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# Measurement of Black Carbon Concentration and Comparison with $PM_{10}$ and $PM_{2.5}$ Concentrations Monitored in Chungcheong Province, Korea

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## ABSTRACT

Black carbon concentrations are closely related to global warming. To characterize the atmospheric aerosols in Chungcheong Province, Korea, we measured the concentrations of black carbon for about eight months (September 2015–April 2016) and compared them with $PM_{10}$ and $PM_{2.5}$ concentrations as well as various meteorological parameters (e.g., wind velocity and wind direction). We used a multi-angle absorption photometer to measure the black carbon; the $PM_{10}$ and $PM_{2.5}$ concentrations, wind velocity, and wind direction were obtained from local monitoring stations. The highest and lowest $PM_{10}$, $PM_{2.5}$, and BC concentrations were observed in spring and fall, respectively. The high concentrations in spring and winter were likely due to the dominance of westerly winds, which transported pollutants, whereas the low concentrations in fall were likely due to increased wind variations, which drove turbulent mixing. Overall, although BC concentrations exhibited directly proportional correlations with $PM_{10}$ and $PM_{2.5}$, the correlations were relatively low, probably because of differences between the sources of these three atmospheric pollutants. These results help clarify the characteristics of BC concentrations over the Korean Peninsula.

***Keywords:*** Black carbon; MAAP; $PM_{10}$; $PM_{2.5}$.

## INTRODUCTION

Elemental carbon refers to carbonaceous aerosols in particulate matter (PM). As a type of elemental carbon, black carbon (BC) encompasses carbonaceous aerosols in PM defined by their optical properties and BC is usually produced by the incomplete combustion of fossil fuels. BC is important in climate change research because it can alter radiative forcing via light absorption (McMurry *et al.*, 2004), making BC one of the most notorious substances among air pollutants for its influence on global warming. Although global warming is considered to be mainly caused by greenhouse gases, research has suggested the possibility that warming of the earth's atmosphere may be caused by BC (Andreae, 2001). Unlike greenhouse gases, BC is composed of solid particles that heat the atmosphere via direct absorption of solar radiation. Because it is only present in the atmosphere for short durations, BC is referred to as a short-lived climate forcer, and has been reported to influence local climate change due to the high variations in BC concentrations among industrialized cities and remote suburbs (Chameides and Bergin, 2002).

Several preliminary studies have assessed the factors affecting BC concentrations. Before industrialization, large-scale forest fires or volcanic activity were the main causes of increased BC concentrations. However, after the Industrial Revolution, particulate emissions from direct combustion of hydrocarbon fuels (e.g., coal and petroleum) increased drastically (McConnell *et al.*, 2007). In particular, PM is generated not only via anthropogenic processes (e.g., fuel combustion, vehicle emissions, and chemical production processes), but also by condensation of $SO_2$ and volatile organic compounds via secondary processes (Volkamer *et al.*, 2006). As such, studies on the secondary generation of aerosols have been actively conducted in recent years. Overall, a great attention has been paid not only to primary (i.e., direct) production, but also to the secondary (i.e., indirect) production of atmospheric PM.

As typical products of primary atmospheric aerosols, we measured and monitored BC concentrations for eight months from September 2015 to April 2016 in Chungcheong Province, Korea, to clarify regional BC emissions. Chungcheong Province is located in central South Korea far from the Seoul Metropolitan Area; therefore, it is recognized

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as being less affected by pollutants from the Seoul Metropolitan Area and other urban regions. Furthermore, we assessed the variations in BC concentrations in atmospheric aerosols in relation to $PM_{10}$ and $PM_{2.5}$ concentrations, as well as wind direction and wind velocity. Using these data, we identified the main meteorological factors influencing the behavior of $PM_{10}$, $PM_{2.5}$, and BC.

## EXPERIMENTAL METHODS

We used a multi-angle absorption photometer (MAAP) for the measurement of BC. MAAPs employ a filter-based technique to measure the light absorption of BC, where atmospheric aerosols are deposited onto a filter substrate and a laser beam with a wavelength of 637 nm is shot toward the deposited filter. Two detectors located on the same side as the laser source measure the light back-scattered by BC deposited on the filter. In addition, a detector located on the opposite side of the laser source measures the light transmitted through the filter. Conventional BC measurement instruments only have a detector on the opposite side of the laser source and do not measure the scattering of light, which means that only transmitted light can be detected. As a result of the detection of signal from back-scattering in MAAPs, the scattering effect can be compensated for by correcting the signal from transmitted light with the signals of the scattered light (Petzold and Schönlinner, 2004). The BC concentration derived from filter-based techniques (e.g., aethalometers and MAAPs) is referred to as *equivalent BC* (eBC). As such, "BC concentration" hereafter represents the equivalent BC concentration.

In the present study, the BC concentration was measured in 1-min increments at the Korea University of Technology and Education (KOREATECH) located in Byeongcheon-myeon, Cheonan city, Chungcheongnam-do (Fig. 1), using a commercially available instrument (MAAP 5012; Thermo Scientific). BC concentrations were monitored from September 2015 to April 2016. The $PM_{10}$ and $PM_{2.5}$ concentrations were obtained from the Air Korea database (http://www.airkorea.or.kr) operated by the Korea Environment Corporation. According to Air Korea, $PM_{10}$ and $PM_{2.5}$ concentrations are measured with unmanned automatic equipment using the β-ray absorption method, where PM is collected on a filter for 1 h and β-rays pass through the PM on the filter. Then, changes in absorption or extinction before and after the deposition of PM for 1 h are measured and converted into mass concentration. The principle of the β-ray absorption method is similar to the quantification of BC by filter-based instruments (e.g., aethalometers). In this study, we used PM data from Ochang-eup, Cheongju city, Chungcheongbuk-do (Fig. 1), from September 2015 to April 2016.

The seasonal mean BC, $PM_{10}$, and $PM_{2.5}$ concentrations were calculated from raw data for fall 2015 (September–November 2015), winter 2015 (December–February 2016), and spring 2016 (March–April 2016).

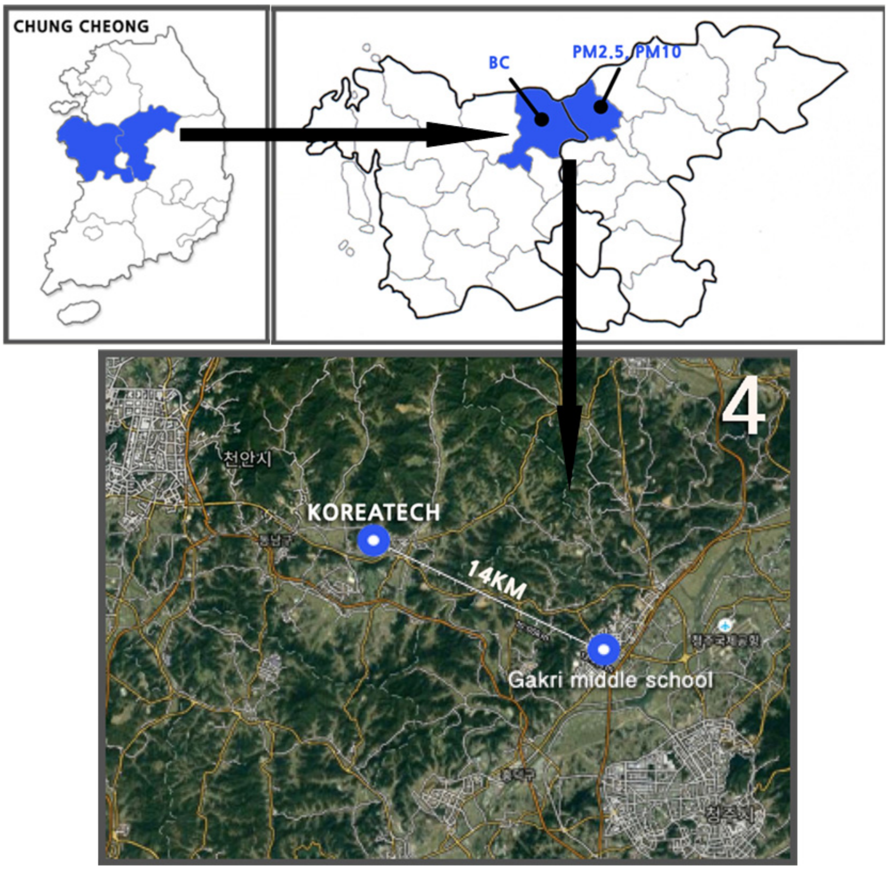


**Fig. 1.** Location of monitoring site.

Wind direction and wind speed displayed hourly were collected from the Korea Meteorology Administration (KMA) database (http://www.kma.go.kr). Wind direction and wind speed were measured at Shibang-dong, Cheonan, Chungcheongnam-do, which is located 14 km from KOREATECH (Fig. 1). Wind rose diagrams of wind direction and wind speed obtained from September 2015 to April 2016 are shown in Fig. 2. It should be noted that these wind rose diagrams show only wind intensity and direction, not BC concentrations. In fall 2015, south-easterly winds were equally dominant as westerly winds. However, in winter 2015, westerly winds were dominant. In spring 2016, westerly winds were more dominant than easterly winds. Overall, westerly winds were dominant during the measurement period from fall 2015 to spring 2016.

## RESULTS AND DISCUSSION

### *Concentrations of BC, $PM_{10}$, and $PM_{2.5}$*

Table 1 presents the monthly average BC, $PM_{10}$, and $PM_{2.5}$ concentrations from September 2015 to April 2016. In fall 2015, winter 2015, and spring 2016, the average BC concentrations were 1.39 µg $m^{-3}$, 1.57 µg $m^{-3}$, and 2.30 µg $m^{-3}$, the average $PM_{10}$ concentrations were 36.7 µg $m^{-3}$, 48.8 µg $m^{-3}$, and 66.4 µg $m^{-3}$, and the average $PM_{2.5}$ concentrations were 30.9 µg $m^{-3}$, 37.7 µg $m^{-3}$, and 41.9 µg $m^{-3}$, respectively. Upon initial inspection, the trends in BC concentrations appeared to be similar to those of $PM_{10}$ and $PM_{2.5}$ concentrations. For instance, the highest and lowest average concentrations of BC, $PM_{10}$, and $PM_{2.5}$ were observed in spring and fall, respectively. As shown in Fig. 2, westerly winds were dominant in spring. Thus, the high concentrations in spring were likely related to the influence of Asian Dust transported by westerly winds. In addition, the higher concentrations of BC, $PM_{10}$, and $PM_{2.5}$ in winter and spring were possibly related to the transport of primary air pollutants produced via combustion processes from surrounding areas via westerly winds.

Meanwhile, BC, $PM_{10}$, and $PM_{2.5}$ concentrations in fall were slightly lower than those in winter. The wind direction

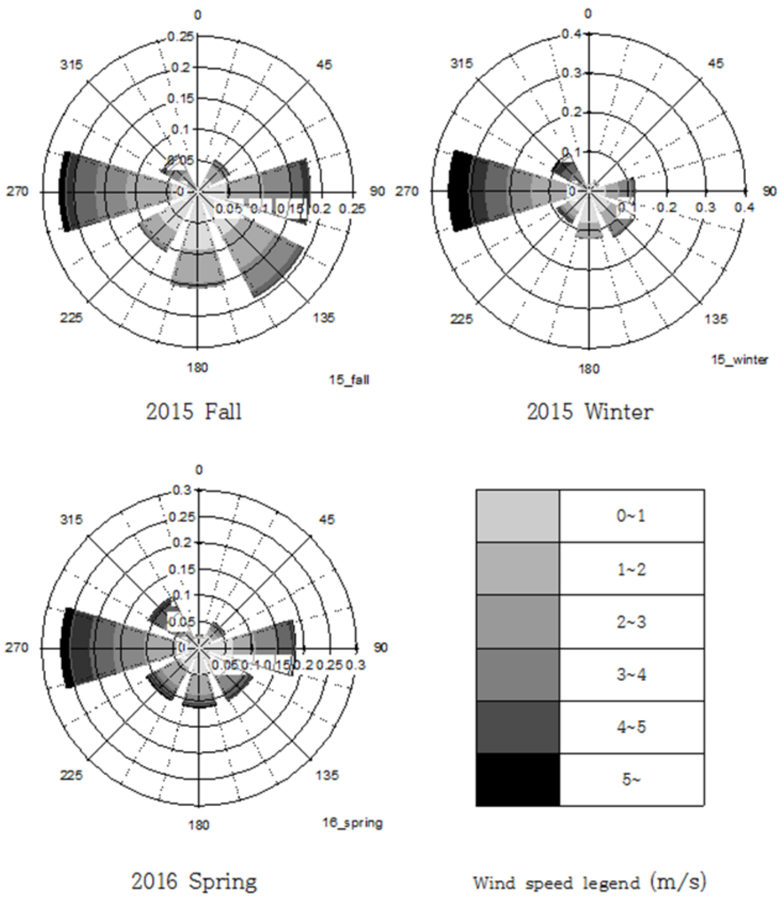


**Fig. 2.** Wind rose diagrams for 3 seasons.

**Table 1.** Monthly average for BC, $PM_{10}$, and $PM_{2.5}$ concentrations (unit: µg $m^{-3}$).

| Month | Sep. | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | Apr. |
|---|---|---|---|---|---|---|---|---|
| $PM_{10}$ | 31.6 | 43.6 | 34.9 | 52.9 | 48.6 | 44.8 | 63.8 | 69.0 |
| $PM_{2.5}$ | 21.2 | 37.0 | 34.6 | 40.5 | 38.9 | 33.7 | 44.1 | 39.6 |
| eBC in $PM_{2.5}$ | 0.79 | 1.71 | 1.67 | 1.41 | 1.21 | 2.08 | 2.15 | 2.44 |

pattern in fall 2015 differed from that in winter 2015 (Fig. 2), with greater wind direction variations in fall 2015. These conditions could support turbulent mixing, reducing overall air pollutant concentrations. By contrast, the relatively consistent wind direction in winter 2015 could support the formation of atmospheric laminar flow mainly from the west, enabling the formation of a stable and stagnant air mass over the Korean Peninsula. In addition, the low BC, $PM_{10}$, and $PM_{2.5}$ concentrations in fall may have been caused by decreased production of fine PM, although further studies are necessary to confirm these trends and mechanisms.

Fig. 3 shows the 24-h running average of the data collected during the eight-month measurement period. The discontinuity of BC concentrations in Fig. 3 reflects the fact that the measurement instrument was temporarily stopped for maintenance. Although the seasonal BC concentrations initially appeared to follow the same trends as $PM_{10}$ and $PM_{2.5}$ concentrations, a closer examination of the data in Fig. 3 revealed that BC concentrations did not follow the same trends as $PM_{10}$ and $PM_{2.5}$ concentrations. This can be explained by the fact that PM consists not only of BC, but also other substances (e.g., sulfates, nitrates, or minerals). For example, in December 2015, BC concentrations decreased, whereas $PM_{10}$ and $PM_{2.5}$ concentrations increased (Fig. 3). Meanwhile, from January 2016 to mid-February 2016, BC concentrations increased markedly while $PM_{10}$ and $PM_{2.5}$ concentrations decreased slightly. Overall, the relationship between BC concentrations and PM concentrations may vary spatially or temporally depending on their sources or transport patterns.

Fig. 4 shows a bar chart of the mass concentration composition of BC, $PM_{10}$, and $PM_{2.5}$. Notably, the proportion of $PM_{2.5}$ was high throughout the study period, indicating that coarser particles (i.e., $PM_{10}$) were relatively rare. We speculated that $PM_{2.5}$ newly formed through secondary processes was dominant in this area, although it was beyond the scope of this study determine the mechanism driving the high proportions of $PM_{2.5}$.

### *Linear Regression Analysis of BC, $PM_{10}$, and $PM_{2.5}$ Concentrations*

We analyzed the correlations among BC, $PM_{10}$, and $PM_{2.5}$ with linear regression, where the coefficient of determination ($R^2$) was obtained from the linear regression of BC versus $PM_{2.5}$ or $PM_{10}$ concentrations and $PM_{2.5}$ versus $PM_{10}$ concentrations.

Table 2 shows the $R^2$ values of the linear regressions among BC, $PM_{10}$, and $PM_{2.5}$ concentrations. Except for the $R^2$ between $PM_{10}$ and $PM_{2.5}$ in winter 2015, the $R^2$ values were generally low, indicating that BC was not strongly correlated with $PM_{10}$ and $PM_{2.5}$. Although the results in Fig. 3 suggested that the BC concentrations appeared to generally follow $PM_{10}$ and $PM_{2.5}$ concentrations on a seasonal scale, the seasonal average BC concentrations were less correlated with $PM_{10}$ and $PM_{2.5}$ concentrations based on linear regression.

#### *Correlation between BC and $PM_{10}$*

We performed a linear regression analysis of BC and $PM_{10}$ concentrations during the three seasons in the study period. Although BC concentrations appeared to be directly proportional to $PM_{10}$ concentrations, the calculated $R^2$ was low (Fig. 5). $PM_{10}$ mostly consists of soil-derived dust particles, which are generated in large amounts from various

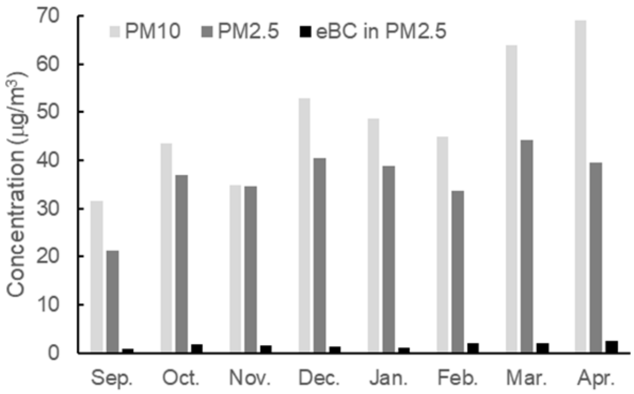


**Fig. 4.** Monthly composition of mass concentration for eBC in $PM_{2.5}$, $PM_{10}$, and $PM_{2.5}$.

**Table 2.** Correlation coefficients ($R^2$) between $PM_{10}$ and BC; $PM_{2.5}$ and BC; and $PM_{10}$ and $PM_{2.5}$ concentrations.

| | 2015 Fall | 2015 Winter | 2016 Spring |
|---|---|---|---|
| eBC-$PM_{10}$ | 0.52 | 0.31 | 0.40 |
| eBC-$PM_{2.5}$ | 0.47 | 0.45 | 0.58 |
| $PM_{10}$-$PM_{2.5}$ | 0.53 | 0.90 | 0.61 |

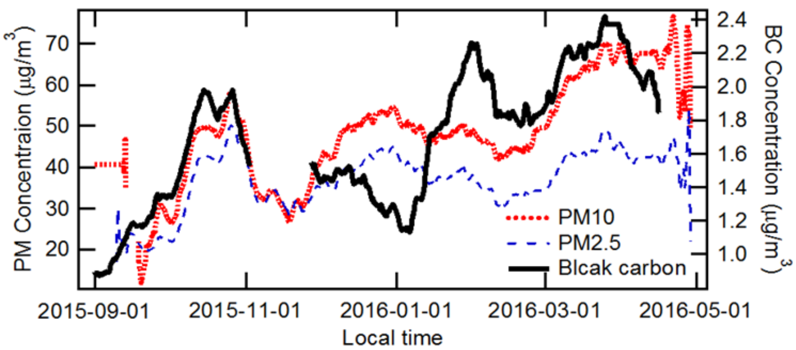


**Fig. 3.** BC, $PM_{10}$, and $PM_{2.5}$ concentrations monitored for 8 months.

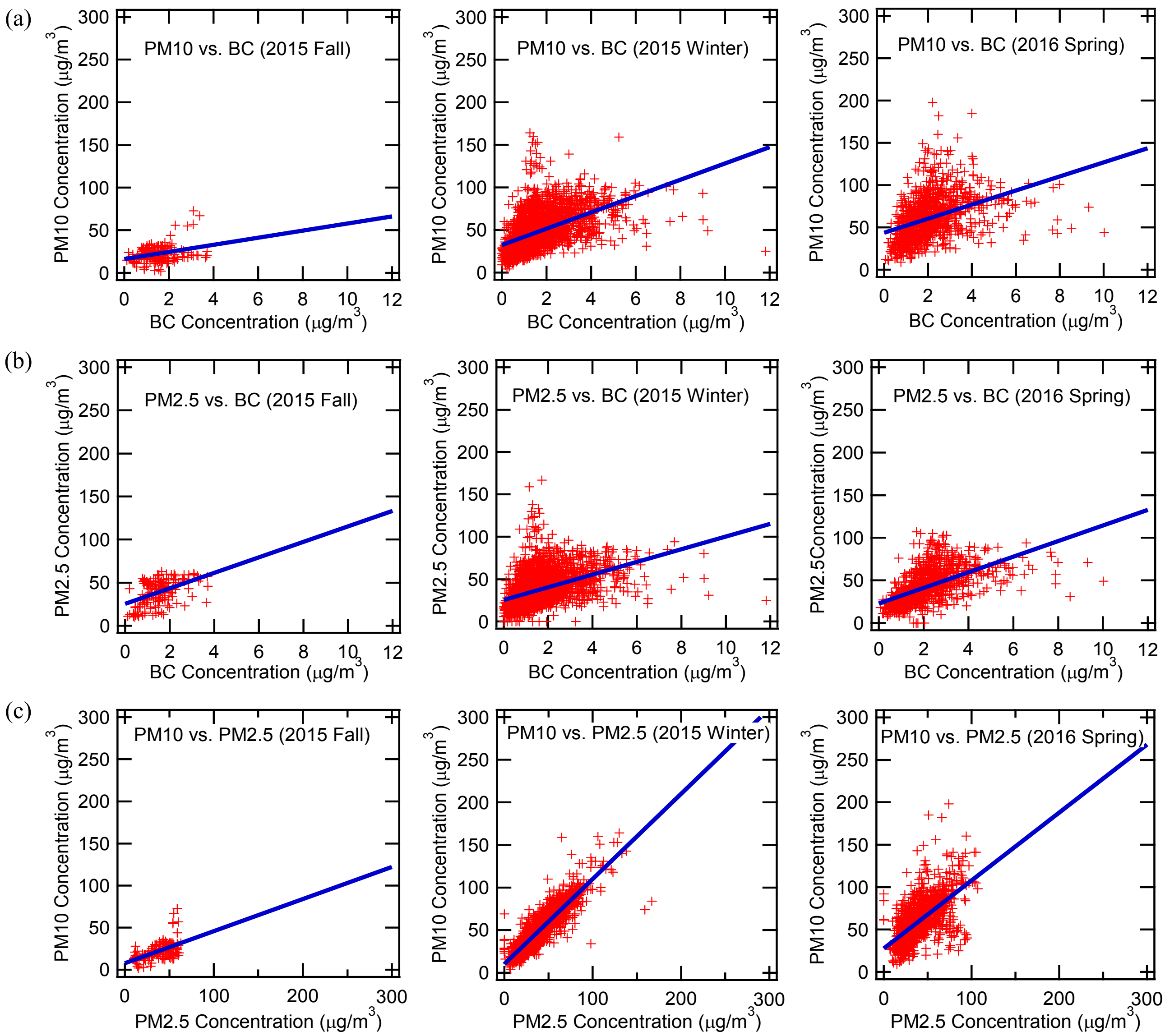


**Fig. 5.** Correlation graphs for (a) $PM_{10}$ concentration vs. BC concentration, (b) $PM_{2.5}$ concentration vs. BC concentration, and (c) $PM_{10}$ concentration vs. $PM_{2.5}$ concentration.

types of emission sources and has a short atmospheric residence time due to their larger size, thereby contributing less to increases in BC concentrations. By contrast, BC consists of carbonaceous particles smaller than 1 µm generated from incomplete combustion of hydrocarbon fuel. In particular, in the study area, there are some unpaved roads in small cities with relatively few mobile pollution sources. Therefore, the low correlation between BC and $PM_{10}$ could be explained by the differences in $PM_{10}$ and BC sources. The $R^2$ between BC and $PM_{10}$ was lower in winter 2015 than in the other seasons (Table 2), indicating that fine dust in winter was weakly related to BC. In other words, the regression analysis indicated that BC and $PM_{10}$ had different compositions and emission sources.

*Correlation between BC and $PM_{2.5}$*

Next, we performed a linear regression analysis of BC and $PM_{2.5}$ concentrations during the three seasons in the study period. The correlations between BC with $PM_{2.5}$ concentrations were similar in fall 2015 ($R^2 = 0.47$), winter 2015 ($R^2 = 0.45$), and spring 2016 ($R^2 = 0.58$) (Fig. 5). The $R^2$ values were higher than those between BC and $PM_{10}$, but still relatively low, suggesting that the $PM_{2.5}$ did not contain a large proportion of BC, and that BC concentrations were not highly correlated with $PM_{2.5}$ concentrations in the study area. Mobile pollution (e.g., diesel vehicle exhaust) is the main source of BC, whereas $PM_{2.5}$ typically originates from secondary formation from atmospheric industrial plant emissions. Therefore, the contribution of BC to $PM_{2.5}$ concentrations was likely low given that the measurements were performed in a small city, where mobile sources did not appear to influence the concentrations.

*Correlation between $PM_{10}$ and $PM_{2.5}$*

Finally, we performed a linear regression analysis of $PM_{10}$ and $PM_{2.5}$ concentrations during the three seasons in the study period. $PM_{10}$ and $PM_{2.5}$ concentrations were positively correlated in fall 2015 ($R^2 = 0.53$), winter 2015 ($R^2 = 0.90$), and spring 2016 ($R^2 = 0.61$) (Fig. 5). The particularly high correlation in winter 2015 may have been driven by the transport of primary pollutants generated from increased fossil fuel use for heating in continental Asia to the Korean Peninsula via westerly winds (Choi, 2008). In contrast, the lowest correlation was observed in fall 2015. Fossil fuel use for heating purposes was likely lower in fall than in winter. In addition, south-easterly and easterly winds were equally dominant as westerly winds in fall 2015, whereas westerly winds were dominant in winter 2015 (Fig. 2). Therefore, $PM_{2.5}$ was retardedly entrained by the Korean Peninsula, resulting in the relatively low correlation between $PM_{2.5}$ and $PM_{10}$ in fall.

***Analysis on Event Days***

Periods with particularly high $PM_{10}$, $PM_{2.5}$, and BC concentrations can be observed in Fig. 3. We attempted to examine the cause of such events by referring to monthly reports generated by the KMA. In particular, $PM_{10}$, $PM_{2.5}$, and BC concentrations increased from mid-October to early November in 2015 (Fig. 6). Based on the monthly KMA reports, Asian Dust may have been one of the reasons for these increases. From the KMA report, Asian Dust originating from Inner Mongolia on October 26 passed over the Yellow Sea, and was observed over the Korean Peninsula on October 26. Asian Dust events are rare in October, although other fall events have been observed in 2009 and 2014, suggesting that Asian Dust transport may not occur exclusively in spring, but also occasionally in fall. As mentioned previously, the discontinuity in the BC measurements in Fig. 6 was due to regular maintenance of the measurement instrument.

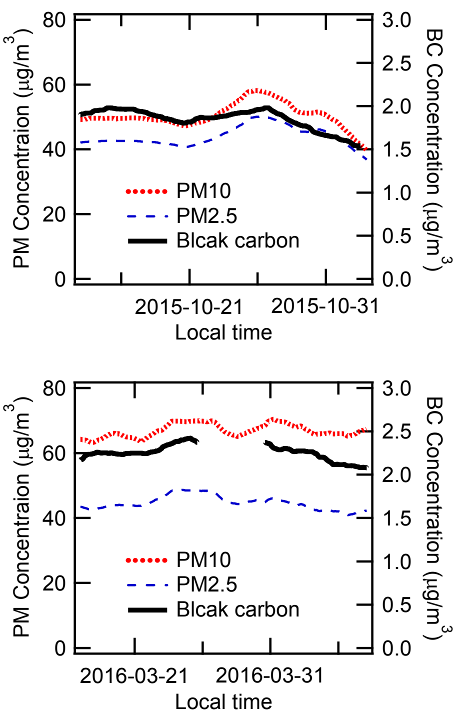


**Fig. 6.** BC, $PM_{2.5}$, and $PM_{10}$ concentrations on two event days.

High $PM_{10}$ and $PM_{2.5}$ concentrations were observed in March 2016 (Fig. 6). From the monthly KMA report, an Asian Dust event even occurred at the end of March, when Asian Dust originating from Mongolia, the Inner Mongolian Plateau, and northern China was transported over the Korean Peninsula via north-westerly winds, increasing PM concentrations.

## CONCLUSIONS

We analyzed the concentrations of BC, $PM_{10}$, and $PM_{2.5}$ from September 2015 to April 2016 in central Korea and compared them with various meteorological parameters. The highest and lowest $PM_{10}$, $PM_{2.5}$, and BC concentrations were observed in spring and fall, respectively. $PM_{10}$ concentrations were high in spring due to Asian Dust transported via westerly winds. In winter, incomplete combustion of fossil fuels used for heating in continental Asia resulted in the transport of emissions over the Korean Peninsula via westerly winds, augmenting PM concentrations. Finally, the low PM concentrations in fall were likely due to increased wind variations driving turbulent mixing.

The BC concentrations generally showed low correlations with $PM_{10}$ and $PM_{2.5}$ concentrations in the three studied seasons. Sometimes, BC exhibited directly proportional relationships with both the $PM_{10}$ and $PM_{2.5}$ concentrations, albeit with low $R^2$ values. The low correlations were possibly due to differences between the sources of BC (i.e., vehicles), $PM_{2.5}$ (i.e., secondary pollution from industrial plant emissions), and $PM_{10}$ (i.e., soil-derived dust). In particular, the low contribution of BC to $PM_{2.5}$ may have been attributable to the study site being located in a small city with little influence from mobile pollution sources.

The $PM_{10}$ and $PM_{2.5}$ concentrations showed a directly proportional relationship, with $R^2$ values as high as 0.90 in winter 2015. This correlation was likely due to the use of fossil fuels for heating in continental Asia—where the primary pollutants generated via incomplete combustion of heating fuel were introduced to the Korean Peninsula via westerly winds from the western coast of Korea—in addition to high concentrations of pollutants from industrial plants. By contrast, the relatively low correlation ($R^2 = 0.53$) in fall was likely caused by south-easterly winds, which blocked the influx of westerly-wind-driven Asian Dust over the Korean Peninsula.

The BC concentrations were high from late October to early November in 2015. According to the monthly KMA report, an Asian Dust event originating in Inner Mongolia occurred during this period. Additionally, in March 2016, Asian Dust from Mongolia was transported over the Korean Peninsula. As such, it is necessary to study the correlation between BC and Asian Dust in greater detail to clarify the contribution of BC to PM concentrations. Given these results, the potentially inaccurate belief held by some researchers that BC is only correlated with $PM_{2.5}$ and $PM_{10}$ warrants further investigation. Overall, this study helps clarify the characteristics of BC over the Korean Peninsula.

We believe that the BC concentrations obtained in this research can be used as urban background values for this region.

## ACKNOWLEDGMENTS

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