Meteorological Characteristics during Periods of Greatly Reduced PM_{2.5} Concentrations in March 2020 in Seoul

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ABSTRACT

In March 2020, the average concentration of PM_{2.5} in Seoul decreased by 44% compared to that in March 2019 (from 45 $\mu\text{g m}^{-3}$ to 25 $\mu\text{g m}^{-3}$). In this study, the synoptic and local meteorological conditions during the period with reduced PM_{2.5} concentrations were analyzed. The synoptic meteorological conditions during March 2020 show a common characteristic of strong zonal flow and winds. Therefore, air circulation was active and meteorological conditions were unfavorable to long-range transboundary transport. Local meteorological conditions such as wind and turbulent motion at the surface were sensitive to PM_{2.5} concentrations. Our analyses indicate that the greatly reduced PM_{2.5} concentrations were mainly influenced by synoptic rather than local conditions. Decreased demand for heating of buildings due to warmer temperatures in March 2020, the economic slowdown following the outbreak of COVID-19, and the implementation of guidelines aimed at controlling particulate matter (PM) were other important causes of reduced PM_{2.5} emissions. A decrease in long-range transboundary transport contributed to the reduced PM_{2.5} concentrations.

Keywords: Seoul, Low PM_{2.5} concentrations, Synoptic meteorology, Local meteorology, COVID-19

1 INTRODUCTION

Seoul, the capital city of South Korea, is a megacity with approximately 10 million inhabitants in an area of 605 km². The terrain around Seoul is dominated by the complex terrain of the surrounding mountains, which range in elevation from 600 m to 900 m, except to the west. The Han River enters Seoul from the east and flows to the west, as shown in Fig. 1. Studies have shown that the concentration of particulate matter with $\leq 2.5 \mu\text{m}$ diameter (PM_{2.5}) is affected by local emissions, meteorological conditions, and long-range transport processes (Park *et al.*, 2019, 2020).

The first case of COVID-19 in South Korea was confirmed on January 20, 2020 (KCDC, 2020a). On February 23, 2020, the Korean government raised its COVID-19 alert to the highest level of “red” in order to strengthen the overall response system (KCDC, 2020b).

The Korean Ministry of Environment reported that the average PM_{2.5} concentrations in Seoul from December 2019 to March 2020 decreased by 27% (from 33 $\mu\text{g m}^{-3}$ to 24 $\mu\text{g m}^{-3}$) compared to the same period one year earlier (KMOE, 2020). Emissions of PM₁₀ from coal power plants, large factories, and ports and shipping were reduced by 2,524, 2,766, and 4,565 tons, respectively, in December 2019 to March 2020 (KMOE, 2020). In Seoul, the average PM_{2.5} concentrations in March 2020 during the COVID-19 epidemic decreased by 44% from 45 $\mu\text{g m}^{-3}$ to 25 $\mu\text{g m}^{-3}$,

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Fig. 1. Inner model domain and location of Seoul City Hall (cross), and surface meteorological observation (Songwol, diamond) and upper-air measurement (Osan, circle) stations in the study area

compared to the average concentration in March 2019 (KMOE, 2020). The Korean Ministry of Environment attributes the reduced $PM_{2.5}$ concentrations to meteorological conditions (43%), the economic slowdown resulting in decreased human activities following the outbreak of COVID-19 (domestic 18%, China 21%) and the implementation of targeted policies to reduce PM concentrations (18%) (KMOE, 2020). Satellite measurements released by the National Aeronautics and Space Administration (<https://earthobservatory.nasa.gov/images/146362/airborne-nitrogen-dioxide-plummets-over-china>) show that from January to March 2020, NO_2 concentrations over China rapidly decreased from the beginning of the COVID-19 outbreak. There are evidence that the reductions are partly related to the economic slowdown following the outbreak of COVID-19.

China experienced a significant reduction in NO₂ concentrations in February 2020. The anomalies of NO₂ concentrations relative to the mean (2010–2020) for 2020 are reduced by an average of 15% (approximate) in March and 25% (approximate) in February over China (Metya *et al.*, 2020). The Ministry of Ecology and Environment of China (MEE) reported that the average PM_{2.5} concentration in 337 cities in China from January 20, 2020 to March 12, 2020 decreased by 19.6% (from 56 µg m⁻³ to 45 µg m⁻³) compared to the same period in the previous year (MEE, 2020).

KMA (2020a) reported that the monthly average temperature in South Korea in March 2020 was 7.9°C (standard deviation 2°C), the second highest since March 1973. The most important regions in Asia and Europe (northern Italy, Spain, and Japan) that were subject to outbreaks of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) also recorded a similar warmer winter with mean monthly air temperature up to 2°C higher than the long-term means (Sfica *et al.*, 2020). Warmer conditions have played a favorable role in personal mobility and gathering, as well as in the survival of the virus in the environment (Sfica *et al.*, 2020). Meteorological conditions are an important external factor that can affect pollutant accumulation and diffusion, and chemical processes in a region. Synoptic and local meteorological conditions play an important role in controlling concentrations of air pollutants (Li *et al.*, 2019; Park *et al.*, 2019). Meteorological factors such as relative humidity, wind speed, and temperature have non-negligible impacts on local PM_{2.5} concentration (Cheng and Lam, 1998; Wen *et al.*, 2018; Meng *et al.*, 2020). Horizontal distributions of PM₁₀ concentrations in the Seoul Metropolitan Area are strongly governed by the wind and temperature (Park *et al.*, 2019).

Synoptic meteorological conditions play an important role in high PM₁₀ concentrations observed in spring and winter in the Seoul Metropolitan Area (Park *et al.*, 2020). The high concentrations are accompanied by weak migratory anticyclone systems over the Korean Peninsula (Park *et al.*, 2020). In Taiwan, six synoptic weather patterns associated with air pollutants such as PM₁₀, PM_{2.5}, and O₃ have been identified (Hsu and Cheng, 2019). The winter weather conditions that correspond to the intrusion of the Asian continental anticyclone, affected by the continental high-pressure peripheral circulation and a weak synoptic weather pattern, are associated with higher air pollutant concentrations (Hsu and Cheng, 2019). In a study on the relationship between air pollution and synoptic circulation in northern China, higher air pollutant concentrations were mainly related to cyclonic southern (S), southeastern (SE) and southwestern (SW), and eastern (E) circulation, whereas lower air pollutant concentrations were associated with anticyclonic northern (N) and western circulation (W) (Li *et al.*, 2019). High PM_{2.5} concentrations in the United States are correlated with 850 hPa geopotential height under anticyclonic conditions (Tai *et al.*, 2010). During air pollution events, a high-pressure system on the surface is formed and a ridge is established at the upper levels (Guo *et al.*, 2020). The near-surface horizontal divergence or pumping action at the top of the boundary layer promotes horizontal or vertical diffusion of surface air pollutants (Wang and Zhang, 2020).

From January to February 2020, the national mean PM_{2.5} concentration in Korea was lower than the national mean during the same period in 2019, and the monthly mean in March 2020 was significantly lower than that in March 2019 (Min *et al.*, 2020). The national average concentrations of PM_{2.5} and PM₁₀ in Korea in March 2020 during COVID-19 were 45.45% (16.98 µg m⁻³) and 35.56% (21.61 µg m⁻³) lower, respectively, compared to the same period in 2019 (Min *et al.*, 2020). However, significant effects of meteorological conditions on reducing PM_{2.5} and PM₁₀ concentrations (KMOE, 2020) have not been considered (Min *et al.*, 2020). Most citizens in Korea, including environmental scientists, believe that the decrease in PM_{2.5} concentrations from January to March 2020 can be attributed solely to reduced emissions due to human behavior changes such as social distancing and economic slowdown. Most studies related to decreased air pollution associated with the COVID-19 epidemic have focused on human behavior rather than on the meteorological impacts. The main point of this study was to investigate synoptic meteorology and local meteorological conditions in the surface and atmospheric boundary layer (ABL) with respect to PM_{2.5} concentrations in March 2020 during the COVID-19 epidemic, compared to those in March 2019. The goal of this study was to ascertain whether meteorological characteristics played an important role in affecting PM_{2.5} concentrations and contributed to the measured decrease in PM_{2.5} concentrations, compared to other factors such as the economic impacts, and to improve our understanding of the factors influencing PM_{2.5} concentrations in Seoul during the COVID-19 epidemic.

2 DATA AND METHODS

The approach used in this study utilizes data for synoptic and surface meteorology (National Center for Atmospheric Research (NCAR)) and data from an upper sounding observation network (Korea Meteorological Administration (KMA)) and air quality monitoring network (Korea Ministry of Environment (KMOE)) together with micrometeorological characteristics in the ABL predicted by the Air Pollution Model (TAPM; Hurley, 2008). Hourly $\text{PM}_{2.5}$ concentrations monitored at 25 urban quality stations in Seoul from March 2019 to March 2020 were used (<http://www.airkorea.or.kr>). The variation in the daily mean $\text{PM}_{2.5}$ concentrations at 25 stations in March during 2019, 2020, and 2016–2020 is shown in Fig. 2. Fig. 2 shows the five cases in 2019 when $\text{PM}_{2.5}$ concentrations were higher than in March 2020. Four cases (case 1, March 3–7; case 2, March 10–13; case 3, March 19–22; and case 4, March 26–29) are used in this study because March 14–17 had $\text{PM}_{2.5}$ concentrations below the 24-hr air quality standard ($35 \mu\text{g m}^{-3}$). As shown in Table 1, $\text{PM}_{2.5}$ concentrations in March 2020 were lower than both mean $\text{PM}_{2.5}$ concentrations in March 2019 and mean $\text{PM}_{2.5}$ concentrations in March from 2016 to 2020.

To compare the synoptic meteorological characteristics of the four cases shown in Fig. 2, NCAR final run (FNL) data from the Global Data Assimilation System (GDAS), covering the Far East Asian region centered on the Korean Peninsula ($20^{\circ}\text{--}60^{\circ}\text{N}$ and $100^{\circ}\text{--}150^{\circ}\text{E}$), were used. In this study, geopotential height and horizontal wind field at each isometric elevation were used. Differences between March 2019 and March 2020 were obtained by averaging the data at each altitude (1000, 925, 850 hPa). In addition, the average field for each period of the four cases was calculated and the difference between years was compared.

Local meteorology, including wind speed and direction, temperature, and relative humidity was obtained from the Seoul Automatic Synoptic Observation Station (located at Songwol, indicated by a diamond in Fig. 1; <https://data.kma.go.kr>). The station is located 1.2 km northwest of Seoul City Hall. Vertical profiles of virtual potential temperature at the Osan World Meteorological Organization (WMO) monitoring station (circle in Fig. 1) were used. The Osan monitoring station is located 43 km south of Seoul.

Fig. 2. Daily variation in $\text{PM}_{2.5}$ concentrations in Seoul during March 2019, 2020, and 2016–2020 (dotted lines represent the monthly mean in March 2019, 2020, and 2016–2020).

Table 1. $\text{PM}_{2.5}$ mean concentrations ($\mu\text{g m}^{-3}$) for four cases in March during 2019, 2020, and 2016–2020.

Year	March 5	March 12	March 20	March 27	March
2019	135	49	68	60	45
2020	27	14	9	21	25
2016–2020	46	42	39	47	35

Micrometeorology, expressed as heat flux and turbulence parameters in the ABL, was predicted using TAPM based on grids of $100 \times 100 \times 25$ at three domains (12 km, 4 km, 2 km) centered on Seoul City Hall (latitude $37^{\circ}33.970'N$ and longitude $126^{\circ}58.671'E$; cross in Fig. 1). For the initial conditions of the meteorological variables, Global Assimilation and Prediction System (GASP) data with a resolution of $75 \text{ km} \times 100 \text{ km}$ (<ftp://ftp.csiro.au/TAPM>) and surface and land use data ($1 \text{ km} \times 1 \text{ km}$) from the United States Geological Survey (USGS; Hurley, 2008) were used.

3 RESULTS AND DISCUSSION

3.1 Synoptic Meteorological Characteristics

The synoptic meteorological conditions play an important role in high PM_{10} concentration (Tai *et al.*, 2010; Li *et al.*, 2019; Guo *et al.*, 2020). The high concentrations are accompanied by weak migratory and stationary anticyclone systems over the Korean Peninsula (Park *et al.*, 2019, 2020). The high air pollution concentration in Taiwan is affected by the continental high-pressure peripheral circulation and a weak synoptic weather pattern (Hsu and Cheng, 2019).

In this study, the synoptic meteorological characteristics were analyzed using the difference between March 2020 with low PM concentration and March 2019 with high concentration. The difference shown in Figs. 3–7 is the difference between the geopotential height and the wind, calculated from the period mean in 2020 minus the period mean in 2019. Calculating differences in this way means that the positive domain in Figs. 3–7 has a higher value for the geopotential height in 2020, indicating a greater tendency for high pressure in the region in 2020. If the wind vector calculated in this way appears in a westerly direction, it means that the easterly wind tendency was stronger in 2020 than 2019. The magnitude of the wind vector in Figs. 3–7 depends on the difference between the two periods. Therefore, large and small wind vectors shown in Figs. 3–7 indicate strong and weak variations, respectively.

Fig. 3 shows the difference between the period mean field at each isobaric plane (1,000, 925, and 850 hPa) in March 2020 and March 2019 using NCAR FNL data.

There is a negative area of difference in geopotential height, extending to the east and west, which is centered on $55^{\circ}N$, far northwest of the Korean Peninsula. In inland China, west of the Korean Peninsula, there are small zones where the difference in geopotential height is negative, and is similar at 1,000, 925, and 850 hPa. The period mean wind direction in the Korean Peninsula in March 2020 is comparatively more westward than that in 2019, and this characteristic is stronger in the lower than the upper layer. This shows that the high-pressure system to the west and north of the Korean Peninsula was weaker in March 2020 compared to 2019, with a stronger easterly wind component. The results from the overall period mean difference in March show

Fig. 3. Difference between the period mean geopotential height and wind in March 2020 and March 2019 [(a) 1,000 hPa, (b) 925 hPa, (c) 850 hPa].

that there is a greater difference in areas far from the Korean Peninsula than on the Korean Peninsula.

The differences in averages for the first case period, March 3 to March 7, are presented in Fig. 4. With the Korean Peninsula at the center, the positive zone of geopotential height difference appears in the southeast and northeast parts of the Japanese archipelago, and the negative zone appears in areas close to 50°N to 60°N and 100°E to 125°E. Wind differences around the western part of the Korean Peninsula are strong in the case of 1,000 hPa in the northwest direction in the West Sea. This difference indicates a shift to southwest-facing deviations as the altitude rises to 925 hPa and 850 hPa. Thus, during this period, there is a stronger tendency for high pressure in 2020 than in 2019 and the air flowing into and out of the Korean Peninsula through the lower atmosphere from China has weakened.

Fig. 5 shows the difference in average field for the second case period (March 10–March 13). The zone of positive deviation in geopotential height, located north of the Korean Peninsula, exists at an altitude of 1,000 hPa and slightly further south at altitudes of 925 hPa and 850 hPa. The deviation of high-pressure wind appears around this positive deviation zone. In other words, most of the wind deviations in areas near China's coast are in the northwesterly direction, while

Fig. 4. Difference between the period mean geopotential height and wind on March 3 to 7 in 2020 and in 2019 [(a) 1,000 hPa, (b) 925 hPa, (c) 850 hPa].

Fig. 5. Difference between the period mean geopotential height and wind on March 10 to 13 in 2020 and in 2019 [(a) 1,000 hPa, (b) 925 hPa, (c) 850 hPa].

Fig. 6. Difference between the period mean geopotential height and wind on March 19 to 22 in 2020 and in 2019 [(a) 1,000 hPa, (b) 925 hPa, (c) 850 hPa].

Fig. 7. Difference between the period mean geopotential height and wind on March 26 to 29 in 2020 and in 2019 [(a) 1,000 hPa, (b) 925 hPa, (c) 850 hPa].

those far north of the Korean Peninsula appear stronger as the wind deviations in the easterly direction move to the upper levels. Such characteristics explain why air was less inclined to flow into the Korean Peninsula from China in 2020 than in 2019.

The difference for the third case (March 19–March 22) is shown in Fig. 6. According to this analysis, the north (centered on 50°N) has an east-west distribution of areas representing negative geopotential height differences. The center of this area of negative deviation is in the north of the Japanese archipelago. In the far southeast of the Japanese archipelago, there is a positive deviation zone center. Due to these differences in synoptic characteristics, wind deviation around the Korean Peninsula appears to be strengthening on average in the northeasterly direction at an altitude of 1,000 hPa, but the wind deviation decreases farther west across the Korean Peninsula. The deviation of air current in 925 hPa and 850 hPa is west-northwest, and its value increases from 925 hPa to 850 hPa. Analysis of synoptic meteorological characteristics indicates that air currents entering the Korean Peninsula may flow faster in the easterly direction in 2020 compared to 2019.

The meteorological features of the difference during March 26 to March 29, corresponding to the fourth case, are shown in Fig. 7. The center of weak negative difference in geopotential height

exists in the southern part of the Korean Peninsula, and the surrounding winds show an anti-clockwise deviation. This kind of wind deviation is coupled with the influence of the area of positive geopotential height deviation, which is distributed from west to east and centers on the Korean Peninsula. This increases the size of the wind deviation in the north and south of the West Sea of Korea. The direction of this deviation is on average north to south at 1,000 hPa, northeast to southwest at 925 hPa, and east to west at 850 hPa, which is larger than at 925 hPa. Synoptic meteorological conditions during this period in 2020 prevented the flow of air from inland China into the Korean Peninsula.

3.2 Meteorology at Surface and Boundary Layers

The daily variation in wind speed and direction, temperature, and humidity in March 2019 and 2020 at Songwol station (Fig. 1) are shown in Fig. 8. The average wind speed in March 2020 (2.5 m s^{-1}), with lower $\text{PM}_{2.5}$ concentrations, is higher than that in March 2019 (2.1 m s^{-1}), with higher $\text{PM}_{2.5}$ concentrations. In particular, the wind speed during high $\text{PM}_{2.5}$ event days in March 2019 is much lower than the wind speed in March 2020. The prevailing wind direction in March 2020 and 2019 is south-southwest and north-northwest, respectively. The average temperature in March 2020 (7.7°C), with lower $\text{PM}_{2.5}$ concentrations, is higher than that in March 2019 (7.1°C), with higher $\text{PM}_{2.5}$ concentrations. However, temperatures for March 2 to March 6, 2020, a period with 60% cloud cover, are much lower than those in 2019. The average relative humidity in March 2020 (46%) is lower than that in March 2019 (51%). In particular, relative humidity during high $\text{PM}_{2.5}$ event days in March 2019 is much higher than the average relative humidity in March 2020, except for days with greater cloud cover. The time series (Fig. 8) indicates that the wind speed has a roughly diurnal variation, with higher wind speed and westerlies during the day and lower wind speed and easterlies at night. Local winds are dominant under clear skies and when a weak synoptic system is present (Park, 2018). The influence of factors such as wind, temperature, and relative humidity on $\text{PM}_{2.5}$ concentrations is similar to findings from previous studies (Park *et al.*, 2019; Meng *et al.*, 2020; Zou *et al.*, 2021).

Net radiation and sensible heat are important drivers of $\text{PM}_{2.5}$ concentrations because they directly affect the evolution of turbulent motion in the boundary layer (Park, 2018). Turbulence is the dominant mechanism for the vertical mixing of air pollutants (Du *et al.*, 2013). Net radiation, sensible heat, and turbulent parameters predicted by TAPM in central Seoul were analyzed. The observed meteorology at Songwol Station (Fig. 1) was used to validate the simulated results. Results were evaluated using statistical performance measures such as the index of agreement (IOA), root mean square error (RMSE), and correlation coefficient (R). Table 2 shows the RMSE, R, and IOA for March 2019 and March 2020. The IOA for temperature, RH, u and v component in March 2019 are 0.77, 0.59, 0.63 and 0.52, respectively. The IOA for temperature, RH, u and v component in March 2020 are 0.74, 0.56, 0.57 and 0.46, respectively. These values show that the meteorology was simulated reasonably well for all cases. The statistical performance in this study is similar to that in recent studies in the Seoul Metropolitan Area (Park *et al.*, 2019, 2020).

Fig. 9 shows the daily variation in radiation and turbulent parameters in central Seoul for March 2019 and 2020. The average net radiation and sensible heat in March 2020 (106.0 W m^{-2} and 105.7 W m^{-2}), with lower $\text{PM}_{2.5}$ concentrations, are higher than those in March 2019 (97.2 W m^{-2} and 95.4 W m^{-2}), with higher $\text{PM}_{2.5}$ concentrations. Net radiation and sensible heat during high $\text{PM}_{2.5}$ event days in March 2019 are much lower in general than those in March 2020 but are higher on March 4 (90% from 01 Local Solar Time (LST) to 05 LST and 80% from 13 LST to 18 LST) in the period from March 3 and 7 with cloud cover of 60% (KMA, 2020b). Net radiation and sensible heat show a diurnal pattern typical of an urban area (Park *et al.*, 2019). The sensible heat in March was approximately 100 W m^{-2} , reflecting anthropogenic heat in Seoul (Lee *et al.*, 2019).

Convective velocity ranged from 0.6 m s^{-1} to 2.8 m s^{-1} in March 2019 and from 0.7 m s^{-1} to 2.6 m s^{-1} in March 2020, with the maximum in the afternoon and minimum in the early morning related to net radiation. Convective velocity was higher during periods with lower $\text{PM}_{2.5}$ concentrations than in periods with higher $\text{PM}_{2.5}$ concentrations, again with the exception of March 4 when cloud cover was 60%. Friction velocity ranged from 0.4 m s^{-1} to 1.0 m s^{-1} in March 2019 and from 0.4 m s^{-1} to 1.3 m s^{-1} in March 2020 with the maximum during higher wind speeds and the minimum during lower wind speeds. Friction velocity was higher during periods with

Fig. 8. Time series of surface meteorological factors in the Seoul Metropolitan Area during March 2019 and 2020 (black rectangle represents days with high concentration in 2019 and low concentration in 2020).

Table 2. Root mean square error (RMSE), correlation coefficient (R), and index of agreement (IOA) between simulated and observed temperature ($^{\circ}\text{C}$), relative humidity (RH; %), and U (m s^{-1}) and V (m s^{-1}).

Case		Surface Meteorology			
		Temp	RH	U	V
March 2019	RMSE	2.20	17.09	1.45	1.36
	R	0.93	0.76	0.70	0.59
	IOA	0.77	0.59	0.63	0.52
March 2020	RMSE	2.06	18.77	1.34	1.24
	R	0.89	0.70	0.63	0.45
	IOA	0.74	0.56	0.57	0.46

Fig. 9. Time series of net radiation, sensible heat flux, convection velocity, friction velocity, mixing height, and Monin-Obukhov length in Seoul simulated by TAPM during March 2019 and 2020 (black rectangle represents days with high concentration in 2019 and low concentration in 2020).

lower PM_{2.5} concentrations than periods with higher PM_{2.5} concentrations, regardless of cloud cover (Park, 2018).

Mixing height ranged from 430 m to 1,986 m in March 2019 and from 444 m to 1,987 m in March 2020, with the maximum occurring in the afternoon and the minimum occurring in the early morning. Mixing height is generally higher during periods with lower PM_{2.5} concentrations than in periods with higher PM_{2.5} concentrations (Park *et al.*, 2019; Zou *et al.*, 2021). Monin-Obukhov length ranged from 62 m to 999 m in March 2019 and from 97 m to 999 m in March 2020. Monin-Obukhov length is the height at which turbulence is generated more by buoyancy than by wind shear. As turbulent energy is generated by buoyancy during unstable conditions, Monin-Obukhov length is generally higher in periods with lower PM_{2.5} concentrations than during periods with higher PM_{2.5} concentrations and is usually negative during the day and positive at night (Li *et al.*, 2018).

Fig. 10 shows the vertical profile of virtual potential temperature at the Osan WMO monitoring station at 09 LST and 21 LST on days with the highest PM_{2.5} concentrations in March 2019 and the lowest PM_{2.5} concentrations in March 2020. The formation and evolution of high PM_{2.5} concentration events are closely related to temperature inversion layers (Li *et al.*, 2018; Zou *et al.*, 2021). The inversion strength below 2 km at 9 LST and 21 LST was 7.5 K km⁻¹ and 5.7 K km⁻¹ on March 5, 2019 on the day with the highest concentration, and 6.7 K km⁻¹ and 6.9 K km⁻¹ on March 5, 2020 on the day with the lowest concentration (Table 3). The inversion strength during periods with higher PM_{2.5} concentrations in the morning was greater than that during periods with lower PM_{2.5} concentrations, except for one case (March 12, 2019) that occurred during strong easterly winds around the West Sea. The inversion layer in the Seoul Metropolitan Area in spring is frequently formed by radiative cooling (Park *et al.*, 2019, 2020). The inversion layer was present in the morning in both March 2019 and March 2020, although the inversion strength in March 2020 with lower PM_{2.5} concentrations was lower than that in March 2019 with higher PM_{2.5} concentrations. The results of our analysis indicate that the reduction in PM_{2.5} concentrations in March 2020 during the COVID-19 epidemic was mainly influenced by synoptic meteorological conditions.

4 CONCLUSIONS

During March 2020, the center of a high-pressure system was located between the east coast of China and the central part of the West Sea near the Korean Peninsula. Therefore, inflowing air from continental China did not enter the Korean Peninsula. In the northern part of the Korean Peninsula, low pressure was widely distributed from west to east. There was a strong high-pressure area extending from the east to the west on the Korean Peninsula. A strong divergence of pressure fields around the Korean Peninsula occurred. The high-pressure system over the Korean Peninsula expanded eastward in March 2020 relative to March 2019. The low-pressure system north of the Korean Peninsula was stronger than in March 2019. High pressure systems result in strong easterly wind near the West Sea. The average wind direction in March 2020 in the Korean Peninsula was relatively more easterly compared to that in 2019, and this characteristic was stronger in the lower atmosphere than in the upper atmosphere. We estimate that the PM_{2.5} concentrations during March 2020 were reduced to approximately 9 µg m⁻³ (maximum) by the synoptic meteorological conditions around the northern and eastern areas of the Korean Peninsula.

An inversion layer at the surface, resulting from radiative cooling, frequently forms in March over the Seoul Metropolitan Area. Therefore, the inversion layer is likely to be present regardless of the PM_{2.5} concentrations, even though the inversion strength is greater during periods with higher PM_{2.5} concentrations. Our analyses show that the magnitude of net radiation and convection velocity were inversely related to PM_{2.5} concentrations, except on days with cloud cover of 60%. We found that friction velocity was inversely related to PM_{2.5} concentrations regardless of cloud cover. Convection and friction velocity were positively related to temperature and wind speed. Turbulent motion in the Seoul Metropolitan Area during March was mainly dominated by buoyancy rather than mechanical turbulence.

The results presented here suggest that the greatly reduced PM_{2.5} concentrations in March 2020 were mainly influenced by synoptic meteorology rather than local meteorology. During

Fig. 10. Vertical profiles of virtual potential temperature observed at the Osan World Meteorological Organization (WMO) upper-air measurement station at 09 Local Solar Time (LST) (00Z) and 21 LST (12Z).

Table 3. Strength (K km^{-1}) of the temperature inversion below 2 km at 0900 Local Solar Time (LST) and 2100 LST at Osan World Meteorological Organization (WMO) upper-air measurement station.

Date		09 LST	21 LST
5 March	2019 ¹	7.5	5.7
	2020 ²	6.7	6.9
12 March	2019 ¹	5.4	2.5
	2020 ²	7.3	3.8
20 March	2019 ¹	8.2	6.8
	2020 ²	4.9	6.0
27 March	2019 ¹	7.7	5.3
	2020 ²	6.2	4.9

¹ highest day; ² lowest day.

March 2020, air circulation was active and meteorological conditions were unfavorable to long-range transboundary transport. The reduced emissions related to warm seasonal temperatures during late spring in 2020, together with the economic slowdown following the outbreak of COVID-19, contributed in a large way to the reduced PM_{2.5} concentrations. The implementation of targeted policies aimed at reducing PM_{2.5} emissions and a decrease in long-range transboundary transport also contributed to the reduction in PM_{2.5} concentrations.

As a next step, the mechanisms that explain the differences between the synoptic meteorological conditions between March 2019 and March 2020 should be studied to improve understanding of how meteorological impacts lead to decreased PM_{2.5} concentrations. We recommend further studies to explore PM_{2.5} concentrations in India and China following the COVID-19 lockdown, due to their large human populations. Future studies should evaluate whether meteorological impacts or changes in human activities are more dominant in their effect on PM_{2.5} concentrations.

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