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Lessons from COVID-19 and Seoul: Effects of Reduced Human Activity from Social Distancing on Urban CO_2 Concentration and Air Quality

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ABSTRACT

Social restriction in cities to curb infection rates of COVID-19 has become an opportunity to investigate the relationship between humans and the urban atmosphere. We evaluate the impact of the decline in human activities as a result of social distancing on the urban CO_2 concentrations and air quality in Seoul during February and March of 2020 compared to 2019. Due to the reduction in human activity in 2020, local measurements of CO and NO_2 show a decrease in background concentration (up to –11.9% and –41.7%, respectively) and urban enhancement (up to –16.7% and –38.1%, respectively) compared to the previous year. In contrast, the background concentration of CO_2 increases by 3.9% in 2020. Ratios of CO:CO_2 and NO_2:CO_2 also show a decrease in 2020 compared to the previous year, signaling an improvement in the urban air quality of Seoul. Moreover, the insignificant change in wind speed and wind direction during the months of February and March 2020 compared to 2019 implies that CO_2, CO, and NO_2 concentrations have not been influenced by meteorological conditions, but mainly by changes in emissions from decreased human activity. Despite the rise in background CO_2 concentration, urban contributions of CO_2 show a decline of –12.6%, indicating that cities with high emissions have the potential to reduce urban CO_2 enhancements and air pollutant concentrations, and ultimately impact the global atmosphere.

Keywords: COVID-19, Social distancing, Urban emissions, Air quality

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1 INTRODUCTION

On 11 March 2020, the Word Health Organization (WHO) declared the highly infectious novel Coronavirus disease 2019 (COVID-19) as a global pandemic (WHO, 2020a). As of 1 September 2020, over 1.8 million new COVID-19 cases and 38,000 new deaths have been reported from across the world (WHO, 2020b). The emergence of COVID-19 has resulted in countries taking various emergency measures to contain the virus from spreading, ranging from social distancing to shelter-in-place regulations, and even drastic government orders of a complete quarantine or lockdown of entire cities. Such orders have led to a slowdown in economic activity as well as a substantial decrease in human activity. Subsequently, the reduction in everyday human activity has caused a significant change in the atmosphere across the globe, with reports of decreases in greenhouse gas and air pollutant emissions (Bauwens *et al.*, 2020; Le Quéré *et al.*, 2020; Shi and Brasseur, 2020; Xu *et al.*, 2020a; Xu *et al.*, 2020b; Zhang *et al.*, 2020). In particular, as urban air quality is heavily dependent on human activities such as vehicle use, home heating, and industrial activity (Clerbaux *et al.*, 2008; Lamsal *et al.*, 2013), social restrictions in cities to "flatten the curve" and slow down the spread of the virus has become a prime opportunity for a natural experiment to observe the relationship between human activity and the urban atmosphere, and further explore the possibility of mitigating climate change. However, recent studies on COVID-19 have mostly focused on emission reductions, while analysis of atmospheric concentrations of gases and their impact on air quality is still in need.

As the source of more than 70% of greenhouse gas and air pollutant emissions, cities are the best places to see the interaction between anthropogenic activity and its impact on the urban atmosphere (UN Habitat, 2011; Duren and Miller, 2012). Seoul, a megacity with over 9 million inhabitants, is deemed as one of the biggest emitters of CO_2 and air pollutants among other cities in the world (Moran *et al.*, 2018). At the end of February 2020, the South Korean government followed the advice of the Korea Centers for Disease Control and Prevention (KCDC) and raised the infectious disease crisis warning to the highest level, issuing intense social distancing policies and closing down schools, non-essential businesses, and religious facilities. This also led to the restriction of outdoor activities, gatherings, and travel, causing many people to stay indoors. Thus, Seoul became an ideal setting to measure what effects decreased human activity as a result of social distancing have on the urban atmosphere and air quality.

In this study, we evaluate the impact of the decline in human activity due to social distancing on the urban atmosphere of Seoul during February and March of 2020 in comparison to the respective months of 2019. We investigate the changes in socioeconomic data of traffic volume, floating population, and energy consumption before and after the implementation of social distancing. In addition, using the established network of available ground measurements and satellite data, we assess various aspects of the local atmosphere of Seoul from a representative greenhouse gas, CO_2, to air pollutants, CO and NO_2, during our period of study to observe the impacts of reduced human activity on the urban air quality.

2 METHODS

We focus our study on the impact of human activity on the concentrations of CO_2 and air pollutants CO and NO_2. Data on local CO_2 concentrations from ground measurements in Seoul are available starting from 2019. Therefore, the following data used in this study is between 2019 and 2020, which is consistent with the period of data obtained from CO_2 measurements.

2.1 Socioeconomic Data

We use the socioeconomic data of traffic volume, floating population, and energy consumption, which most visibly represent the amount of human activity in Seoul during February and March of 2019 and 2020. The total weekly volume of on-road traffic is obtained from the Seoul Transport Operation & Information Service (TOPIS) data on daily count of on-road vehicles. The number of vehicles passing in front of the detectors installed on major highways and urban expressways in Seoul are counted consecutively at one-hour intervals and made public on the TOPIS official website (https://topis.seoul.go.kr). Floating population data for the districts of Seoul are retrieved from the Seoul Open Data Platform (https://data.seoul.go.kr). Floating population refers to the total amount of pedestrian traffic occurring in a unit area or specific location at a given time, and this number is estimated by the Seoul Metropolitan Government in cooperation with the mobile carrier KT using public big data from KT mobile phones and LTE signals that are owned by the Seoul Metropolitan Government (Jeong and Moon, 2014). Lastly, the monthly electric consumption data by energy sector is retrieved from the Korea Electric Power Corporation (KEPCO), which supplies the nation's electric power (https://bigdata.kepco.co.kr).

2.2 Ground Observations

CO_2 is a long-lived, chemically stable species often co-emitted with other pollutants during anthropogenic activities such as fossil fuel combustion, and can be used as indicators of other pollutants in urban atmospheric monitoring (Wunch *et al.*, 2009). We use the hourly-averaged CO_2 data measured on the rooftop of a tall building in Yongsan located in the center of Seoul (37°31′26′′N, 126°57′49″E and 113 m a.s.l). The equipment installed is an LI-850 (LI-COR CO_2/H_2O analyzer), which provides a continuous monitoring of CO_2 with a temporal resolution of 1 minute (Park *et al.*, 2020). To compare air pollutants with the measured CO_2, we selected the nearest air

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quality monitoring station located 3.9 km away (37°32′24″N, 127°00′18″E and 62 m a.s.l). The urban air quality monitoring station, operated by the Seoul Institute for Health and Environment, is used to observe average air pollutant concentrations in areas around Seoul and determine whether environmental standards are achieved. Two of the criteria air pollutants measured at the urban air quality monitoring station, CO and NO_2, are used in this study. CO is produced from combustion processes where the relative amount of CO is contingent on the efficiency and completeness of the combustion and acts a suitable tracer for pollutant emissions and transport (Turnbull *et al.*, 2011; Silva *et al.*, 2013). NO_2 is formed and emitted to the atmosphere when fossil fuels are combusted at high temperatures and, due to its short chemical lifetime, is concentrated near its emission sources, making it advantageous in estimating anthropogenic emissions from fossil fuel combustion (Richter *et al.*, 2005; Silva *et al.*, 2017). Thus, the amount of NO_2 usually reflects the emissions of traffic activity and power plant operations well. The instruments installed at the air quality monitoring stations for CO is the KIMOTO CO analyzer (CA-751), which uses the non-dispersive infrared method, and for NO_2 is the KIMOTO NO_x analyzer (NA-721), which uses the chemiluminescent method. The daily, hourly-averaged data is retrieved from AIRKOREA (www.airkorea.or.kr), the open-access website that publishes real-time air pollution information. All ground datasets in this study are widely used in air quality research in Seoul (Choi *et al.*, 2014; Kim *et al.*, 2014; Ghim *et al.*, 2015; Sim *et al.*, 2020).

Due to its characteristics of being long-lived and chemically stable, CO_2 is well-mixed with biospheric fluxes and the effects of long-range transport. Therefore, such influences must be put into consideration and background concentrations should be removed in the assessment of urban CO_2 concentrations (Kort *et al.*, 2012; Briber *et al.*, 2013; Hutyra *et al.*, 2014). We used the method of Bares *et al.* (2018) to extract the urban enhancement values of each species and disentangle the contribution of recently emitted pollutants in urban areas from background values. We define the background concentration as the lowest first percentile concentration within a 24 h window of the measured data, which is then subtracted from each data point to determine the excess concentrations due to urban emissions (i.e., urban enhancements) of each species.

Furthermore, measurements of both greenhouse gases and air pollutants on the ground allow a comparison of air quality using the ratios of $CO:CO_2$ and $NO_2:CO_2$. As air pollutants share common combustion sources with anthropogenic CO_2, comparing CO_2 together with CO and NO_2 allows us to characterize emission sources and assess their link to air quality (Konovalov *et al.*, 2016). Multiple studies have utilized the ratios of trace gases to urban enhancements of anthropogenic CO_2 concentrations to analyze air quality in cities (Suntharalingam *et al.*, 2004; Worden *et al.*, 2012; Silva *et al.*, 2017; Bares *et al.*, 2018). We carried out a regression analysis and calculated the slope to define the emission ratios of the observed CO_2 to air pollutants CO and NO_2.

2.3 Satellite Observations

The Tropospheric Monitoring Instrument (TROPOMI) onboard the Copernicus Sentinel-5 Precursor satellite, launched in October 2017, is a sun-synchronous nadir-looking grating spectrometer that performs measurements of the solar light reflected by the Earth's atmosphere in the UV-VIS (270–495 nm), NIR (710–775 nm), and SWIR (2305–2385 nm) spectral domain (Veefkind *et al.*, 2012). The large swath and high signal-to-noise ratio of the instrument enable daily global observations of air quality and detection of trace gases using single orbit overpasses (Borsdorff *et al.*, 2019). We use the high spatial resolution column data measurements of CO (5.5 km × 7 km, SWIR) and NO_2 (5.5 km × 3.5 km, UVN) collected from Seoul and the surrounding Gyeonggi-do Province during February to March of 2019 and 2020. We use data with the recommended quality assurance value greater than 0.75 for all the overpasses used in our study. Multiple studies have used TROPOMI CO and NO_2 retrievals to study top-down emission characteristics in megacities as well as to determine impacts on air quality (Goldberg *et al.*, 2019; Lama *et al.*, 2019; Bauwens *et al.*, 2020).

2.4 Meteorological Data

Meteorological data such as wind direction and wind speed are obtained from the Automatic Weather System (AWS) located near the Yongsan CO_2 measurement site (37°31'13.4"N

126°58'34.0"E and 32 m a.s.l). Wind speed and wind direction data are collected at one-minute intervals and averaged to hourly observations. The data can be retrieved from the Korea Meteorological Administration National Climate Data Center (https://data.kma.go.kr/).

3 RESULTS

3.1 Reductions in Human Activity

To observe the changes in the traffic volume in Seoul, we compared the total number of vehicles on-road Seoul during the two years of the period of study. Figs. 1(a) and 1(b) show the weekly total traffic volume in Seoul from February to March for 2019 and 2020. Compared to the previous year, the traffic volume in February and March of 2020 shows a decrease of –3.6% and –8.9%, respectively. Aside from Monday to Wednesday, there is an overall decline in traffic volume in February 2020 compared to February 2019. The decrease in traffic volume from

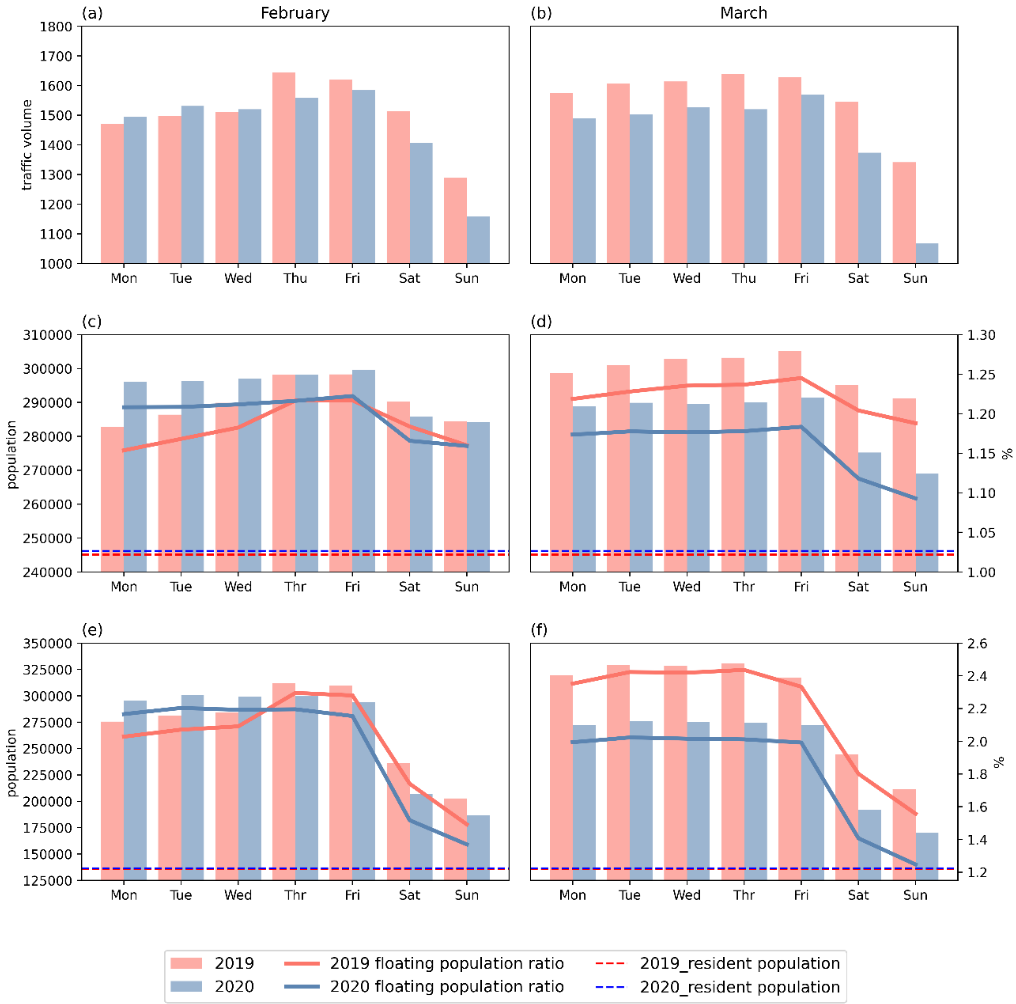

Fig. 1. Socioeconomic data of traffic volume and floating population representing human activity in Seoul. Weekly total count of traffic volume in Seoul is presented in (a) for February and (b) for March of 2019 and 2020. Comparison of weekly floating population data of Yonsan-gu is displayed in (c) for February and (d) for March of the years 2019 and 2020, and weekly floating population data of Jung-gu is displayed in (e) for February and (f) for March of the years 2019 and 2020. Bars indicate the total count of traffic volume and floating population, bold lines indicate the ratio of floating population over residing population, and dotted lines indicate resident population of the area. Orange represents the year 2019 and blue represents the year 2020.

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Monday to Wednesday in 2019 compared to the subsequent year can be explained by the Korean Lunar New Year, which was celebrated from 4-6 February 2019. In March 2020, there is a significant reduction in traffic volume for both weekdays and weekends in comparison to the corresponding months of the prior year.

Next, we estimate the dispersion of human activity in Seoul by analyzing the floating population data by district. We present the floating population data of Yongsan-gu, the district where the ground measurements are located, and Jung-gu, one of the most densely populated areas in Seoul, for February and March of 2019 and 2020 (Figs. 1(c) to 1(f)). Yongsan-gu is a district with a combination of commercial areas and residential areas. In February 2020, the floating population of Yongsan-gu does not show much difference to the year prior. Only the weekends have a slighter decrease of –0.8%, while weekdays show an increase of 2.2% in floating population compared to the same month of 2019. On the other hand, in March 2020, the floating population of Yongsan-gu has a decrease of –4.1% during the weekdays and a decrease of –7.2% during the weekends compared to the previous year. In addition, the ratio of the floating population per residential population in 2020 has a decline of –11% compared to 2019. Jung-gu is a business district located in the center of Seoul with various offices and large shopping malls concentrated in the area. The district also shows a similar pattern to that of Yongsan-gu where the floating population increases by 1.8% during the weekdays and decreases by –10.3% in the weekends in February 2020 compared to 2019. In March 2020, however, the floating population shows a greater change compared to that of the previous year with a –15.7% and –20.6% decrease during the weekdays and weekends, respectively, with also a –23% decrease in the ratio of the floating population per residential population.

Finally, we observe the monthly data of total electric consumption per industrial sector in Seoul (Table 1). Overall, there is a reduction in the total amount of electric consumption in February (–5 MWh) and March (–6 MWh) in 2020 compared to 2019. By sector, the largest decrease in energy usage is in educational services; wholesale and retail trade; accommodation and restaurants; electricity, gas, steam and waterworks; and manufacturing. The educational sector has the largest decrease in electricity consumption with –9,160 MWh (–5.3%) in February 2020 and –18,040 MWh (–12.2%) in March of 2020 as schools were closed down due to COVID-19 with the beginning of the school year postponed indefinitely. Businesses such as restaurants, accommodation, and other service-related enterprises also faced difficulties as customers subsided, which is reflected in the data of energy usage. In contrast, sectors such as health and social welfare services (1,967 MWh (1.9%) in February and 6,651 MWh (7.2%) in March); scientific and technical services (60 MWh (0.2%) in February and 1,447 MWh (4.3%) in March); and broadcasting and publishing (11,740 MWh in February (8.6%) and 10,155 MWh (7.4%) in March) display a dramatic increase in energy consumption in 2020 compared to the previous year. Especially, energy consumption data for the year 2020 reflects the escalation of emergencies in public health facilities and the rigorous broadcasting of news events as well as the upsurge of scientific research on virus testing kits and vaccine development.

3.2 Changes in Urban CO_2 Concentrations and Air Quality

To observe the changes in CO_2 concentrations and air quality in the urban atmosphere during the period coinciding with the reduction of human activity, we examine average concentration, background concentration, and excess concentration of CO_2, CO, and NO_2 from ground observations which are presented in Table 2. In February 2020, the average, background, and excess concentrations of all the measured atmospheric constituents show an overall decrease compared to the previous year. Among the three measured species, NO_2 displays the largest decrease of –32.9% and –32.7% in average concentration and background concentration, respectively. CO has a decrease of –14.1% and –9.1% in average concentration and background concentration, respectively, and CO_2 has the least reduction of –0.2% and –0.1% in average concentration and background concentration, respectively. The excess concentrations of all the measured species are lower in February 2020 compared to 2019 with decreases of –34%, –23.8%, and –4.4% for NO_2, CO, and CO_2, respectively.

In March of 2020, CO and NO_2 exhibit a drop in average concentration, background concentration, and excess concentration. Compared to the previous year, CO has a decrease of –15.3% and –11.9%

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Table 1. Total electric consumption data of Seoul by sector for February and March 2019 and 2020. The amount of change indicates the difference in electricity consumption of 2020 compared to 2019.

Industrial Classification	Electricity Consumption (kWh)				Amount of change	
	February 2019	March 2019	February 2020	March 2020	February	March
Construction	52,146,587	47,494,631	51,627,623	48,960,630	–518,964	1,465,999
Public administration	60,697,058	51,108,081	58,962,338	51,489,371	–1,734,720	381,290
Mining	373,681	295,765	379,777	342,347	6,096	46,582
Educational service	174,132,523	148,087,253	164,973,011	130,047,322	–9,159,512	–18,039,931
International and foreign institutions	7,336,813	6,057,210	5,537,697	4,656,632	–1,799,116	–1,400,578
Financial and Insurance	36,008,866	33,962,056	35,746,840	34,223,872	–262,026	261,816
Agriculture, Forestry, and Fisheries	1,631,929	1,337,215	1,527,845	1,310,412	–104,084	–26,803
Wholesale and Retail trade	344,249,211	294,171,911	321,787,161	286,261,614	–22,462,050	–7,910,297
Health and Social welfare services	101,999,608	92,830,140	103,966,272	99,481,205	1,966,664	6,651,065
Real estate and Buy-to-let	1,024,379,018	870,776,420	1,008,481,453	891,702,001	–15,897,565	20,925,581
Business facility management	30,258,791	25,668,611	28,393,962	25,089,937	–1,864,829	–578,674
Accommodation and Restaurant	207,188,286	174,563,059	192,617,573	162,854,572	–14,570,713	–11,708,487
Arts, Sports, and Leisure-related service	54,385,073	44,621,534	49,677,591	38,850,459	–4,707,482	–5,771,075
Transportation	193,534,634	164,515,037	188,315,612	170,751,747	–5,219,022	6,236,710
Electricity, gas, steam and waterworks	92,878,142	85,508,432	85,855,141	77,584,253	–7,023,001	–7,924,179
Scientific and technical services	36,884,024	33,622,250	36,944,098	35,068,886	60,074	1,446,636
Manufacturing	148,488,168	131,884,466	137,328,052	129,378,363	–11,160,116	–2,506,103
Broadcasting and Publishing	135,939,439	138,196,172	147,679,671	148,351,239	11,740,232	10,155,067
Sewage treatment	43,537,803	46,184,974	47,899,600	48,965,313	4,361,797	2,780,339
Association, Organization, and Personal service business	91,565,429	74,601,809	84,935,828	68,040,051	–6,629,601	–6,561,758
Total	2,837,631,284	2,465,500,796	2,752,648,344	2,453,417,862	–5,002	–6,134

Table 2. Results of average concentration (Avg. conc.), background concentration (Back. conc.), and excess concentration (Ex. conc.) of CO_2, CO, and NO_2 from ground measurements during February and March of 2019 and 2020, respectively. Ratio indicates percentage change in concentrations in 2020 compared to 2019.

Gas		2019			2020			Ratio of 2020 relative to 2019		
		Avg. conc.	Back. conc.	Ex. conc.	Avg. conc.	Back. conc.	Ex. conc.	Avg. conc.	Back. Conc.	Ex. conc.
Feb	CO_2 (ppm)	449.61	427.85	23.73	448.87	427.28	22.69	–0.16%	–0.13%	–4.38%
	CO (ppm)	0.64	0.44	0.21	0.55	0.40	0.16	–14.06%	–9.09%	–23.81%
	NO_2 (ppb)	40.83	24.22	17.29	27.39	16.29	11.42	–32.92%	–32.74%	–33.95%
Mar	CO_2 (ppm)	443.17	424.63	19.36	457.20	440.96	16.92	3.16%	3.85%	–12.60%
	CO (ppm)	0.59	0.42	0.18	0.50	0.37	0.15	–15.25%	–11.90%	–16.67%
	NO_2 (ppb)	39.64	22.68	17.55	23.82	13.23	10.87	–39.91%	–41.67%	–38.06%

for average concentration and background concentration, respectively. In comparison, NO_2 has a substantial decline of –39.9% and –41.7% of average concentration and background concentration, respectively. The excess concentrations for both CO and NO_2 have a reduction of –16.7% and –38.1%, respectively, compared to March of the previous year. On the other hand, in March 2020, CO_2 displays an increase in both average concentration and background concentration with a rise of 3.2% and 3.9%, respectively, compared to the corresponding month in 2019. However, despite the rise in average and background concentrations of CO_2, the excess concentration of CO_2

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continues to decline from February (–4.4%) and well into March (–12.6%) of 2020. In other words, although the background concentration of CO_2 increased in 2020, the urban enhancement of CO_2 maintains a pattern of decrease like the air pollutants CO and NO_2 compared to the previous year.

We further examine the urban enhancement ratios of CO:CO_2 and NO_2:CO_2 of February and March for both 2019 and 2020 to assess the impact on urban air quality as shown in Fig. 2. For both months, air pollutants CO and NO_2 per CO_2 show a decrease in slopes in 2020 as opposed to 2019. Compared to the previous year, the ratio of CO:CO_2 decreases by –20.8% and –7.4% in February and March 2020, and the ratio of NO_2:CO_2 decreases by –35.7% and –16.7% in February and March 2020, respectively. This signifies that the concentration of air pollutants in the atmosphere has reduced more rapidly during the two months of 2020 compared to that of 2019 than the concentration of carbon dioxide which is stable and stays in the atmosphere for a considerable amount of time.

Finally, we observe satellite observations of the average concentrations of air pollutants CO and NO_2 over Seoul and the surrounding Gyeonggi-do Province for the corresponding months of the period of study as presented in Fig. 3. Consistent with the ground measurement results, satellite observations show a decrease in CO and NO_2 both in February and March 2020 compared to the previous year. In 2020, CO has an average decrease of -5.6×10^{-3} mol m^{-2} (–11.5%) in February and -3.8×10^{-3} mol m^{-2} (–8.2%) in March, and NO_2 has an average decrease of -6.5×10^{-5} mol m^{-2} (–28.1%) in February and -8.5×10^{-6} mol m^{-2} (–4.6%) in March

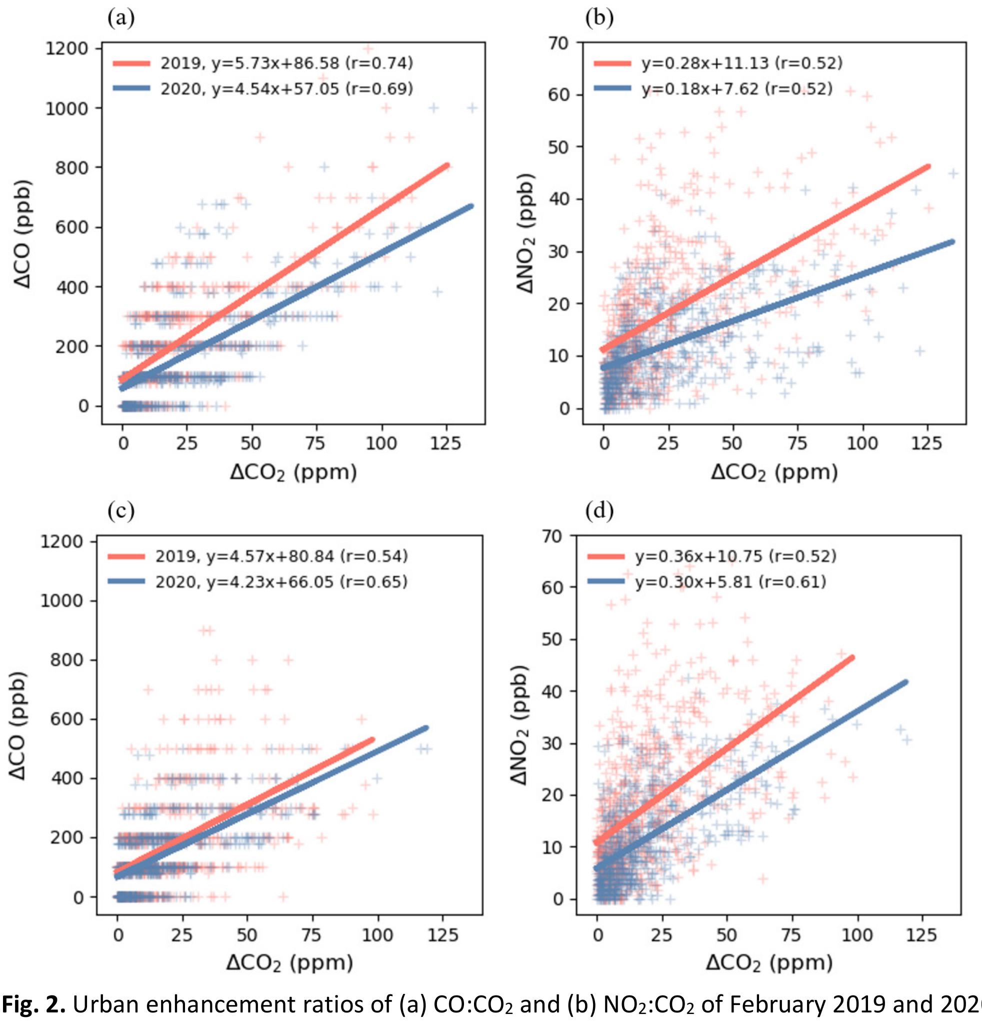

Fig. 2. Urban enhancement ratios of (a) CO:CO_2 and (b) NO_2:CO_2 of February 2019 and 2020 and urban enhancement ratios of (c) CO:CO_2 and (d) NO_2:CO_2 of March 2019 and 2020. Bold lines represent the slopes of the ratios. Orange indicates the year 2019 and blue indicates the year 2020.

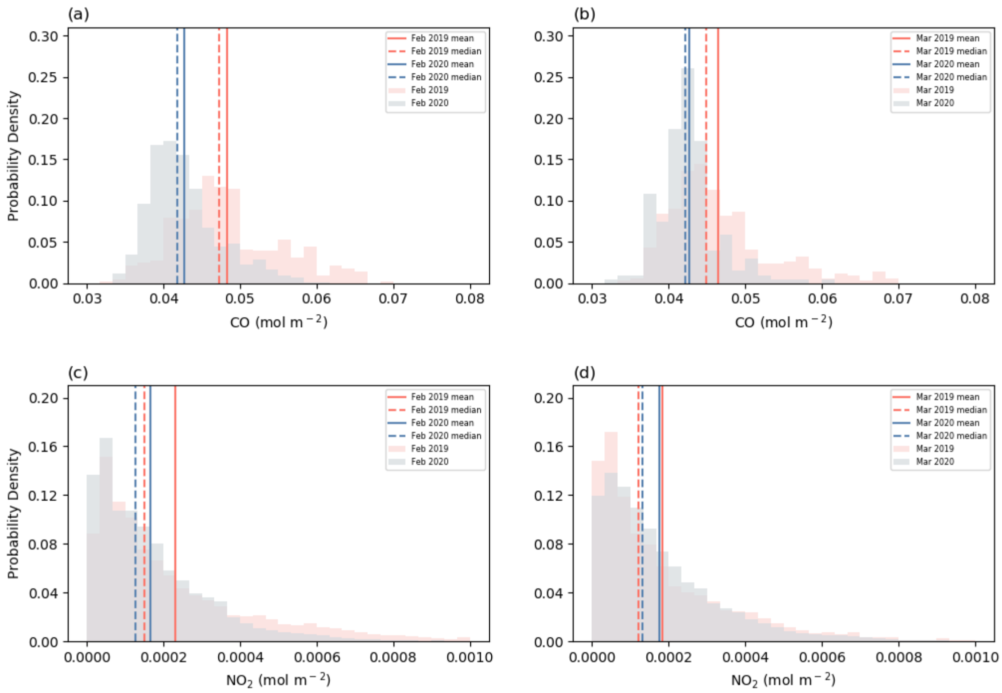

Fig. 3. S-5P TROPOMI satellite observations of Seoul and the surrounding Gyeonggi-do Province of average CO concentrations in (a) February and (b) March of 2019 and 2020, and observations of average NO_2 concentrations of (c) February and (d) March of 2019 and 2020.

in comparison to the previous year. Similar to the urban enhancement ratios measured from the ground, top-down satellite observations of CO and NO_2 also display an overall decrease in the urban atmosphere in 2020.

Meteorological conditions such as wind speed and wind direction play an important role in dispersing pollutants and creating favorable conditions for heavy pollution events within cities (Xu *et al.*, 2020c). To evaluate the influence of dispersion conditions, we observe the effect of local meteorology on the concentrations of CO_2, CO, and NO_2 in Seoul for both 2019 and 2020 (Fig. 4). Local wind speed and wind direction show that meteorological conditions have no significant change in 2020 from the previous year. Wind speed, which influence dispersion conditions, shows an average of 1.5 ± 0.8 m s^{-1} and 1.9 ± 1.2 m s^{-1} in February and March of 2019, respectively, while the average wind speed is 1.6 ± 1.1 m $s^{-1}$and 2.0 ± 1.3 m s^{-1} in February and March of 2020, respectively. Wind speed increased by 8.3% in February and 4.7% in March 2020 compared to the previous year; however, it is difficult to consider such increases to be statistically significant. Thus, minor changes in meteorological conditions indicate that the decrease of CO_2, CO, and NO_2 concentrations in Seoul are mainly driven by the reductions in human activity due to social distancing.

4 DISCUSSION AND CONCLUSIONS

This study examined the impact of decreased human activity on the urban atmosphere of Seoul due to social distancing actions to prevent the spread of COVID-19 using data from various measurements. Results of traffic and floating population data show that there has been a significant decline in human activity in Seoul during February and March 2020 compared to the corresponding months in 2019. The South Korean government declared the highest level of alert for national action to fight against the infectious disease on 23 February 2020. Aside from the increase during the weekdays in February 2020, there is a steady decline in both traffic volume and floating population as fewer people moved around the city for work, leisure, or other activities. The reduced traffic volume and floating population from Monday to Wednesday in

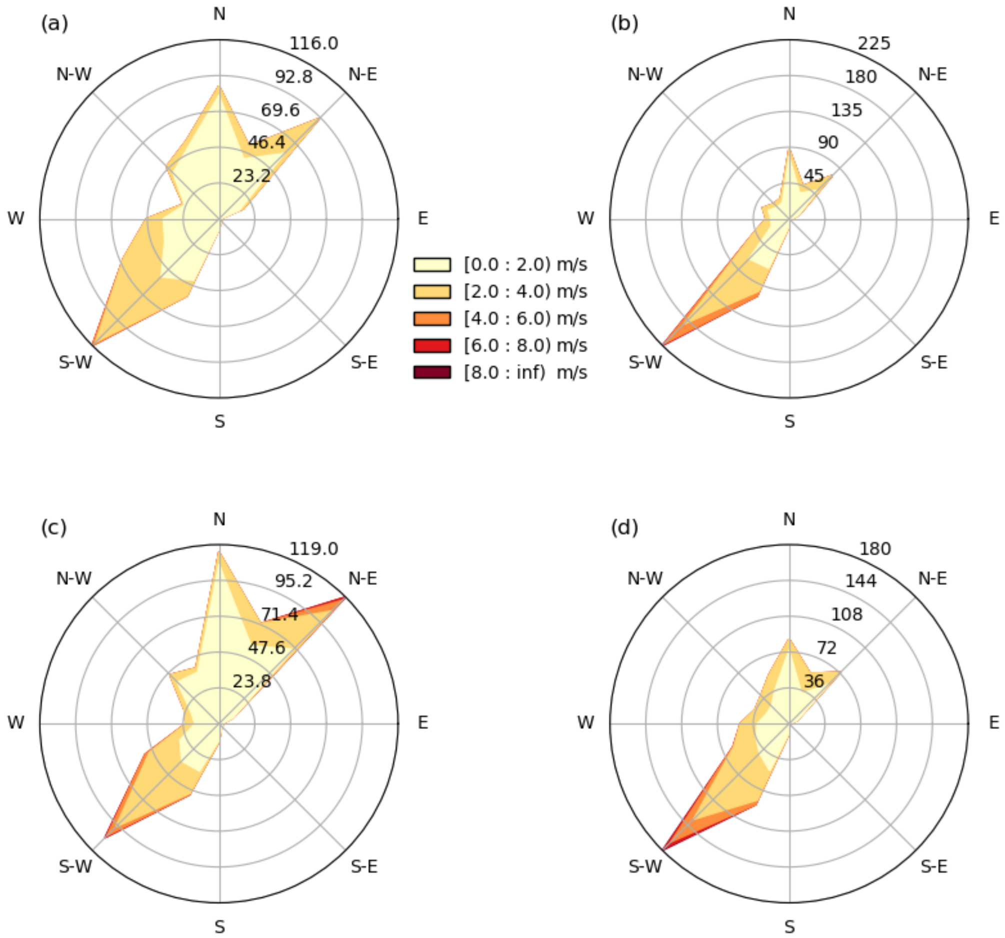

Fig. 4. Wind speed and wind direction of Seoul measured near the ground measurement sites during (a) February and (b) March of 2019 and (c) February and (d) March of 2020. The color bar represents strengths of wind speed.

February 2019 can be explained by the Korean Lunar New Year holiday, which was celebrated from Monday to Wednesday, 4–6 February 2019, in which during this period many people traveled to their hometowns outside of Seoul to visit family and relatives. The marked drop in both the average traffic volume and floating population is greater in March 2020 as more people worked from home and stayed indoors owing to the high-intensity social distancing policies imposed by the government starting mid-March.

Decreased human activity also resulted in less economic activity and energy consumption as schools and businesses closed down and fewer people traveled or visited non-essential businesses and facilities. The total energy consumption in Seoul decreases for both February and March of 2020 compared to the previous year, and this reduction is seen in almost all of the energy sectors. In contrast to the general decline of energy consumption, health and social welfare services as well as scientific and technical services have a considerable increase in energy consumption as hospitals and laboratories rushed to treat the surge of patients and develop testing kits and vaccines. The increase in energy consumption in such sectors accelerates in March as the spread of COVID-19 reaches its peak. In addition, the broadcasting and publishing sector also show a dramatic rise in energy consumption in February and March 2020 compared to the previous year as the government and broadcasting stations continued to announce and inform the public of the ongoing situation of the pandemic. The household energy consumption data, which could have been another indicator of the patterns of human activity during social distancing, was not available for analysis in our study. This can be considered for analysis in future studies when such data is accessible. Nonetheless, data on traffic volume, floating population, and energy consumption, which explain to an extent the amount of human activity in Seoul, exhibit a general

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decrease in all areas, confirming that the impact of COVID-19 and social distancing resulted in less human activity.

To observe the influence of decreased human activity on urban air quality, we analyze CO_2 and air pollutants CO and NO_2. In Seoul, both the concentrations of CO and NO_2 measured from the ground show a decline in February and a more significant decrease in March 2020 compared to the previous year, following the pattern of traffic volume and floating population data. On-road vehicles and their fuel type are seen as one of the biggest contributors to urban air pollution (Mayer *et al.*, 1999; Hassler *et al.*, 2016). Seoul is densely populated with a large number of motor vehicles and traffic congestion, resulting in idling vehicles and high emissions of air pollutants (Nguyen *et al.*, 2010; Kim and Guldmann, 2011; Kim *et al.*, 2015). In a study using mobile and ground-based measurements to monitor the air quality and urban CO_2 concentrations in Seoul, Sim *et al.* (2020) showed that vehicle emissions, particularly from diesel vehicles, are the major sources of emissions that impact the air quality of downtown Seoul during the wintertime. The larger decrease of air pollutants in March, especially of NO_2, parallel the greater drop in traffic volume during the same month, demonstrating the close link of vehicle usage and air quality. This decline in air pollutant concentrations is also captured in satellite observations of Seoul and the surrounding area. Although satellite observations of air pollutant concentrations show a considerable decline in February, the decrease is smaller in March. Nonetheless, the overall pattern of decrease in 2020 compared to 2019 is shown for both months from satellite measurements. This difference can be due to the fact that ground-based observations are continuous measurements of local events, while satellite observations provide total column mixing ratios that are measured from the top of the atmosphere, which can be influenced by other meteorological events and do not immediately reflect surface-level emissions.

Decreases in urban enhancement ratios of $CO:CO_2$ and $NO_2:CO_2$ for both months in 2020 can also be explained by the effect of human activity on air quality. The decline of slopes of $CO:CO_2$ and $NO_2:CO_2$ in February and March 2020 compared to the corresponding months of the previous year indicates that the concentration of air pollutants per CO_2 concentration in Seoul have decreased. This implies that the reduction of anthropogenic activity from social distancing has influenced the reduction of air pollutant concentration per CO_2 concentration, resulting in an improvement in Seoul's air quality. Moreover, meteorological conditions remain the same in 2020 compared to the previous year, indicating that CO_2, CO, and NO_2 concentrations have neither been greatly influenced by wind speed nor wind direction, but mainly by changes in emissions from decreased human activity.

Contrary to the large decrease of air pollutants in Seoul resulting from social distancing, average and background CO_2 concentrations show a different pattern of change. In February 2020, CO_2 concentrations show a slight decrease in average concentration and background concentration in Seoul compared to the previous year. However, despite the larger reduction of human activity, leading to a larger decline of air pollutants in March 2020, the average and background concentrations of CO_2 increases compared to 2019. It is noteworthy that although there is a rise in the background CO_2 concentration in March, the excess CO_2 concentration, indicating the urban CO_2 enhancement of Seoul, follows the general pattern of decrease along with the excess concentrations of air pollutants CO and NO_2. Regardless of the rise in the background concentration, the urban enhancement of CO_2 continues to show a steady decline due to decreased human activity such as vehicle use and energy consumption within the city during the enforcement of intensive social distancing policies. This decrease is consistent with the estimated decline in CO_2 emissions that has also been observed by Le Quéré *et al.* (2020). Our results show that even with the intense cutback of human activities and emissions, background CO_2 concentrations will continue to rise due to the long-lived characteristics of CO_2 that remain in the atmosphere for about 120 years (Smith, 1993). However, the marked decline in urban enhancements of CO_2 concentrations from social distancing emphasizes the potential of urban areas impacting and reducing local contributions of CO_2 in the atmosphere with the decrease of emissions.

Despite limitations of the lack of data, our study presents various independent socioeconomic and atmospheric observation data which all point to the decreasing trend of values in 2020 compared to 2019. The reduction in human activity due to social distancing has led to a decrease of CO_2 and air pollutants, strengthening the link between impacts of anthropogenic activity on the urban CO_2 concentration and air quality, and demonstrating how intertwined everyday life and the use of fossil fuels have become. In contrast to the overall decrease of air pollutant concentrations in Seoul, the small impact that the curtailed human activity has on the background CO_2 concentration implies that one country's effort to cut back emissions does not make a marked difference on the increasing trend of global background CO_2 concentrations. However, this study presents that regardless of the increase in background CO_2, the local enhancement of CO_2 concentrations in Seoul show a significant decline along with the decrease of air pollutants. This highlights the importance of taking appropriate actions within cities to reduce anthropogenic activity which can effectively decrease urban air pollution and greenhouse gases. Moreover, this study also underlines the critical role and potential of cities in accelerating the decline of atmospheric greenhouse gases and air pollutants to improve urban air quality as well as to mitigate climate change.

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DATA AVAILABILITY

The high-resolution, real-time datasets are provided by the Seoul Metropolitan Government (https://data.seoul.go.kr/dataList/OA-15439/S/1/datasetView.do), Korea Electric Power Corporation (https://bigdata.kepco.co.kr/cmsmain.do?scode=S01&pcode=000167), Seoul Transport Operation & Information Service (https://topis.seoul.go.kr/refRoom/openRefRoom_2.do), and the Seoul Institute for Health and Environment (www.airkorea.or.kr). Meteorological data is retrieved from the Korea Meteorological Administration National Climate Data Center (https://data.kma.go.kr/data/grnd/selectAwsRltmList.do?pgmNo=56). The CO_2 data is from the Seoul National University CO_2 Measurement (SNUCO_2M) network operated by the Integrated Climate Science Lab (climatelab.snu.ac.kr). Sentinel-5 Precursor TROPOMI is part of the EU Copernicus program, and Copernicus Sentinel data 2019-2020 has been used (www.tropomi.eu). Datasets in this work are freely available from the provided website address or upon request.

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