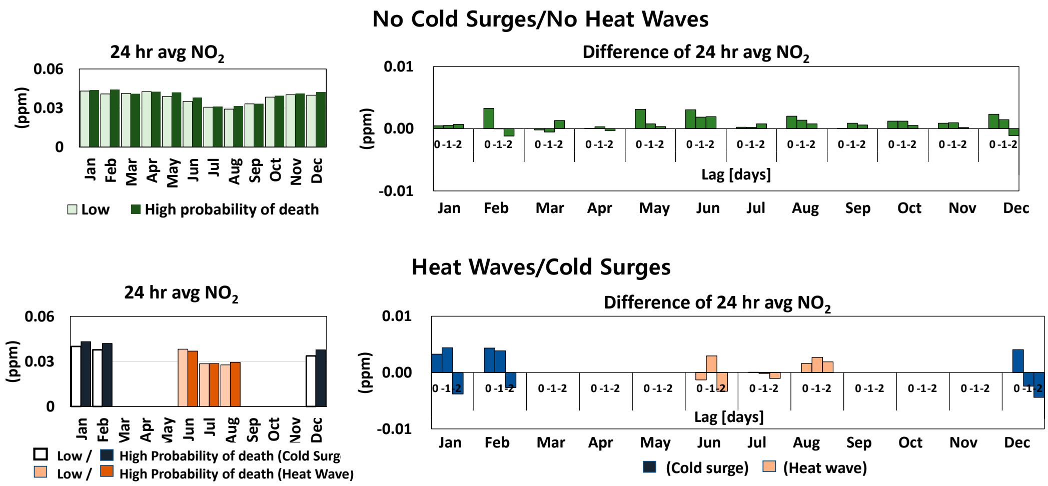


Figure 10. Comparison of monthly average NO_2 levels on days of high and low probability of death and the differences in NO_2 ($NO_{2\text{ (high probability of death)}}$–$NO_{2\text{ (low probability of death)}}$) from zero to two days before death.

Elevated levels of O_3 are often observed from May through August because strong sunlight causes a photochemical reaction that forms O_3 [32–35]. Monthly average O_3 concentrations on H days were slightly higher than those on L days from May through August (Figure 11). O_3 levels on H days were also slightly higher than L days for lag times of one and two days, but the difference was smaller than for a zero-day lag time. However, the difference was significant when a heat wave occurred (Figure 11), indicating that when extreme weather phenomena were observed, the health impact of elevated O_3 levels were more obvious.

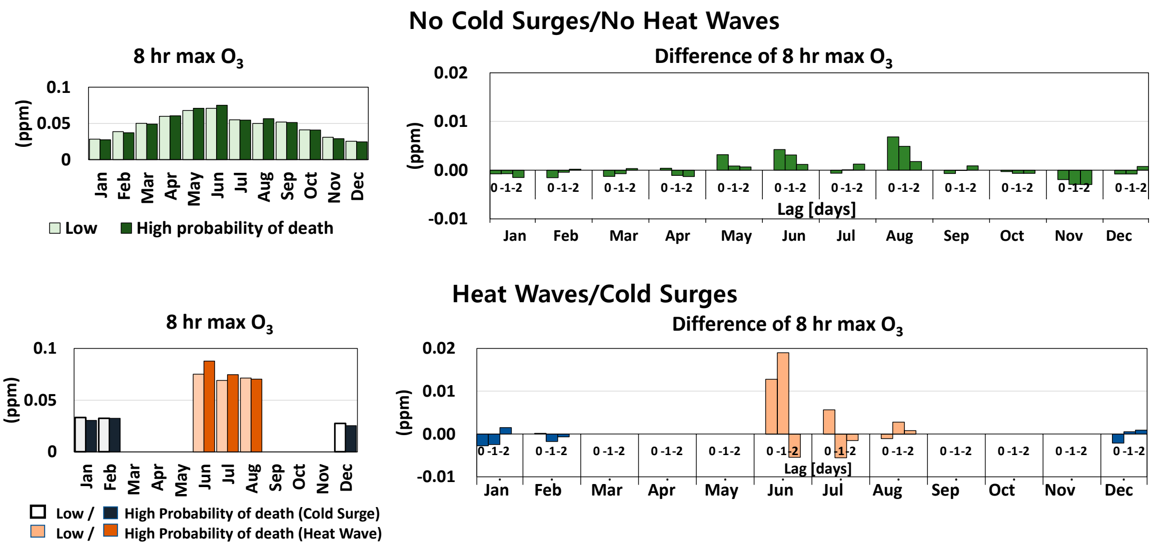


Figure 11. Comparison of monthly O_3 averages on days of high and low probabilities of death and the differences in O_3 ($O_{3\text{ (high probability of death)}}$–$O_{3\text{ (low probability of death)}}$) from zero to two days before death.

Monthly average temperatures did not cause a significant difference between H and L days for lag times from zero to two days (Figure 12). Temperatures on L days were lower than on H days in January and February when cold surges were observed (Figure 12). This result should not be interpreted as meaning high temperatures in winter may increase mortality—instead, it may imply a combined effect of temperature and air pollution on human health. For example, low temperatures were often observed when a relatively clean Siberian air mass moved southward to Korea, so the concentrations of pollutants were lower when cold surges were observed (Figure 3). Thus, partly because of low pollutant levels, decreases in mortality may occur when temperatures are relatively low. The temperatures on H days were significantly lower than on L days, with a lag time of two days when cold surges occurred (Figure 12). This fact was consistent with lag times between the occurrences of cold temperatures, and mortality was known to occur from a few days to several weeks because the effect of temperature on mortality was observed at least two days after the cold temperatures occurred [16,20]. Likewise, mortality can be affected by various combinations of variables. Thus, an analysis of several factors should be considered together to analyze the factors linked with mortality.

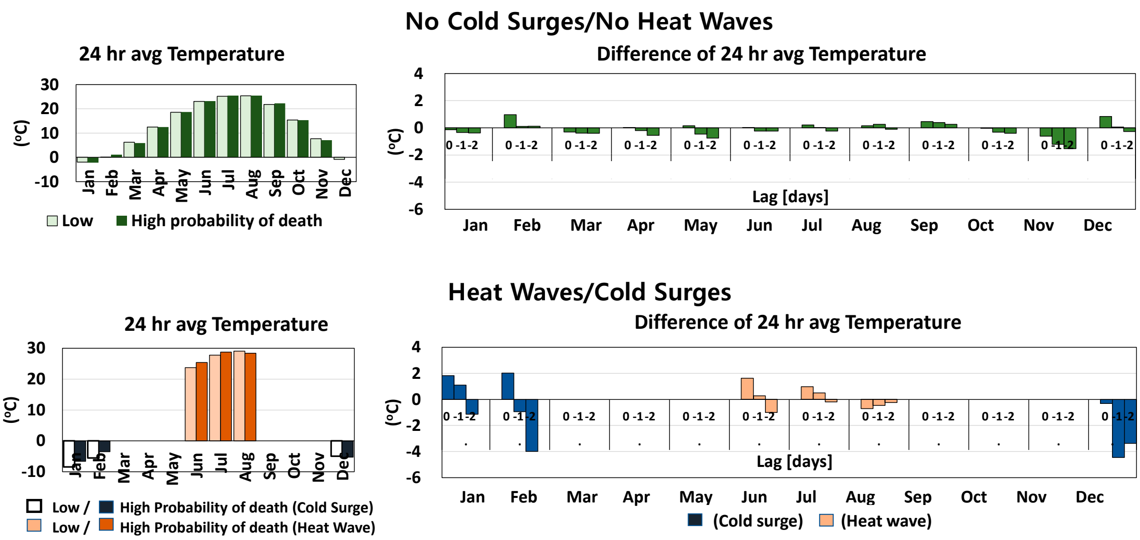


Figure 12. Comparison of monthly average temperatures on days of high and low probability of death and the differences in temperatures (temperature $_{\text{(high probability of death)}}$–temperature $_{\text{(low probability of death)}}$) from zero to two days before death.

Precipitation on H days was relatively lower than on L days in July and August when heavy rainfall was observed (Figure 13). The result is partly because mortality increases as pollutant levels increase and elevated levels of air pollution are often observed when precipitation is low (Figure 4). The precipitation on H days for lag times of one or two days was also lower than on L days. When heat waves were observed in June and in July, the linkage was more apparent between the mortality rate and the amount of precipitation with a lag time of zero (Figure 13). The differences in precipitation between H and L days decreased with increases in lag times.

Wind speeds on H and L days differed little (Figure 14), but wind speed on H days was apparently lower than on L days when cold surges were observed in January, February, and December (Figure 14). The relatively high mortality rates when wind speeds were low are partly because of the elevated pollutant levels—low wind speeds prevent dissipation of air pollution in the polluted cities [36–38]. When heat waves were observed in June, July, and August, wind speed did not apparently differ between H and L days.

Results showed that PM_{10}, $PM_{2.5}$, O_3, and NO_2 concentrations on H days were apparently higher than those on L days, indicating a direct impact of air pollution on human health. It would be interesting to see the interrelation of pollutant species since the impact on human health from air pollution would be caused by the combined effect of multiple species. $PM_{2.5}$ and NO_2 were positively correlated to each other for all seasons, partly because NO_2 emitted by the combustion sources underwent the gas-to-particle conversion in the ambient temperature, and formed the nitrate, which is one of the major components of $PM_{2.5}$ (Table 4). PM_{10} and $PM_{2.5}$ were also positively correlated. The correlation between O_3 and NO_2 is apparent in summer when photochemical formation of O_3 in the presence of NOx and VOC was favored by the strong sunlight and high temperature. Another reason for the positive correlation between pollutant concentrations is that pollutant levels of most species are highly affected by the meteorological conditions. For example, when the ambient air is relatively stable and the planetary boundary layer is low, air pollution is not easily transported to the surrounding areas and is trapped near the ground. Thus, high concentrations of several pollutant species are often observed at the same time. Because the impact of air pollution on human health is caused by multiple air pollutants together, more statistical analysis incorporating the combined effects of various air pollutant species should be conducted in the future.

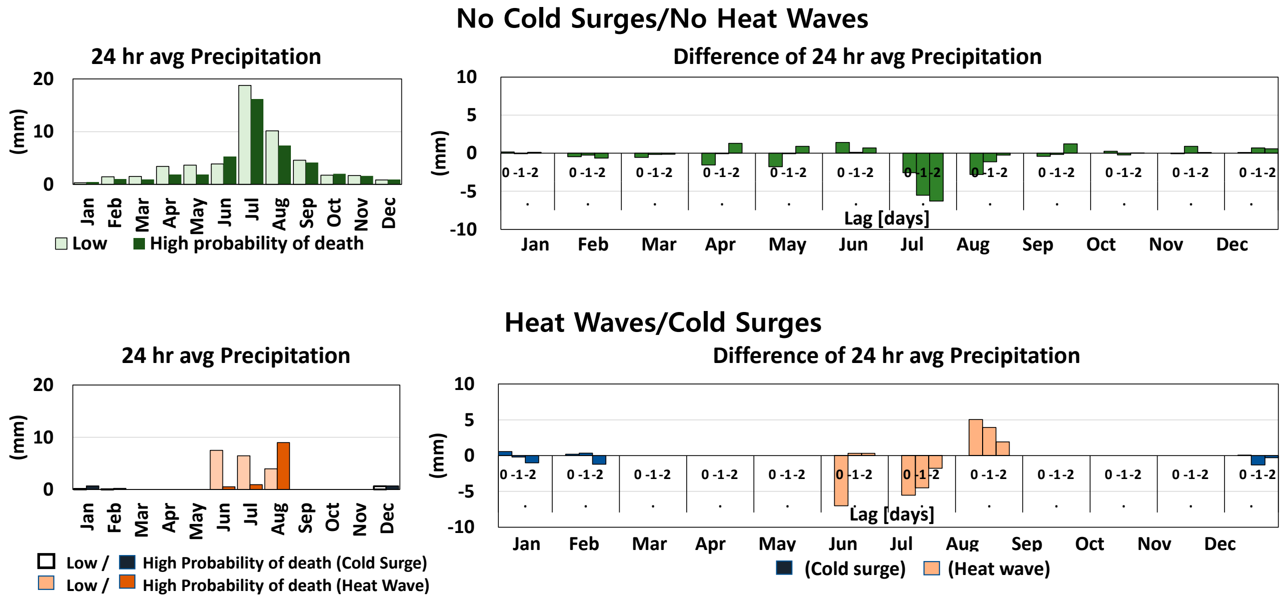


Figure 13. Comparison of monthly average precipitation on days of high and low probability of death and the differences in precipitation (precipitation $_{\text{(high probability of death)}}$−precipitation $_{\text{(low probability of death)}}$) from zero to two days before death.

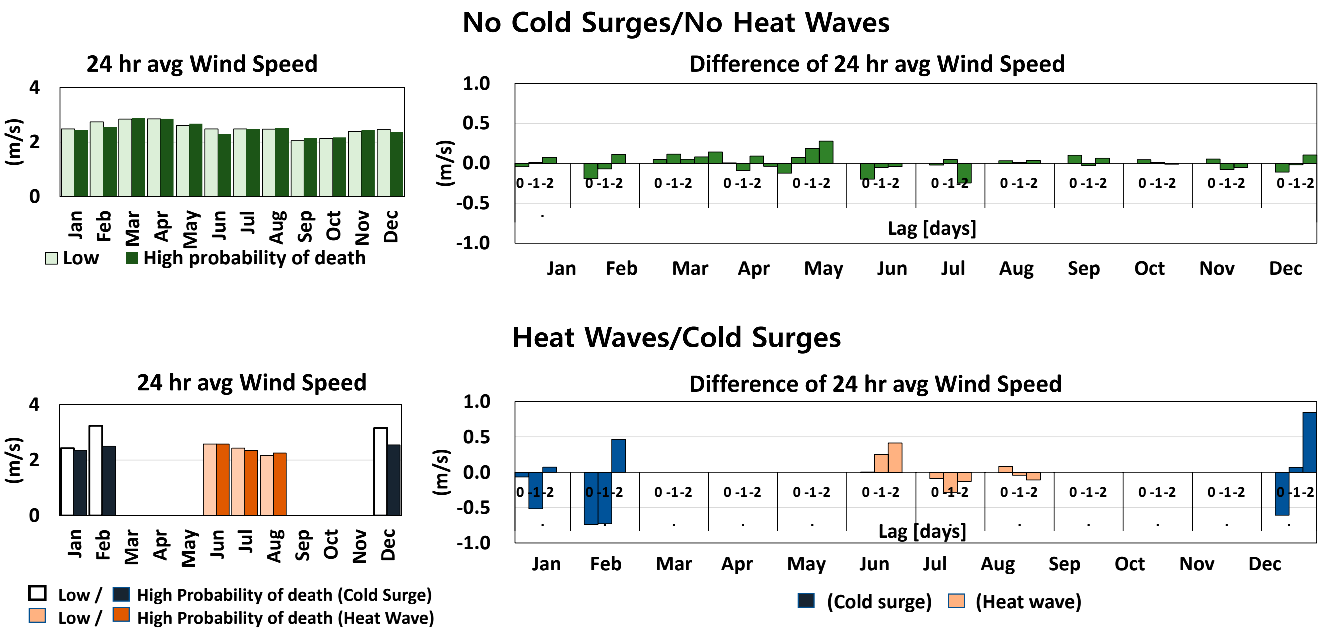


Figure 14. Comparison of monthly average wind speed on days of high and low probability of death, and the differences in wind speed (wind speed $_{\text{(high probability of death)}}$−wind speed $_{\text{(low probability of death)}}$) from zero to two days before death.

Table 4. Correlation coefficient (r) between hourly pollutant concentrations of PM_{10}, $PM_{2.5}$, NO_2, and O_3 from 2008 to 2018 in Seoul, Korea.

	Spring					Fall			
	PM_{10}	$PM_{2.5}$	NO_2	O_3		PM_{10}	$PM_{2.5}$	NO_2	O_3
PM_{10}	1.00	0.58	0.43	0.27	PM_{10}	1.00	0.82	0.66	−0.02
$PM_{2.5}$		1.00	0.46	0.24	$PM_{2.5}$		1.00	0.58	0.02
NO_2			1.00	0.18	NO_2			1.00	−0.17
O_3				1.00	O_3				1.00
	Summer (During Heat Waves)					**Winter (During Cold Surges)**			
	PM_{10}	$PM_{2.5}$	NO_2	O_3		PM_{10}	$PM_{2.5}$	NO_2	O_3
PM_{10}	1.00	0.48	0.71	0.59	PM_{10}	1.00	0.72	0.61	−0.32
$PM_{2.5}$		1.00	0.42	0.51	$PM_{2.5}$		1.00	0.79	−0.36
NO_2			1.00	0.58	NO_2			1.00	−0.61
O_3				1.00	O_3				1.00
	Summer (on Other Days)					**Winter (on Other Days)**			
	PM_{10}	$PM_{2.5}$	NO_2	O_3		PM_{10}	$PM_{2.5}$	NO_2	O_3
PM_{10}	1.00	0.81	0.65	0.60	PM_{10}	1.00	0.62	0.42	−0.13
$PM_{2.5}$		1.00	0.53	0.49	$PM_{2.5}$		1.00	0.49	−0.25
NO_2			1.00	0.54	NO_2			1	−0.48
O_3				1.00	O_3				1

4. Conclusions

Seoul, the capital of Korea with a population of about 10 million people is the country's most populous city, and pollution levels there often exceed the air quality standards. Because high levels of air pollution often threaten human health, an immediate reduction should be made to minimize the harmful effect of air pollution on human health. The goal of this study was to analyze the health effects of criteria pollutants (PM_{10}, $PM_{2.5}$, NO_2, and O_3) in conjunction with meteorological variables (temperature, precipitation, and wind speed). The health effect was analyzed based on the mortality rate from cerebrovascular disease for people aged 65 or older, who are known to be vulnerable to elevated levels of air pollution. In addition to air pollution, extreme weather conditions, such as cold surges or heat waves, have a direct impact on the health of this vulnerable group. To ascertain the combined effect on health of air pollution and extreme weather conditions, we conducted separate analyses of the effect of air pollution on mortality on days of extreme weather conditions in comparison with conditions on other days.

Results showed that PM_{10} and $PM_{2.5}$ levels were relatively higher on H days. When cold surges or heat waves occurred, the differences in PM_{10} or $PM_{2.5}$ levels between H and L days were more obvious, and the differences decreased with the increased lag time. NO_2 levels were also slightly higher on H days, and the difference was more significant when cold surges occurred. Because NO_2 levels were relatively lower in summer, which is when heat waves occur, the differences in NO_2 levels on H and L days were not significant when heat waves occurred. O_3 levels were higher on H days than on L days from May to August. When heat waves occurred, the differences in O_3 levels between H and L days were more obvious. Temperatures on H days were higher than on L days when cold surges or heat waves occurred, but the temperature two days before H days were rather lower than on L days, indicating that a lag time existed between the low temperatures and mortality. Precipitation amounts did not differ significantly between H and L days except in July and in August, when heavy rainfall occurred. The rainfall was obviously low on H days in July and in August when heat waves occurred. The wind speed was relatively low on H days and when cold surges occurred.

Summarizing, ambient concentrations of air pollutants have a direct impact on human health. This impact was more significant under extreme weather conditions such as cold surges or heat waves. Findings from this research show that a reduction of pollutant levels is urgently needed under extreme weather conditions to effectively decrease the adverse health impact. When elevated levels of air pollution are expected, guidelines to minimize the health impact should be provided. If extreme weather conditions and elevated levels of air pollution are expected, stricter guidelines should be provided to protect public health. The results of this study can be used as basic data for policy makers to improve public health.

The study focused on the short-term impact of air pollution on the mortality rate from cerebrovascular disease. However, the long-term effect of particulate matter on human health is a very important issue to be studied. The main health issues when exposed to elevated levels of air pollution include breathing problems, coughing, or pneumonia, asthma, cardiovascular disease, and neurological or mental diseases, attributed to metallic and other chemical elements in $PM_{2.5}$. The combined effects of these problems sometimes result in death. Therefore, the long-term effect of air pollution on human health is crucial in epidemiological study, and factors affecting the long-term health impact should be analyzed in future studies.

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