Changes in air pollution levels after COVID-19 outbreak in Korea

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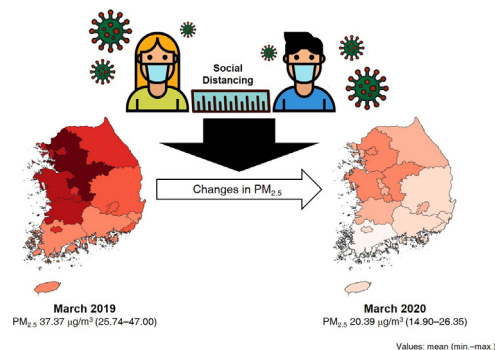[c] Department of Urban Planning and Engineering, Yonsei University, Seoul, Republic of Korea
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HIGHLIGHTS

- Social distancing was implemented in order to control the spread of COVID-19.
- Social distancing may have a certain positive effect in levels of air pollution.
- Ambient $PM_{2.5}$, PM_{10}, NO_2, and CO are related to industrial activities and traffic.
- All $PM_{2.5}$, PM_{10}, NO_2, and CO levels were reduced during social distancing.
- We point toward reducing air pollution in a sustainable post-COVID-19 world.

GRAPHICAL ABSTRACT

March 2019
$PM_{2.5}$ 37.37 μg/m³ (25.74–47.00)

March 2020
$PM_{2.5}$ 20.39 μg/m³ (14.90–26.35)

Values: mean (min.–max.)

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ABSTRACT

In order to control the spread of COVID-19, social distancing measures were implemented in many countries. This study investigated changes in air pollution during the social distancing after the COVID-19 outbreak in Korea. Ambient $PM_{2.5}$, PM_{10}, NO_2, and CO that are particularly related to industrial activities and traffic were reduced during the social distancing in response to the COVID-19 outbreak. In March 2020, immediately after social distancing, mean levels of $PM_{2.5}$, PM_{10}, NO_2, and CO decreased nationwide from last year's mean levels by 16.98 μg/m³, 21.61 μg/m³, 4.16 ppb, and 0.09 ppm, respectively (p-value for the year-to-year difference <0.001, $=0.001$, $=0.008$, <0.001), a decrease by 45.45%, 35.56%, 20.41%, and 17.33%, respectively. Changes in ambient O_3 or SO_2 were not observed to be attributable to social distancing. Our findings, that such effort for a short period of time resulted in a significant reduction in air pollution, may point toward reducing air pollution as a public health problem in a more sustainable post-COVID-19 world.

1. Introduction

At the end of 2019, a series of pneumonia of unknown cause emerged in Wuhan, China, identified by its association with a novel coronavirus (Huang et al., 2020a). This coronavirus quickly spread throughout China and to other countries; subsequently, the World Health Organization (WHO) officially named it coronavirus disease 2019 (COVID-19) (WHO, 2020c).

In South Korea, the first case of COVID-19 was confirmed on January 20, 2020 (KCDC, 2020a), and the number of confirmed COVID-19 cases

sharply increased. On February 23, 2020, the Korean government raised its alert to the highest COVID-19 level of "red" to strengthen the overall response system (KCDC, 2020b). By mid-March, Korea had become the second most affected country worldwide after China. In order to control the spread of COVID-19, Korea Central Disaster and Safety Countermeasures Headquarters on COVID-19 promulgated "social distancing", followed by "stronger social distancing", and provided government action as well as guidelines for the public and in accordance with pan-government action, postponed opening of the new school year and encouraged telecommuting (KCDC, 2020c). That action, in turn, resulted in a reduction of industrial operation and traffic than normal (Seoul Metro, 2020; The Chosunilbo, 2020).

Ambient air pollution affects a large proportion of the global population (van Donkelaar et al., 2015). According to the WHO, approximately 91% of the world's population resides in places where pollutant levels exceed thresholds of the WHO air quality guidelines; ambient air pollution is estimated to cause 4.2 million premature deaths globally (WHO, 2018). The highest levels of air pollution, especially in Asian mega-cities, were found linked to population growth and industrialization (Autrup, 2010). Additionally, because levels of particulate matter in Korea are higher in winter and spring than in other seasons (Korea Ministry of Environment, 2016), this "social distancing" period falls in the season of air pollution that is already an important environmental problem in Korea.

Although the social distancing and reduction in human activities after the COVID-19 outbreak may lead to side effects of a decline in economic growth, "social distancing" after COVID-19 outbreak may have a certain positive side effect in levels of air pollution. This study aimed to investigate changes in air pollution of particulate matter with aerodynamic diameter less than 2.5 or 10 μm ($PM_{2.5}$, PM_{10}), nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and ozone (O_3) during the "social dancing" period after the COVID-19 outbreak in Korea, using air pollution data hourly-detected from nationwide monitoring stations. In particular, we focused on the most important air pollutants in Korea (i.e., in $PM_{2.5}$, PM_{10}, NO_2, and CO) that are related to industrial activities and traffic, and we evaluated 1) daily variation of nationwide air pollution between December 1st and April 30th, i.e., from the global onset of COVID-19 to the social distancing period in Korea, 2) the year-to-year difference of monthly air pollution (compared to the previous three years), and 3) regional variation during the social distancing period (compared to the same period last year).

2. Methods

2.1. COVID-19 data collection

Worldwide data of COVID-19 confirmed cases in each country including Korea, the U.S., and China were collected from Coronavirus disease (COVID-2019) situation reports of WHO (WHO, 2020a). Because the daily number of COVID-19 confirmed cases before January 20, 2020 was not available in the WHO data, we referred to a case report by Huang et al. (December 1st–January 2nd), an editorial by Hui et al. (January 3rd–9th), and the situation report series of the China CDC (January 10th–19th) (Chinese CDC, 2020; Huang et al., 2020a; Hui et al., 2020). COVID-19 confirmed case was defined as a positive COVID-19 laboratory RT-PCR (Real Time-Polymerase Chain Reaction) test.

In Korea, detailed information on COVID-19 alert levels and social distancing were provided by the Korea Centers for Disease Control and Prevention (KCDC) and Central Disaster and Safety Countermeasures Headquarters on COVID-19 of the Korea Ministry of Health and Welfare (Central Disease Control Headquarters, 2020; KCDC, 2020a; KCDC, 2020b; KCDC, 2020d; Korea Ministry of Health and Welfare, 2020).

2.2. Air pollution data collection

Data of ambient air pollution between December 1st and April 30th of the most recent four years were collected from 446 nationwide atmospheric monitoring stations to be able to capture urban background air pollution in Korea, provided by the Korea Ministry of Environment (http://www.airkorea.or.kr/web). The location of monitoring stations is presented in Supplemental Fig. 1. At each monitoring station, ambient air pollution of $PM_{2.5}$, PM_{10}, NO_2, CO, SO_2, and O_3 concentrations were detected hourly, then nationwide daily average and regional average per 17 administrative divisions were computed from those values. Also, monthly mean air pollution was computed for the average per each month; monthly mean was not computed when the available number of daily measures was less than 75% (National Institute of Environmental Research, 2019b).

2.3. Analysis

Statistical data analysis was performed using SAS software (version 9.4; SAS Institute Inc.). Values of $p < 0.05$ were considered as statistically significant. Concentrations of all air pollutants were normally distributed, and mean and standard deviation (SD) were used to describe the concentration of air pollutants. Paired t-test was used for comparing the differences of $PM_{2.5}$, PM_{10}, NO_2, and CO levels on the same day in the current year versus each prior year. Further, in order to show regional variation of air pollution levels, a graphical model was developed with a geographic information system using QGIS software (version 3.8.2).

2.4. Sensitivity analysis

We examined two other air pollutants, SO_2 and O_3, of less importance in Korea, and compared the differences of SO_2 and O_3 levels on the same day in the current year versus each prior year using paired t-test.

3. Results

Fig. 1 presents daily changes in the total number of confirmed COVID-19 cases between December 1, 2019 and April 30, 2020. The onset of unknown-caused pneumonia cases began in Wuhan, China in early December 2019, and the number of confirmed cases of COVID-19 increased rapidly in China—40 cases by December 31, 2019. In the world, 9826 cases by January 31; 85,403 cases by February 29; 750,890 cases by March 31; and 3,090,445 cases by April 30, 2020 were identified.

In Korea, the COVID-19 date of onset was January 20, 2020 when the first case was confirmed in an imported person from Wuhan, China. On the same day, the Korean government raised the COVID-alert level to "yellow". The number of confirmed cases in Korea increased gradually until mid-February, but the number sharply increased after February 18, 2020 with a regional outbreak from the religious cluster in Daegu metropolitan city—11 cases by January 31; 3150 cases by February 29; 9786 cases by March 31; and 10,765 cases by April 30, 2020. On February 23rd, the Korean government raised the COVID-alert to the highest level of "red", and "social distancing" spontaneously began from citizens. Finally, on February 29th, to prevent wide-scale public COVID-19 infection, the Korean government officially suggested "social distancing" through March 21st, and subsequently declared "stronger social distancing" for a total of four weeks through April 19th. Social distancing levels, their government action, and guideline for the public are described in Table 1. In particular, "stronger social distancing" included mandatory closing of public facilities (e.g., libraries, swimming pools, museums, national parks), halting facilities susceptible to cluster infection (e.g., religious, indoor sports, entertainment facilities), and suggested "delaying or canceling" non-essential gatherings and refraining from non-essential ventures from home.

Fig. 2 presents daily changes of air pollution (Korea national average of daily $PM_{2.5}$, PM_{10}, NO_2, and CO concentrations) between December 1st and April 30th over the most recent four years. Around the first onset of confirmed COVID-19 case (January 20, 2020), ambient $PM_{2.5}$,
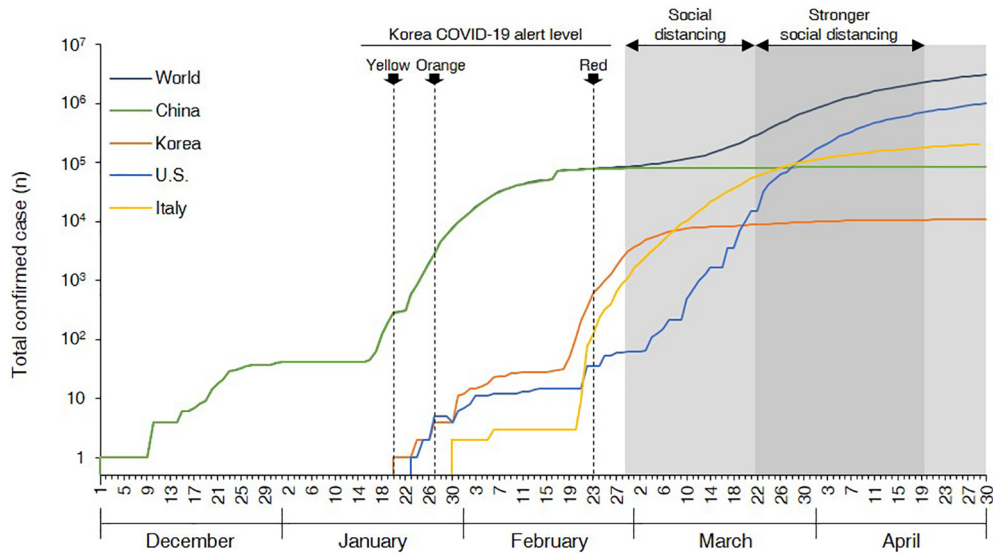
Fig. 1. Daily changes in total confirmed COVID-19 in Korea through April 30, 2020.
Highlighted shadow presents social distancing period.

PM_{10}, NO_2, and CO concentrations began to reveal slight differences from those in 2019, 2018, and 2017. After the regional pandemic of Daegu city (February 18th; COVID-19 alert level raised to "red" on February 23rd) and social distancing (officially from February 29th), ambient concentration levels were substantially lower than levels in previous years. During the social distancing and stronger social distancing period (February 29–April 19, 2020), Korean daily standard value of $PM_{2.5}$, i.e., 35 $\mu g/m^3$, was not exceeded at any date, while $PM_{2.5}$ at 16, 9,

Table 1
Social distancing to prevent COVID-19 in Korea.

Social distancing levels		Social distancing	"Stronger" social distancing	Extending stronger social distancing	"Relaxed way" of social distancing
Period		2020.02.29–2020.03.21 (alert level "Red", 2020.02.23)	2020.03.22–2020.04.05	2020.04.06–2020.04.19	2020.04.20–2020.05.05
Government action	General	-Importance of personal hygiene practice and social distancing	-Prevention of further spreading to communities	-Prevention of further spreading to communities	-Maintain social tension in relaxed way of social distancing
	Public facilities*	n.a.	-Stop the operation	-Stop the operation	-Outdoor and dispersed facilities: gradually "reopen" under quarantine rules -Outdoor and densely populated facilities: "resumed" under being dispersed
	Facilities susceptible to cluster infection†	n.a.	-Halt the operation	-Halt the operation	-Religious, indoor sports, and entertainment facilities were adjusted from halting operation to "refraining"
	Public transportation	n.a.	-Separately assign seats between passengers to keep a certain distance	-Separately assign seats between passengers to keep a certain distance	n.a.
Guideline for public	Personal hygiene	-Wash your hands thoroughly with soap under running water -Cover up your mouth and nose with elbow when sneezing/coughing	-Wash your hands thoroughly with soap under running water -Cover up your mouth and nose with elbow when sneezing/coughing	-Wash your hands thoroughly with soap under running water -Cover up your mouth and nose with elbow when sneezing/coughing	-Wash your hands thoroughly with soap under running water -Cover up your mouth and nose with elbow when sneezing/coughing
	Crowded place	-Avoid visiting	-"Delay or cancel" nonessential gathering, travel, etc. -Refrain from going out except for buying necessities, visiting a doctor, and commuting to/from work -Keep a 2-meter distance	-"Delay or cancel" nonessential gathering, travel, etc. -Refrain from going out except for buying necessities, visiting a doctor, and commuting to/from work -Keep a 2-meter distance	-"Delay or cancel" nonessential gathering, travel, etc. -Refrain from going out except for buying necessities, visiting a doctor, and commuting to/from work -Keep a 2-meter distance

* Public facilities including libraries, swimming pools, museums, national park, etc.
† Facilities susceptible to cluster infection including religious, indoor sports, entertainment facilities, etc.
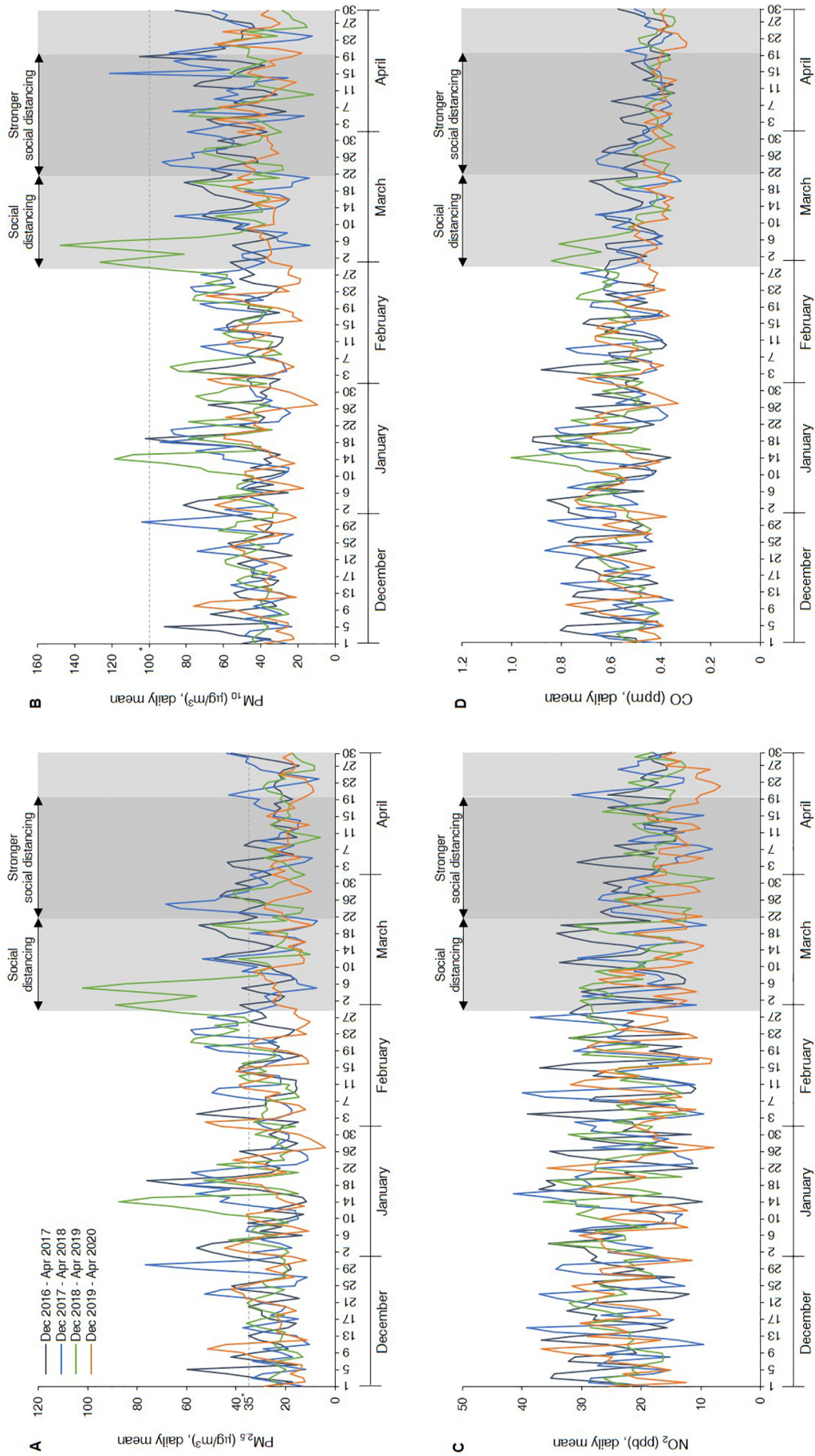
Fig. 2 Daily mean concentrations of air pollutants in Korea, between December 1 and April 30 of recent four years. (A) $PM_{2.5}$ (B) PM_{10} (C) NO_2 (D) CO.
Highlighted shadow presents social distancing period.
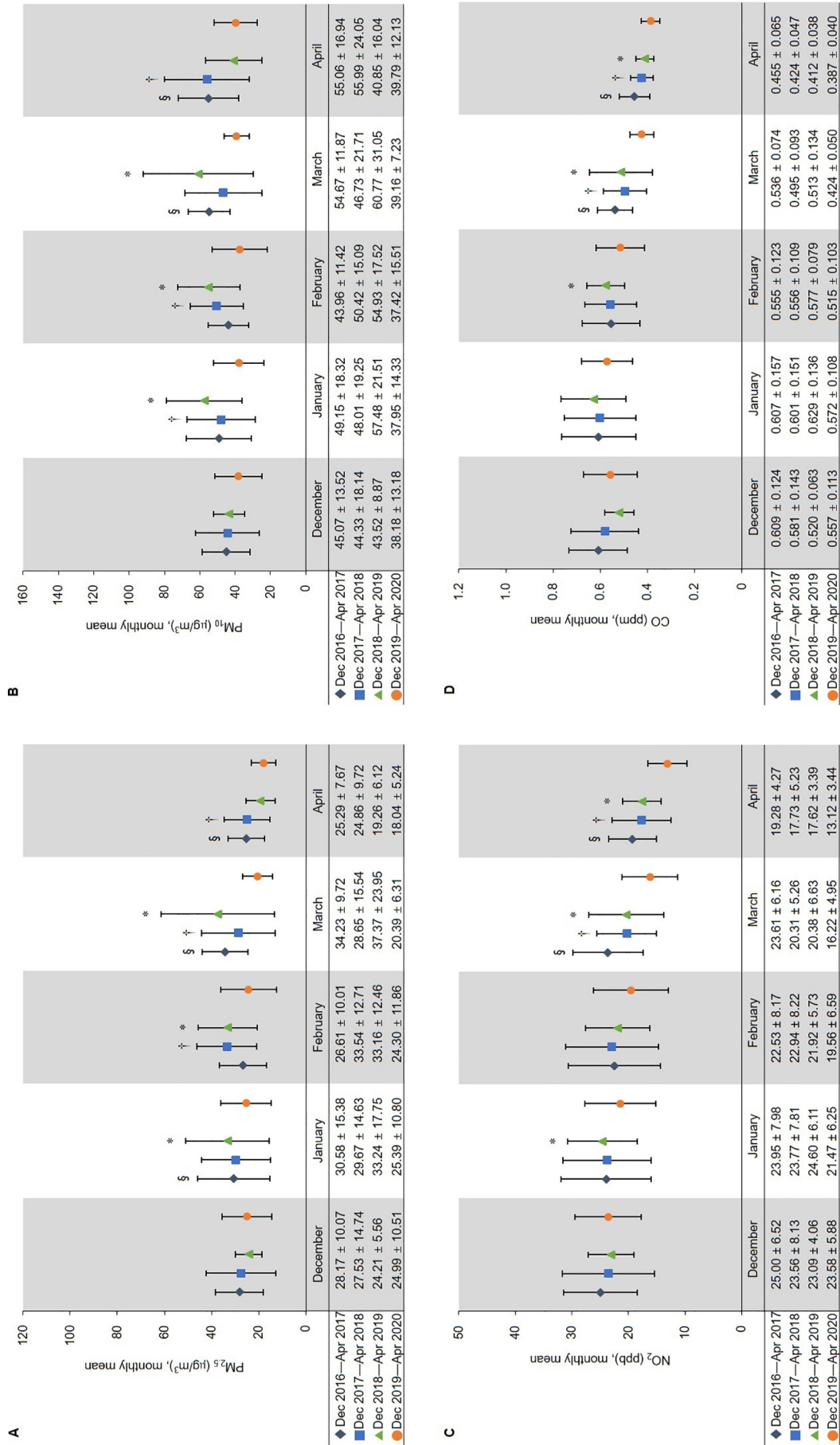* Korean daily air quality standard.

Fig. 3. Monthly mean ± SD concentrations of air pollutants in Korea, between December and April of the most recent four years.
All values present mean ± SD of all daily concentrations per each month.
Paired t-test was used for comparison of (A) $PM_{2.5}$, (B) PM_{10}, (C) NO_2, and (D) CO levels on the same day in the current year versus each prior year.
* $p < 0.05$ vs. 1 prior year; † $p < 0.05$ vs. 2 prior year; § $p < 0.05$ vs. 3 prior year.

A

PM_{2.5} (μg/m³), monthly mean	December	January	February	March	April
Dec 2016—Apr 2017	28.17 ± 10.07	30.58 ± 15.38	26.61 ± 10.01	34.23 ± 9.72	25.29 ± 7.67
Dec 2017—Apr 2018	27.53 ± 14.74	29.67 ± 14.63	33.54 ± 12.71	28.65 ± 15.54	24.86 ± 6.12
Dec 2018—Apr 2019	24.21 ± 5.56	33.24 ± 17.75	33.16 ± 12.46	37.37 ± 23.95	19.26 ± 6.12
Dec 2019—Apr 2020	24.99 ± 10.51	25.39 ± 10.80	24.30 ± 11.86	20.39 ± 6.31	18.04 ± 5.24

B

PM_{10} (μg/m³), monthly mean	December	January	February	March	April
Dec 2016—Apr 2017	45.07 ± 13.52	49.15 ± 18.32	43.96 ± 11.42	54.67 ± 11.87	55.06 ± 16.94
Dec 2017—Apr 2018	44.33 ± 18.14	48.01 ± 19.25	50.42 ± 15.09	46.73 ± 21.71	55.99 ± 24.05
Dec 2018—Apr 2019	43.52 ± 8.87	57.48 ± 21.51	54.93 ± 17.52	60.77 ± 31.05	40.85 ± 16.04
Dec 2019—Apr 2020	38.18 ± 13.18	37.95 ± 14.33	37.42 ± 15.51	39.16 ± 7.23	39.79 ± 12.13

C

NO_2 (ppb), monthly mean	December	January	February	March	April
Dec 2016—Apr 2017	25.00 ± 6.52	23.95 ± 7.98	22.53 ± 8.17	23.61 ± 6.16	19.28 ± 4.27
Dec 2017—Apr 2018	23.56 ± 8.13	23.77 ± 7.81	22.94 ± 8.22	20.31 ± 5.26	17.73 ± 5.23
Dec 2018—Apr 2019	23.09 ± 4.06	24.60 ± 6.11	21.92 ± 5.73	20.38 ± 6.63	17.62 ± 3.39
Dec 2019—Apr 2020	23.58 ± 5.88	21.47 ± 6.25	19.56 ± 6.59	16.22 ± 4.95	13.12 ± 3.44

D

CO (ppm), monthly mean	December	January	February	March	April
Dec 2016—Apr 2017	0.609 ± 0.124	0.607 ± 0.157	0.555 ± 0.123	0.536 ± 0.074	0.455 ± 0.065
Dec 2017—Apr 2018	0.581 ± 0.143	0.601 ± 0.151	0.556 ± 0.109	0.495 ± 0.093	0.424 ± 0.047
Dec 2018—Apr 2019	0.520 ± 0.063	0.629 ± 0.136	0.577 ± 0.079	0.513 ± 0.134	0.412 ± 0.038
Dec 2019—Apr 2020	0.557 ± 0.113	0.572 ± 0.108	0.515 ± 0.103	0.424 ± 0.050	0.387 ± 0.040

and 13 days during the same period in 2017, 2018, and 2019 exceeded the 35 μg/m³, respectively. Similarly, PM_{10} did not exceed at any date in 2020, but 1, 1, and 6 days in 2017, 2018, and 2019 were higher than the Korean daily standard value, i.e., 100 μg/m³.

Fig. 3 presents monthly mean concentrations of each air pollutants, in December-to-April, over recent four years and compared the year-to-year (paired the same date at current versus prior year). In December 2019, all of the $PM_{2.5}$, PM_{10}, NO_2, and CO concentrations showed no significant difference with the three prior years. In January and February 2020, their monthly means were significantly lower than those in at least one prior year. In March 2020, their monthly means were statistically lower than those in all prior years. In April 2020, their monthly means were significantly lower than those in at least two prior years. Particularly, in March 2020, immediately after official "social distancing", the monthly mean of $PM_{2.5}$ was 20.39 ± 6.31 (mean ± SD) μg/m³, which was significantly lower than the monthly means of all three previous years: 34.23 ± 9.72 μg/m³ in 2017, 28.65 ± 15.54 μg/m³ in 2018, 37.37 ± 23.95 μg/m³ in 2019 (*p*-value for the difference *<0.001, =0.006, <0.001*). The March-mean of PM_{10} was 39.19 ± 7.23 μg/m³, which was significantly lower than 54.67 ± 11.87 μg/m³ in 2017 and 60.77 ± 31.05 μg/m³ in 2019 (*p*-value for the difference *<0.001* and *=0.001*). The March-means of NO_2 and CO were 16.22 ± 4.95 ppb and 0.424 ± 0.050 ppm, which were significantly lower than all three years (all *p*-values for the difference *<0.05*). Compared to March 2019, i.e., one year before, the nationwide mean concentrations of March 2020 decreased by 45.45% for $PM_{2.5}$, 35.56% for PM_{10}, 20.41% for NO_2, and 17.33% for CO. Results for the year-to-year comparison of March-means between 2017, 2018, 2019, and 2020 years are shown in Table 2 and results of December, January, February, and April-means are in Supplemental Tables 1, 2, 3, and 4.

In sensitivity analysis, we examined monthly mean concentrations of two other air pollutants, i.e., SO_2 and O_3, in December through April over the most recent four years, then compared them year-to-year (Supplemental Fig. 2 and Supplemental Tables 5, 6, 7, 8, and 9). Monthly means of SO_2 concentrations had been gradually decreasing in December, January, February, March, and April in every prior year, regardless of social distancing. Monthly mean of O_3 in March 2020 was significantly lower than that in only one prior year.

The map in Fig. 4 shows the monthly mean air pollution of 17 South Korea administrative divisions in March 2019 and March 2020. Compared with the same period last year, we observed that the $PM_{2.5}$, PM_{10}, NO_2, and CO concentrations were reduced throughout the country. The March-means of $PM_{2.5}$ were in the range of 14.90-to-26.35 μg/m³ (minimum-to-maximum) in 2020 and 25.74-to-47.00 μg/m³ in

2019, and 16 regions (all except Chungcheongnam-do) in this year had $PM_{2.5}$ values below the minimum in last year (25.74 μg/m³, Gyeongsangnam-do). The March-means of PM_{10} were in the range of 30.97-to-48.87 μg/m³ in 2020 and 48.23-to-72.42 μg/m³ in 2019, and 16 regions (all except Gyeonggi-do) in this year had PM_{10} below the minimum in last year (48.23 μg/m³, Jeollanam-do) (Fig. 4.B.). The March-means of NO_2 were in the range of 8.13-to-27.52 ppb in 2020 and 12.26-to-33.45 ppb in 2019 (Fig. 4.C.), and the March-means of CO were in the range of 0.297-to-0.529 ppm in 2020 and 0.332-to-0.642 ppm in 2019 (Fig. 4.D.).

4. Discussion

Although COVID-19 is now a worldwide disaster (Wu and McGoogan, 2020) affecting more than 4 million people and 27 thousand of deaths (WHO, 2020b), the present study suggests that the measures to interrupt the spread of COVID-19 provide a positive effect in air pollution levels through decreased human activities. This study focused on ambient $PM_{2.5}$, PM_{10}, NO_2, and CO that are major air pollutants related to industrial energy consumption and/or traffic volumes, and found a significant reduction in all $PM_{2.5}$, PM_{10}, NO_2, and CO levels during the social distancing period, compared to the same period in previous years. In March 2020, immediately after beginning social distancing, national average of ambient air pollution revealed a significant decline of 45.45% (16.98 μg/m³) in $PM_{2.5}$, of 35.56% (21.61 μg/m³) in PM_{10}, of 20.41% (4.16 ppb) in NO_2, and of 17.33% (0.09 ppm) in CO levels compared to March last year. This reduction in air pollution is possibly due to the reduction in domestic sources after Korean COVID-19 onset and additionally due to the reduction in trans-boundary pollutants, after the Chinese COVID-19 pandemic.

After the outbreak of COVID-19, all levels of human activities were reduced, including operation of industrial facilities, traffic, and individual activities. Particulate matter including $PM_{2.5}$ and PM_{10} are known as among the most important air pollutants. Although there are various different sources of $PM_{2.5}$ and PM_{10}, their major sources in Korea include windblown dust, industrial emission, and road traffic; residential fuel combustion and cooking; and secondary reactions in the atmosphere (National Air Pollutants Emission Service, 2016). Ambient NO_2 and CO, also important indicators of environmental pollution, are primarily from the exhaust of urban vehicles and the combustion of fossil fuels by power plants and industrial facilities in Korea (National Air Pollutants Emission Service, 2016; Wang and Su, 2020). After the COVID-19 onset in Korea (late-January), people spontaneously began to minimize social gathering and avoid visiting crowded places. Since the social distancing and stronger (intensive) social distancing (from late-February), people refrained from going out except for essential situations, and all national public facilities stopped operation. The Korea Ministry of Education reported a strong action to postpone the new school year at all levels from kindergarten to high school (Korea Ministry of Education, 2020), and finally planned sequential school openings between May 20th and June 8th. Indeed, in the 1st week of March, immediately after beginning social distancing, the volume of road traffic and public transportation in Seoul had decreased by 7.2% and 34.5%, compared to the weeks before the onset of COVID-19 in Korea (NEWSIS, 2020). In addition, industries temporarily closed, and telecommuting at home was encouraged across many occupations. For example, the operation rate of automotive factories reduced by 50% after the COVID-19 outbreak (KBS NEWS, 2020).

In China, strong social distancing measures began in late 2019 and quarantine measures were implemented in January in Wuhan. Afterward, over 80 Chinese cities enacted isolation measures to prevent the spread of COVID-19 (Zambrano-Monserrate et al., 2020). A preliminary case study of China reported a decline in the volume of coal consumption during that country's lockdown and observed a reduction in tropospheric NO_2 emission using the satellite monitor. In addition, that study suggested that NO_2 emission was initially reduced near Wuhan and

Table 2
The year-on-year comparison of monthly mean ± SD of air pollution in March.

Year	2017	2018	2019	2020
$PM_{2.5}$ (μg/m³)	34.23±9.72 (ref)	28.65±15.54 0.093	37.37±23.95 0.521	20.39±6.31 <0.001
p-value		(ref)	0.140	0.006
			(ref)	<0.001
PM_{10} (μg/m³)	54.67±11.87 (ref)	46.73±21.71 0.083	60.77±31.05 0.346	39.16±7.23 <0.001
p-value		(ref)	0.072	0.085
			(ref)	0.001
NO_2 (ppb)	23.61±6.16 (ref)	20.31±5.26 0.041	20.38±6.63 0.060	16.22±4.95 <0.001
p-value		(ref)	0.970	0.002
			(ref)	0.008
CO (ppm)	0.536±0.074 (ref)	0.495±0.093 0.060	0.513±0.134 0.353	0.387±0.040 <0.001
p-value		(ref)	0.578	<0.001
			(ref)	<0.001

All values present mean ± SD of all daily concentrations per each month.
Paired *t*-test was used for comparison of $PM_{2.5}$, PM_{10}, NO_2, and CO levels on the same day in the current year versus each prior year.

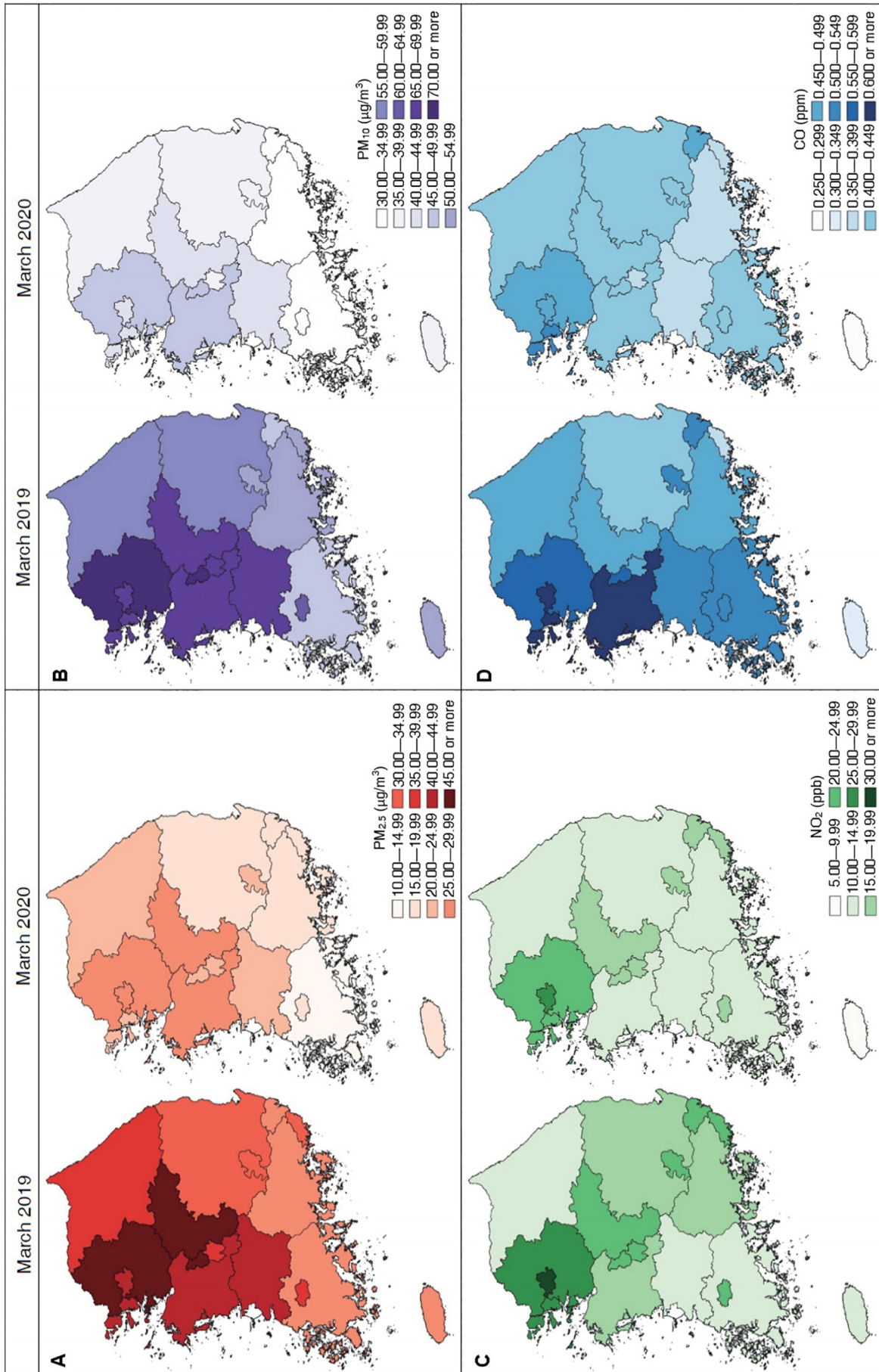Fig. 4. Regional air pollution map: the year-on-year change in monthly mean of March. All values present monthly mean of daily (A) $PM_{2.5}$, (B) PM_{10}, (C) NO_2, and (D) CO concentrations in March per each 17 region.

eventually spread to the whole country (Wang and Su, 2020). Our finding that air pollution in Korea was slightly reduced from January (before Korea COVID-19 outbreak) may be explained, in part, by the reduction in trans-boundary pollutants from China after Chinese quarantine measures and social distancing were in place.

Many other countries adopted public policies of social distancing. For example, in Spain, lockdown measures were implemented from March 14th, two weeks after the COVID-19 epidemic onset in Spain. Tobías et al. observed air pollution changes during the lockdown in Barcelona, and noted that means of urban background PM_{10} and traffic NO_2 decreased by 28% and 51% during the two weeks of lockdown (vs. one month mean before lockdown) (Tobías et al., 2020). A sharp reduction in NO_2 emission in European countries including Spain as well as France, Germany, and Italy was found via European Space Agency satellite monitoring (Zambrano-Monserrate et al., 2020). Similarly, there is evidence of air pollution changes after COVID-19 outbreak in non-European countries including the U.S., Brazil, and Morocco (Berman and Ebisu, 2020; Nakada and Urban, 2020; Otmani et al., 2020).

In Korea, we could not observe ambient O_3 and SO_2 changes attributable to the social distancing. Inconsistent to findings in Chinese studies (Fan et al., 2020; Huang et al., 2020b), we could not observe an increase of O_3 during the social distancing. The levels of O_3 in Korea were not altered and even decreased. Although a decrease in SO_2 was observed during the social distancing and stronger social distancing period, its decrease was not limited to that period. In Korea, the levels of ambient SO_2 have showed the steady decrease from 1989 until recent year, which was due to the Korean governmental efforts to reduce SO_2, e.g., the standard for sulfur content (in 1981), regulation banning solid fuel use in certain regions (in 1985), and mandatory use for liquefied natural gas (LNG) in certain facilities (in 1988) (National Institute of Environmental Research, 2019a). In addition, the major source of SO_2 in Korea is fossil fuel combustion at power plants and additionally industrial facilities (National Air Pollutants Emission Service, 2016). Therefore, SO_2 decrease in the current study is unlikely to be attributable to the reduced industrial activity and traffic during the social distancing.

One should be cautious in interpreting our findings that compared air pollution across different years (Zhao et al., 2020) because air pollution levels, particularly PM, SO_2, and CO, may be affected by meteorological factors. Also, evidence of reduced air pollution from several countries may not be directly generalizable to other countries, because the manner of social distancing measures may vary depending on countries.

The COVID-19 crisis has allowed us an opportunity to evaluate effects on the ambient environment from reduced industrial activity and traffic. Recently, Rosenbloom and Markard suggested that COVID-19 recovery programs can lay the foundation for transition toward a more sustainable post-COVID-19 world (Rosenbloom and Markard, 2020). Our findings of significant reduction in air pollution (ambient $PM_{2.5}$, PM_{10}, NO_2, and CO) in Korea after social distancing against the COVID-19 is such a temporary and regional example toward clean air. However, this study supports the need to further reduce current levels of fossil fuel consumption in order to more effectively control air quality, and suggests a clue to a public health problem attributable to air pollution.

CRediT authorship contribution statement

Min Jae Ju: Investigation, Formal analysis, Writing - original draft. **Jaehyun Oh:** Investigation, Formal analysis, Writing - review & editing. **Yoon-Hyeong Choi:** Methodology, Writing - original draft, Writing - review & editing.

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.

Data sharing

Data of air pollution used in this study are freely available from the sources cited (http://www.airkorea.or.kr/web).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141521.

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