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Reduction in urban atmospheric CO₂ enhancement in Seoul, South Korea, resulting from social distancing policies during the COVID-19 pandemic

Chaerin Park, Sujong Jeong, Yong-seung Shin, Yeong-seop Cha, Ho-chan Lee

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A B S T R A C T
With the spread of the COVID-19 virus globally, cities worldwide have implemented unprecedented social distancing policies to mitigate infection rates. Many studies have demonstrated that improved air quality and reduced carbon emissions have resulted from the COVID-19 pandemic. Yet, questions remain regarding changes in atmospheric CO₂ concentrations because of the complex cycles involving the interaction of CO₂ with the natural environment. In this study, we compared the changes in urban CO₂ enhancement ($\Delta$CO₂) reflecting the contribution of local CO₂ emissions to the atmospheric CO₂ in urban areas, according to the intensity of social distancing policies implemented during the COVID-19 pandemic in Seoul, South Korea. We used data from three CO₂ ground observation sites in the central area of Seoul and outside the urban area of Seoul. By comparing the urban CO₂ concentration in Seoul with that of the background area using two different methods, considering both vertical and horizontal differences in CO₂ concentration, we quantified the $\Delta$CO₂ of the pre-COVID-19 period and two COVID-19 periods, during which intensive social distancing policies with different intensities were implemented (Level 1, Level 2.5). During the pre-COVID-19 period, the average $\Delta$CO₂ calculated using the two methods was 24.82 ppm, and it decreased significantly to 16.42 and 14.36 ppm during the Level 1 and Level 2.5 periods, respectively. In addition, the urban contribution of Seoul to atmospheric CO₂ concentration decreased from 5.27% during the pre-COVID-19 period to 3.54% and 3.19% during the Level 1 and Level 2.5 periods, respectively. The results indicate that the social distancing policies implemented in Seoul resulted in reduced local CO₂ emissions, leading to a reduction in atmospheric CO₂ concentration. Interestingly, it also shows that the extent of atmospheric CO₂ concentration reduction can be greatly affected by the intensity of policies. Our study suggests that changes in human activity could reduce the urban direct contribution to the background CO₂ concentration helping to further mitigate climate change.

1. Introduction
Owing to increased CO₂ emissions from the usage of fossil fuel, global CO₂ concentrations continue to increase, exceeding 400 ppm from observation taken in 2015 (Friedlingstein et al., 2019). Increasing atmospheric CO₂ concentrations promoted by human activity contributes to climate change (Stocker, 2014). Accelerated climate change has recently triggered the increased frequency of extreme and abnormal weather conditions, such as heat waves and heavy rains, on a global basis (Coumou and Rahmstorf, 2012). Although initiatives have aimed to reduce CO₂ emissions worldwide, such as international agreements at the city and national levels, CO₂ concentrations are increasing despite these efforts (Rosenzweig et al., 2010; Friedlingstein et al., 2019).

However, recent studies show that global CO₂ emissions decreased significantly in early 2020, owing to the onset of the COVID-19 pandemic (Han et al., 2020; Le Quéré et al., 2020; Rugani and Caro, 2020; Zambrano-Monserrate et al., 2020). The outbreak of the COVID-19 virus began in December 2019 in Wuhan, China, spreading rapidly worldwide. In response to the COVID-19 pandemic, cities have implemented unprecedentedly strong social distancing policies to slow the spread of the virus (Hudda et al., 2020; Ju et al., 2020; Shakil et al., 2020). The social distancing policies affected routine human activities, such as reduced vehicle transportation and energy consumption (e.g., in schools and offices) compared with those before the COVID-19 pandemic.
pandemic, impacting CO₂ emissions (Han et al., 2020; Le Quéré et al., 2020; Rugani and Caro, 2020; Zambrano-Monserrate et al., 2020). According to a preliminary study, global CO₂ emissions during the COVID-19 pandemic were reduced by 17% compared to a baseline before the pandemic (Le Quéré et al., 2020). Furthermore, CO₂ emissions on a national basis also significantly decreased, including by 20% and 11% in China and Italy, respectively, during the COVID-19 pandemic (Han et al., 2020; Rugani and Caro, 2020).

Although recent studies have shown reductions in carbon emissions (e.g., an indicator of carbon consumption), appropriate analysis regarding the extent to which atmospheric CO₂ concentrations (e.g., the output of carbon combustion) decreased in response to reduced CO₂ emissions has been lacking. The atmospheric CO₂ concentration is affected not only by CO₂ emissions but also by complex cycles involving the atmosphere or biosphere (Xueref-Remy et al., 2018). However, on a city scale, it is possible to estimate the impact of social distancing policy on changes in urban CO₂ concentration. In a city, atmospheric CO₂ concentrations can be strongly influenced by either direct (e.g., transportation and energy use for heating or cooling) or indirect causes (e.g., atmospheric transport from outside the city). Here, the direct contribution of local carbon emissions to the observed atmospheric CO₂ concentrations is called urban CO₂ enhancement (Verhulst et al., 2017; Xueref-Remy et al., 2018). In general, urban CO₂ enhancement is calculated from the difference between the CO₂ concentration in a city and an urban background area (Rice and Bostrom, 2011; Hutrya et al., 2011; Büns and Kuttler, 2012; McKain et al., 2012; Moore and Jacobson, 2015; Pan et al., 2016; Verhulst et al., 2017; Gao et al., 2018; Xueref-f-Remy et al., 2018). If there are limited anthropogenic CO₂ emissions within the city area, then the CO₂ concentration in the city should be similar to the CO₂ concentration in the background area. In other words, the extent to which atmospheric CO₂ concentrations increased due to CO₂ emissions in urban areas can be evaluated by how much the atmospheric CO₂ concentration has increased since it was entered into the urban areas from the background. With the adoption of the concept of urban CO₂ enhancement, the impact of various local emission factors on urban CO₂ concentrations can be highlighted.

In this study, we evaluated the impact of reduced human activity on regional CO₂ concentrations during the COVID-19 pandemic in Seoul, South Korea. Seoul is known as one of the largest megacities worldwide. It is also known as one of the largest emitters of CO₂ among major metropolitan areas (Moran et al., 2018; Nangini et al., 2019; Park et al., 2020a). The COVID-19 virus began to spread to a serious level in Seoul in February 2020, and very stringent social distancing policies had been implemented phase-by-phase since March 2020. Thus, the effect of the stepwise social distancing policies on CO₂ concentration can be determined (Ju et al., 2020). The social distancing policies implemented in Seoul are considered to be the most successful worldwide, and as more intensive policies have been implemented since September 2020, the effect of policy intensity on CO₂ concentration reduction can be evaluated. In addition, real-time observations of CO₂ concentration are being performed in Seoul; thus, it is possible to analyze the effect of CO₂ emission reduction on atmospheric CO₂ concentration in real-time (Park et al., 2020b). These recent measures provide a good opportunity to examine the effect of reducing atmospheric CO₂ concentration based on the degree to which CO₂ emissions are reduced in stages.

2. Method

2.1. CO₂ concentration data and analysis

Data from the Seoul National University CO₂ Measurement (SNUCO₂M; Park et al., 2020b) were used to analyze urban CO₂ concentrations in Seoul. SNUCO₂M is an atmospheric CO₂ concentration measuring instrument equipped with an LI-850 CO₂ sensor (LI-850, Licor Inc., Lincoln, NE, USA) and several customized components, measuring CO₂ concentration every second and storing the average CO₂ concentration per minute in a data logger. The stored data can be monitored and downloaded remotely in real-time through a co-equipped LTE router. A two-point calibration was performed for the SNUCO₂M once every two weeks using zero gas (0 ppm) and two span gases of CO₂ (400 and 1000 ppm). The maximum error range of SNUCO₂M is 0.71% from the observed value, indicating that it is suitable for measuring a wide range of urban CO₂ concentrations (Park et al., 2020b).

SNUCO₂M was installed at several sites around the Seoul Capital Area. In this study, two sites from the SNUCO₂M network were used. One site was located on the roof of the Yongsan Building (YSB, 37.523°N, 126.963°E), operating since October 2018. The inlet was installed at a height of 113 m above mean sea level (asl), unaffected by surrounding structures, allowing the sampling of well-mixed urban air. The YSB site is located in the center of Seoul with a suitable observation height, enabling the measurement of the effects of CO₂ emissions in Seoul for all time zones. The other site was the Namsan Seoul Tower (NST, 37.551°N, 126.988°E), operating since July 2019. The SNUCO₂M at NST is located horizontally near the YSB site (i.e., 3.5 km apart), but the inlet was installed at a much higher altitude (420 m asl). A comparison of CO₂ concentrations from YSB and NST facilitates an evaluation of CO₂ concentration based on altitude.

In addition to the two urban sites in Seoul, CO₂ concentrations were measured at the top of the Gwanak Mountain, located far from the central area of Seoul (GWA, 37.443°N, 126.967°E, 629 m asl; Park et al., 2020b). GWA has been in operation as a representative background atmospheric CO₂ site of Seoul since January 2009. A Picarro CO₂ analyzer (G2131, Picarro Inc., Santa Clara, CA, USA) was installed at the site, and the CO₂ analyzer had a precision of <200 ppb and was calibrated regularly using the same method as the SNUCO₂M. Hourly averaged CO₂ concentration data were used in this study after removing the outlying CO₂ concentration data at the three sites, caused by malfunction of the instrument and calibration.

The observed CO₂ concentration data were analyzed using two methods (Park et al., 2020b) to quantify urban CO₂ enhancement ($\Delta$CO₂ = CO₂Urban – CO₂Background), representing the urban contribution of atmospheric CO₂ concentration from Seoul. In brief, the first method considered the difference in vertical CO₂ concentrations in the Seoul Capital Area. By comparing the CO₂ concentrations measured at YSB and NST, located adjacent to each other but at different altitudes, the CO₂ enhancement ($\Delta$CO₂) could be quantified (i.e., a local effect). At night, when the planetary boundary layer (PBL) in Seoul decreases below 400 m, NST is located above the PBL, and the incoming air transported from the background area outside the Seoul urban area is observed; meanwhile, YSB remains located below the PBL, and the air within Seoul urban area is continuously observed. Considering this vertical variability in PBL, the difference in CO₂ concentration between YSB and NST observed from 03:00–06:00 local standard time (LST), when the PBL is at its lowest in Seoul, is used as the $\Delta$CO₂ of Seoul ($\Delta$CO₂ = CO₂YSB – CO₂NST).

The second method uses the horizontal difference in CO₂ concentration, which compares the CO₂ concentration at Seoul with that in the outer background area. We quantified $\Delta$CO₂ by comparing the CO₂ concentrations between YSB and GWA ($\Delta$CO₂ = CO₂YSB – CO₂GWA). Background CO₂ concentration data that were measured when the GWA was located below the PBL were removed to minimize the impact of air masses transported from Seoul. Therefore, CO₂ concentrations from 20:00–08:00 (LST), when the GWA was always located above the PBL, were used.

To increase the reliability of our results, we used two urban enhancement quantification methods, taking into account both vertical and horizontal differences. For a more detailed description of the CO₂ observation data and analysis methods used, refer to Park et al. (2020b).

2.2. Ancillary data

Traffic volume and the floating population, which correlate well
with anthropogenic CO$_2$ emissions, were used as CO$_2$ emission proxies to show the extent to which CO$_2$ emissions induced by human activity (Yang et al., 2015; SMG, 2017). Traffic volume data, provided by the Seoul Transport Operation & Information Service (TOPIS), represent the flow and outflow of on-road vehicles for certain sections of road per hour. The floating population data are provided by the Seoul Metropolitan Government and mobile carrier KT, measuring the amount of floating population at a certain point each hour from mobile-phone LTE signals (Jeong and Moon, 2014). Traffic volume and floating population data can be downloaded from their corresponding websites (SMG, 2021; TOPIS, 2021). Hourly traffic volume and floating population data observed near the YSB site during the research period, from July 2019 to September 2020, were used.

The effects of meteorological parameters on urban CO$_2$ concentrations were examined. Here, hourly averaged meteorological parameters from the Automatic Weather System (AWS) adjacent to the YSB site during the research period were used. The AWS is managed by the Korea Meteorological Administration, measuring temperature, precipitation, wind speed, and wind direction. Meteorological data can be downloaded from the following open meteorological data portal (KMA, 2021).

### 2.3. Research period Classification

The period in which CO$_2$ concentrations were observed at all YSB, NST, and GWA sites is divided into three separate periods. The period from July 21, 2019 to December 31, 2019, before the COVID-19 virus was manifested in Seoul, is classified as the pre-COVID-19 period (Table 1).

The period following the occurrence of COVID-19 is classified into two periods, Level 1 and Level 2.5, based on each phase of the “Intensive Social Distancing (ISD)” policy in Seoul. Level 1 includes the period from March 22, 2020 to April 19, 2020. As shown in Table 1, during the Level 1 period, ISD policies were strongly implemented in Seoul for the first time, with telecommuting replacing most school and work activity.

Level 2.5 occurred from August 30, 2020 to September 13, 2020 and includes policies from the “Step 2.5 Intensive Social Distancing” phase. During the Level 2.5 period, policies much stronger than those from the Level 1 period were enabled, with all activities involving the prohibition of indoor gatherings of more than 50 people, and the restriction of all private facilities, including restaurants and cafes, to operation only between the hours of 05:00–21:00 (LST).

### Table 1

| Classification | Period | Description |
|----------------|--------|-------------|
| Pre-COVID-19 | July 21, 2019–December 31, 2019 | Normal condition of Seoul with no restrictions. |
| Level 1 | March 22, 2020–April 19, 2020 | - Recommendation to refrain from going out for meetings, eating out, events, travel, etc. - Restricting the number of employees in offices through telecommuting. - Shutdown of public facilities. - Suspension of the operation of religious facilities, indoor sports facilities, and entertainment facilities. - Recommendation for closing schools, kindergartens, daycare centers, and postponing the opening of schools. - Same as Level 1. |
| Level 2.5 | August 30, 2020–September 13, 2020 | - Mandatory remote classes for schools, kindergartens, and day care centers. - No gatherings for 50 or more indoor or 100 or more outdoor guests. - No business in private facilities, e.g., restaurant, cafe, from 9:00 p.m. to 5:00 a.m. |

### 3. Results

Fig. 1 shows the monthly mean CO$_2$ concentrations at the three observation sites from July 2019 to September 2020. Months with more than 50% of data missing owing to sensor calibration were excluded. Although, on average, the CO$_2$ concentration for all three observation sites is the lowest in summer at 424.11 ppm and the highest in winter at 449.76 ppm, with a distinct seasonal variability of 25.64 ppm, there is a large difference in the CO$_2$ concentration at each observation site. The mean CO$_2$ concentration in YSB during this period is 442.99 ppm, which is 11.00 and 13.34 ppm higher than that of NST (432.00 ppm) and GWA (429.65 ppm), respectively. In general, the three observation sites well represent variations in urban and local background CO$_2$ concentrations in downtown Seoul. In addition, the average CO$_2$ concentration over the three stations (e.g., 434.88 ppm) is higher than that from Mauna Loa by 22.23 ppm obtained from the National Oceanic and Atmospheric Administration (Thoning et al., 1989; NOAA, 2021).

Using the observed CO$_2$ concentration data, urban enhancement in Seoul was quantified in two ways. Fig. 2a shows a box plot of $\Delta$CO$_2^1$ for each period quantified using method 1, which considers the difference in vertical CO$_2$ concentration. The average $\Delta$CO$_2^1$ during the pre-COVID-19 period is 22.56 ppm but decreases to 14.23 ppm during the Level 1 period and 10.99 ppm during the Level 2.5 period (Table 2). The 95th percentile of $\Delta$CO$_2^1$, a proxy for high CO$_2$ concentration emissions in Seoul, decreased more significantly from 59.04 ppm during the pre-COVID-19 period to 40.94 and 36.15 ppm during Level 1 and Level 2.5 periods, respectively. We calculated the urban contribution for each period (urban contribution = $\Delta$CO$_2$/CO$_2$ concentration × 100; Fig. 2b) to compare the percentage of $\Delta$CO$_2^1$ accounting for atmospheric CO$_2$ concentrations in Seoul. The degree to which the CO$_2$ concentration due to urban emissions affected the atmospheric CO$_2$ concentration for each period was 4.81%, on average, during the pre-COVID-19 period but decreased to 3.07% and 2.46% during the Level 1 and Level 2.5 periods, respectively. Compared with the pre-COVID-19 period, Seoul’s urban contribution was reduced by half, and Seoul’s CO$_2$ concentration showed a decreasing tendency from 451.76 ppm during the pre-COVID-19 period to 451.38 and 434.54 ppm during the Level 1 and Level 2.5 periods, respectively. In contrast, background CO$_2$ concentration increased from the pre-COVID-19 period to the Level 1 period (429.20–437.14 ppm) and slightly decreased to 423.55 ppm during the Level 2.5 period.

Fig. 3a shows a box plot of $\Delta$CO$_2^2$ using method 2, which considers the horizontal difference in the CO$_2$ concentration. The average $\Delta$CO$_2^2$ was 27.08 ppm during the pre-COVID-19 period but decreased to 18.61 and 17.73 ppm during Level 1 and Level 2.5 periods, respectively. The 95th percentile of $\Delta$CO$_2^2$ also showed values of 73.71, 52.12, and 42.06 ppm, during the pre-COVID-19, Level 1, and Level 2.5 periods, respectively, indicating a more pronounced declining trend than the mean value. In addition, the average contribution of $\Delta$CO$_2^2$ to the atmospheric CO$_2$ concentration of Seoul trended downward as 5.72%, 4.01%, and 3.92%, respectively, and the CO$_2$ concentration in the Seoul urban area decreased, with values varying from 453.39 to 452.61 and 442.12 ppm, during the pre-COVID-19, Level 1, and Level 2.5 periods, respectively (Fig. 3b). However, the background CO$_2$ concentration showed an equal level or slightly increasing tendency, from 426.31 ppm in pre-COVID-19 period to 434.01 and 424.30 ppm in the Level 1 and Level 2.5 periods. $\Delta$CO$_2^2$ values obtained through method 1 and method 2, which considered the vertical and horizontal CO$_2$ concentration differences in Seoul, respectively, were highly correlated ($r = 0.87, p < 0.001$; figure not shown), suggesting similar results.

To verify that this reduction in CO$_2$ concentration emitted from Seoul’s urban area occurred as a result of social distance policy based on the COVID-19 pandemic, we confirmed the extent to which CO$_2$ emissions decreased in Seoul using CO$_2$ emission proxies (i.e., traffic volume and floating population) measured around the YSB site. Fig. 4 shows the amount of traffic and the floating population around YSB for each
Compared with the pre-COVID-19 period, the traffic volume during Level 1 and Level 2.5 decreased by 10.73% and 43.25%, and the floating population decreased by 12.55% and 14.11%, respectively, indicating that the social distancing policy led to a decrease in CO\textsubscript{2} emissions from human activity. Compared with the same period during the pre-COVID-19 year, the traffic volume and floating population decreased by 11.19% and 16.02% for the Level 1 period and 43.15% and 12.07% for the Level 2.5 period, respectively.

4. Discussion and conclusion

In this study, the observed CO\textsubscript{2} concentration in downtown Seoul was analyzed to determine whether the social distancing policy implemented as a result of the occurrence of COVID-19 led to a reduction in the urban atmospheric CO\textsubscript{2} concentration. The $\Delta$CO\textsubscript{2} value, which can be considered as the CO\textsubscript{2} concentration emitted from the Seoul urban area, decreased by an average of 8.04 ppm during the Level 1 period and 10.46 ppm during the Level 2.5 period compared to a pre-COVID-19 baseline. In particular, the 95th percentile of $\Delta$CO\textsubscript{2}, which reflects...
high CO$_2$ concentration emissions in the city, was significantly reduced, indicating that human activity highly affects CO$_2$ emissions. The $\Delta$CO$_2$ values obtained in this study were consistent in both methods, considering the horizontal and vertical differences in CO$_2$ concentration, respectively. Furthermore, t-tests results showed that the decrease in $\Delta$CO$_2$ between the pre-COVID-19 and Level 2.5 periods was statistically significant ($p < 0.001$).

In addition to $\Delta$CO$_2$, the urban contribution to the atmospheric CO$_2$ concentration of Seoul also reduced. During the pre-COVID-19 period, the urban contribution of Seoul was 5.27%, on average, but decreased to 3.54% and 3.19% during the Level 1 and Level 2.5 periods, respectively. This is assumed to be due to an increase in the background CO$_2$ concentration, although the urban CO$_2$ concentration of Seoul reduced due to rapid decrease in CO$_2$ emissions caused by the social distancing policies. In other words, CO$_2$ concentration in cities that are known to generate most of the world’s CO$_2$ emissions can be effectively reduced by policies that curb human activity (Duren and Miller, 2012; Schwandner et al., 2017). In addition, $\Delta$CO$_2$ and the urban contribution of Seoul over the Level 2.5 period showed a greater reduction than that of the Level 1 period. Since Level 2.5 was implemented for only two weeks, the reduction in CO$_2$ concentration would have been more noticeable if the implementation period was longer. This indicates that the intensity of the policies implemented within the city can greatly affect the reduction in CO$_2$ emissions.

The reduction of atmospheric CO$_2$ concentration in urban areas can be considered a compound result of changes in local weather conditions and direct emission from the city (Xueref-Remy, 2018; Park et al., 2020a). Therefore, we analyzed the correlation between urban CO$_2$

### Table 2

Summary of CO$_2$ concentration, urban enhancement, and urban contribution using two different methods during the pre-COVID-19, Level 1, and Level 2.5 periods. The value in parentheses is the standard deviation ($\pm \sigma$) from the mean value.

| Method | Variables | Period       | Pre-COVID-19 | Level 1 | Level 2.5 |
|--------|-----------|--------------|--------------|---------|-----------|
| Method 1 | Concentration (ppm) | Urban       | 451.76 (25.06) | 451.38 (16.91) | 434.54 (14.03) |
|        |           | Background  | 429.20 (13.05) | 437.14 (8.93) | 423.55 (9.73) |
| Urban enhancement (ppm) | Mean     | 22.56 (19.57) | 14.23 (12.80) | 10.99 (12.62) |
| Urban contribution (%) | 4.81 (3.94) | 3.07 (2.64) | 2.46 (2.79) |
| Urban enhancement (ppm) | 59.04 (12.03) | 12.03 (8.53) | 7.99 (9.99) |
| 95th percentile | 59.04 (12.03) | 12.03 (8.53) | 7.99 (9.99) |

| Method 2 | Concentration (ppm) | Urban       | 453.39 (28.21) | 452.61 (16.97) | 442.12 (16.15) |
|        |           | Background  | 426.31 (12.47) | 434.01 (8.85) | 424.39 (8.34) |
| Urban enhancement (ppm) | Mean     | 27.08 (24.07) | 18.61 (15.39) | 17.73 (14.16) |
| Urban contribution (%) | 5.72 (4.68) | 4.01 (3.15) | 3.92 (3.03) |
| Urban enhancement (ppm) | 73.71 (14.67) | 52.12 (10.85) | 42.06 (9.10) |
| 95th percentile | 73.71 (14.67) | 52.12 (10.85) | 42.06 (9.10) |

![Fig. 3. Box plot of (a) urban enhancement and (b) urban contribution using method 2 during the pre-COVID-19, Level 1, and Level 2.5 periods. Each box plot represents the mean (red), median (blue), 25th and 75th percentiles, and outliers (circle).](image-url)
Taking advantage of these real-time CO2 observations, this study confirmed that the phase-by-phase social distancing policies implemented in Seoul due to the COVID-19 pandemic led to a reduction in human activity and even led to a reduction in the atmospheric CO2 concentration. This suggests that if effective policies that can reduce CO2 emissions from human activity are developed and implemented in cities around the world in the future, they will prevent the rapid rise in global CO2 concentrations and effectively mitigate climate change. The COVID-19 virus has caused tremendous socioeconomic damage; however, it has provided a positive outlook regarding the potential for future climate change and greenhouse gas reduction, demonstrating the important role of effective policies and cities in managing greenhouse gas levels.

Credit roles

Chaerin Park: analysis, writing. Sujong Jeong: supervision, writing. Yong-seung Shin: writing. Yeong-seop Cha: writing. Ho-chan Lee: writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Fig. 4. Bar graph of the traffic volume and a scatter plot of the floating population near the YSB site during the pre-COVID-19, Level 1, and Level 2.5 periods.

enhancement and meteorological parameters (i.e., temperature, precipitation, wind direction, and wind speed) during the research period to examine the impact of meteorological parameters on urban CO2 enhancement. We found that there was no statistically significant correlation between urban CO2 enhancement and temperature and precipitation. In addition, the urban CO2 enhancement did not significantly vary with the direction of the wind at the YSB site. In contrast, CO2 enhancement showed a distinct exponential relationship with wind speed; however, the average wind speed in Seoul was not significantly different during the pre-COVID-19, Level 1, and Level 2.5 periods. This demonstrates that the decrease in atmospheric CO2 concentration during the COVID-19 pandemic results from changes in direct CO2 emissions from Seoul due to social distancing policies.

The reduction in CO2 emissions due to COVID-19 social distancing policies was verified using traffic volume, which accounts for the largest portion of the emission sources in Seoul and floating population, presumed to represent human activity (SMG, 2017). The results show that the traffic volume and floating population around the YSB site decreased by 10.73% and 12.55% during the Level 1 period and by 43.25% and 14.11% during the Level 2.5 period, respectively. Along with the traffic volume, fossil fuel usage from buildings is the second largest source of direct CO2 emissions in Seoul; however, it was difficult to evaluate the effect of implemented policies in real-time using inventory data that accounted for energy use in each building, since inventory data for the present year are typically not available until two to three years later (SMG, 2017). In contrast, the urban CO2 observation data used in this study made it possible to verify the effects of policy-induced atmospheric CO2 concentration reduction in real-time. Therefore, to develop and evaluate policies for future CO2 emissions reduction, it is suggested that these urban CO2 ground observations should be extended.
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