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Global, continental, and national variation in PM$\textsubscript{2.5}$, O$\textsubscript{3}$, and NO$\textsubscript{2}$ concentrations during the early 2020 COVID-19 lockdown

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ABSTRACT

Lockdowns implemented in response to COVID-19 have caused an unprecedented reduction in global economic and transport activity. In this study, variation in the concentration of health-threatening air pollutants (PM$\textsubscript{2.5}$, NO$\textsubscript{2}$, and O$\textsubscript{3}$) pre- and post-lockdown was investigated at global, continental, and national scales. We analyzed ground-based data from $>$10,000 monitoring stations in 380 cities across the globe. Global-scale results during lockdown (March to May 2020) showed that concentrations of PM$\textsubscript{2.5}$ and NO$\textsubscript{2}$ decreased by 16.1% and 45.8%, respectively, compared to the baseline period (2015-2019). However, O$\textsubscript{3}$ concentration increased by 5.4%. At the continental scale, concentrations of PM$\textsubscript{2.5}$ and NO$\textsubscript{2}$ substantially dropped in 2020 across all continents during lockdown compared to the baseline, with a maximum reduction of 20.4% for PM$\textsubscript{2.5}$ in East Asia and 42.5% for NO$\textsubscript{2}$ in Europe. The maximum reduction in O$\textsubscript{3}$ was observed in North America (7.8%), followed by Asia (0.7%), while small increases were found in other continents. At the national scale, PM$\textsubscript{2.5}$ and NO$\textsubscript{2}$ concentrations decreased significantly during lockdown, but O$\textsubscript{3}$ concentration showed varying patterns among countries. We found maximum reductions of 50.8% for PM$\textsubscript{2.5}$ in India and 103.5% for NO$\textsubscript{2}$ in Spain. The maximum reduction in O$\textsubscript{3}$ (22.5%) was found in India. Improvements in air quality were temporary as pollution levels increased in cities since lockdowns were lifted. We posit that these unprecedented changes in air pollutants were mainly attributable to reductions in traffic and industrial activities. Column reductions could also be explained by meteorological variability and a decline in emissions caused by environmental policy regulations. Our results have implications for the continued implementation of strict air quality policies and emission control strategies to improve environmental and human health.

1. Introduction

In 2020, the COVID-19 outbreak has led to unprecedented societal and environmental impacts globally (Le et al., 2020). The World Health Organization (WHO) declared COVID-19 a ‘global pandemic’ on the March 11, 2020 based on increasing rates of COVID-19 cases across the globe (WHO, 2020). Subsequently, to curb virus spread, many countries have enacted dramatic control measures to reduce human interactions, including enforcing strict quarantines, prohibiting large-scale private and public gatherings (He et al., 2020), restricting private and public transportation (Ma and Kang, 2020a,b), encouraging social distancing, imposing curfews, and even locking down entire cities (Zhang et al., 2020a,b). Such lockdowns inadvertently served as natural experiments to evaluate air-quality responses to marked reductions in human

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activities and anthropogenic gas emissions (Venter et al., 2020). As such, the COVID-19 pandemic has not only impacted human health, the economy, employment, and income equality, but also responses to global climate change and secondary health risks.

Recently, multiple studies have investigated the impact of COVID-19 on the atmospheric environment and climate change (Sharma et al., 2020; Shi and Brasseur, 2020). For instance, He et al. (2020), based on comprehensive daily air quality data and difference-in-differences models, identified the plausible causal impact on air quality of virus-containment measures in China, with the Air Quality Index (i.e., the AQI, ranging between 0 and 500 points) in locked-down cities decreasing by 19.84 points. Similarly, Forster et al. (2020) estimated that global NOx emissions declined by as much as 30% in April 2020, contributing to short-term cooling since the start of 2020. They also found that the global response to COVID-19 led to a sudden reduction in both greenhouse gas emissions and air pollutants. Pacheco et al. (2020) reported that air quality in Ecuador was greatly improved during lockdown with a 23% decrement in the NO2 concentration. This trend of increasing air quality was also found in Lima, Peru (Velasquez and Lara, 2020), Rio de Janeiro, Brazil (Nakada and Urban, 2020) Almaty, Kazakhstan (Kerimray et al., 2020), and in four Southern European cities (Nice, Rome, Valencia, and Turin; Sicard et al., 2020). Further, Pata (2020) studied the impact of COVID-19 pandemic on environmental pollution in eight different US cities and found that the ongoing pandemic decreased the PM2.5 emission in the US. Similarly, Sarfraz et al. (2020) investigated the relationship between COVID-19 and NO2 concentration level in New York City and revealed that environmental quality significantly improved during the pandemic. Moreover, Agarwal et al. (2020) analyzed the influence of lockdown measures on air pollution of six megacities of India and six cities in China and concluded that air pollution in considered cities reduced drastically.

This new research suggests that the restriction measures implemented during the COVID-19 pandemic have positively impacted air quality in different countries, but few studies have investigated air quality changes pre- and post-lockdown at global, continental, and national scales due to limitations in global ground-level data. In addition, the aforementioned studies analyzed changes in the mass concentration of air pollutants in 2020 by using 2019 as a baseline, without controlling for the effects of inter-annual climatic variability. While many studies have quantitatively analyzed changes in air pollutant levels in 2020 (Kumari and Tosniwal, 2020; Ma and Kang, 2020a,b), a detailed analysis of the factors underlying those changes remains to be undertaken.

The aim of this study was to reveal the impact of COVID-19 lockdowns on the most health-threatening air pollutants (PM2.5, NO2, and O3) (Lelieveld et al., 2015) at global, continental, and national scales using ground-level measurements from >10,000 air quality stations from 380 cities across the globe. We used the natural breakpoint method to evaluate the spatiotemporal distribution of PM2.5, O3, and NO2 concentrations. To control for inter-annual variability, the relative change rate was used to estimate changes between 2020 and the 5-year average (2015–2019) of each pollutant. Finally, we discuss the impacts of economic output, human activities, and industrial production on global air quality variation during COVID-19 lockdowns.

The results of this study provide new and timely insights into how COVID-19 lockdowns in 2020 affected air quality across the globe and at different scales, thus helping us quantify potential inequalities in pollutant exposure as a result of COVID-19. This work will help policymakers and scientists in devising sustainable environmental management plans to limit air pollution as the world recovers from the COVID-19 pandemic.

2. Materials and methods

2.1. Study area and data sources

This study was carried out over a global scale, focusing on 5 main continents: Asia, Europe, North America, South America, and Australia. We did not include Africa because from the previous analysis on satellite retrieved data, the abnormal change in the continent is not as significant as other continents (Zhang et al., 2020a,b). The primary reasons for no significant change of pollutants found over Africa are as following. First, the background concentration of air pollutants in Africa was lower than that in other regions (Yue and Unger, 2018; Klimont et al., 2017). Second, most African countries failed to implement strict lockdown measures during COVID-19 epidemic. In order to investigate air pollution changes at the national scale, we selected 12 countries around the world as key research objects according to: 1) the time when different countries declared a state of emergency, 2) the cumulative confirmed number of cases and deaths resulted from infections with COVID-19, and 3) Gross National Product (GNP). The selected countries were: China, India, Japan, South Korea, Italy, Spain, France, the UK, the US, Canada, Chile, and Australia. More detailed information about these 12 countries can be found in Table S1.

For the different scales analysis of air quality, data on three main pollutants (PM2.5, NO2, and O3) were used to investigate changes in air quality before and after lockdown measures. Daily air quality data for these pollutants (from January 1, 2015 to June 28, 2020) were collected from the World Air Quality Index (WAQI) project (WAQI, 2020). In addition, new dedicated worldwide COVID-19 datasets of air quality, updated 3 times daily, and covering 380 major cities in the world were collected from the Air Quality Open Data Platform (WAQI, 2020). Fig. 1 shows the distribution of these 380 cities among continents and countries. More than 90% of the cities were distributed in Asia (41%), North America (15%), or Europe (35%). Data for each major city were based on the average data of several monitoring stations and all air pollutants were converted to the US EPA standard (i.e., no raw concentrations, WAQI, 2020).

2.2. Data preprocessing

Prior to the statistical analysis, we conducted three data quality controls to ensure the validity of air pollutant concentration data. First, we excluded from the raw data daily values ≤ 0 and missing values. Second, to calculate monthly mean values, if monitoring data for a given month covered fewer than 27 days due to missing data, data for that month were excluded. Third, we removed abnormal values (>1000 daily; Guo et al., 2017).

We used two approaches to quantify air pollution variation from January to June 2020. First, we calculated monthly comparisons, and, second, we calculated lockdown comparisons (Venter et al., 2020). For the monthly comparisons, we calculated average pollutant levels from January to June each year between 2015 and 2020. The comparison was defined as the difference between 2020 values and the average of values for the 5-year baseline (2015–2019), to account for the effects of inter-annual climatic variability in air pollution.

To avoid averaging potential effects of COVID-19 over the January to June 2020 period, we also calculated air pollution changes using country-specific lockdown periods (Table S1). For instance, China went into lockdown in January 2020, whereas the majority of lockdowns in other countries occurred from March 2020 onwards. We created a dataset of lockdown dates in 577 cities from official websites and mass media from January 1, 2020, to August 30, 2020. We calculated the probability distribution of lockdown start and end dates for these 577 cities (Fig. 2a), as well as the numbers of lockdown days (Fig. 2b). We found that >75% of cities implemented lockdown measures in March 2020 and >50% ended measures in May, with an average of 57 days of lockdown across cities (Fig. 2b). Based on Fig. 2a, in this study, we
defined March to May 2020 as a global lockdown phase to assess global air pollutants.

2.3. Monthly relative rate of change

The monthly relative rate of change (ROC) was used to compare variance in air pollutants exposure in different periods. ROC was defined as follows:

$$ROC_m = \left( \frac{x_{2020m} - x_{2015-2019m}}{x_{2020m}} \right) x_{2020m} \times 100\%$$

where $ROC_m$ is the monthly relative rate of change of pollutant concentration in month $m$, $x_{2020m}$ is the pollutant concentration in $m$ month in 2020, and $x_{2015-2019m}$ is the baseline pollutant concentration in $m$ month from 2015 to 2019. If $ROC_m$ was positive, the pollutant concentration in 2020 was higher compared to the baseline (2015–2019), and conversely, if $ROC_m$ was negative, the pollutant concentration in 2020 was lower compared to the baseline.

3. Results

3.1. Changes in air pollution at the global scale

Fig. 3 shows the daily variation of global-level PM$_{2.5}$, O$_3$, and NO$_2$ concentrations in the first half of 2020 (1st January to 30th June) relative to a 5-year average for the same months. The global ground-level mean changes in concentrations of PM$_{2.5}$ ($-1.3\%$) and NO$_2$ ($-5.8\%$) from the January 1, 2020 to the date of the Wuhan lockdown (January 23, an indicator of the start of the COVID-19 epidemic) were similar to the comparison period (2015–2019) for those months. However, global ground-level O$_3$ concentrations were much lower in 2020 ($-39.9\%$; Fig. 3b). As shown in Fig. 3, global ground-level PM$_{2.5}$ and NO$_2$ concentrations during COVID-19 lockdowns decreased by $-16.1\%$ (Fig. 3a) and $-45.8\%$ (Fig. 3c), respectively, compared to the 5-year average for the same dates. In contrast, global ground-level O$_3$ concentration increased by $5.4\%$ (Fig. 3b). At the end of May 2020, after most countries across the globe announced the lifting of the emergency state, the global ground-level PM$_{2.5}$ and NO$_2$ concentration rebounded, but they were still significantly lower than the level during the same
period in 2019. On the contrary, the global O\textsubscript{3} concentration returned to that during the same period of 2019 in early June 2020.

3.2. Changes in air pollution at the continental scale

Fig. 4 shows the spatial distribution of monthly mean ROC values of ground-level PM\textsubscript{2.5} concentration from January to June 2020 compared to baseline conditions (2015–2019). We observed declines in ground-level PM\textsubscript{2.5} concentration in more than 70% of cities (240 out of 343; Fig. 4 and Table S2). Decreases in extent and magnitude of ground-level PM\textsubscript{2.5} concentration were much higher in Asia and Europe compared with North and South America. Prior to COVID-19 lockdowns, in January and February 2020, the average monthly ground-level PM\textsubscript{2.5} concentration decreased by 10.6% (±19.5%) relative to the 5-year average for the same months. The lowest monthly mean ROC of global PM\textsubscript{2.5} concentration occurred in Europe (54.6 ± 48.5%; Fig. S1). After COVID-19 lockdowns, all selected continents have shown a significant decline in PM\textsubscript{2.5} concentration from March to June 2020 as compared to the 5-year average for the same months. The average monthly ground-level PM\textsubscript{2.5} concentration decreased by −19.1% (±19.0%) in March, −12.1% (±19.2%) in April, −22.6% (±19.2%) in May, and −18.99% (±23.04%) in June. Compared with January 2020, the ROC of global PM\textsubscript{2.5} concentration changed by −16.2% in February, −8.5% in March, −1.5% in April, −12.0% in May, and −2.8% in June. For Asia, the lowest monthly mean ROC (−23.8 ± 16.3%) occurred in March. For Europe and North America, the lowest monthly mean ROCs occurred in May, with values of −24.2% (±21.9%) and −19.2% (±20.3%), respectively. The lowest monthly mean ROC values occurred in April for South America (−23.5 ± 30.1%) and Australia (−31.7 ± 24.3%; Fig. S1).

Maps of monthly mean ROC of ground-level NO\textsubscript{2} concentration are shown in Fig. 5. We observed declines in ground-level NO\textsubscript{2} concentration in more than 70% of cities (263 out of 375) relative to the 5-year average for the same dates (Fig. 5 and Table S2). The maps of monthly mean ROC of ground-level NO\textsubscript{2} concentration showed higher levels of NO\textsubscript{2} concentration in East Asia and Europe and lower levels in South Asia and North America. Monthly mean ROC of ground-level NO\textsubscript{2} concentration was unevenly distributed throughout Europe and North

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**Fig. 3.** Daily global ground-level (a) PM\textsubscript{2.5}, (b) O\textsubscript{3}, and (c) NO\textsubscript{2} mean concentrations across all stations globally (N = 380) from the January 1, 2020 (Day of the Year, DOY = 1) to the June 28, 2020 (DOY = 180). The red line indicates the concentration of pollutants in 2020 (with trend line in black), while the blue line indicates the average concentration of pollutants in the baseline (2015–2019). The vertical black dashed line shows the onset of Wuhan’s lockdown (January 23, 2020) and the red dashed line shows the average onset of the global lockdown (March 10, 2020) as identified in this analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Fig. 4.** Spatial distribution of the monthly relative rate of change (ROC) of ground-level PM\textsubscript{2.5} concentration from January to June 2020. In the insets, the red bar charts show the distribution of cities with different ROCs, while the blue lines show cumulative frequencies. Please note, the global lockdown as identified in this analysis ranges from March to May 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
America, in contrast to Asia. Prior to the COVID-19 lockdowns in January and February 2020, ground-level average monthly NO\(_2\) concentration decreased by \(-13.5\% (\pm 31.4\%)\) and \(-31.8\% (\pm 43.7\%)\) for each month in the world. Specifically, in January and February, all selected continents (except Australia) showed a reduction to some extent in 2020 as compared to 2019. The maximum reduction in monthly mean ROC of ground-level NO\(_2\) concentration in January was observed in Asia \((-19.3 \pm 38.5\%)\), and North America \((-20.3 \pm 43.7\%)\).
3.3. Changes in air pollution at the national scale

Despite the overall average decline in air pollution during lockdown, there was substantial variation among countries, both in terms of the direction and magnitude of change. Daily air pollutant series revealed that the different timings of reductions were synchronous with lockdown measures. Fig. 7 shows trends in ground-level daily PM$_{2.5}$ concentrations in 12 study countries from January to June 2020. Prior to COVID-19 lockdowns, the ground-level daily PM$_{2.5}$ concentrations were similar to the same period averaged over 2015–2019 (Table S5) in China (−3.4%), Italy (−5.4%) and Spain (6.37%), while the ground-level daily PM$_{2.5}$ concentrations were much lower in India (−25.3%), Japan (−25.8%), South Korea (−13.1%), France (−33.6%), the UK (−43.9%), the United States (−12.9%), Canada (−16.1%) and Chile (−15.1%), but instead much higher in Australia (25.6%). Compared to baseline conditions, the ground-level daily PM$_{2.5}$ concentration significantly decreased during the lockdown and the most pronounced decline occurred in India (−50.8%) followed by South Korea (−39.9%), Australia (−20.2%), Chile (−19.8%), Japan (−17.8%), and Canada (−13.0%), with large declines observed in only the early lockdowns in China (−24.0%) and Italy (−20.5%; Fig. 7 and Table S5). Compared with before the COVID-19 lockdown, daily mean ROC of ground-level PM$_{2.5}$ concentration changed after COVID-19 lockdown by −25.5% in India, −26.2% in South Korea, −45.7% in Australia, −4.7% in Chile, −20.6% in China, and −15.1% in Italy. In addition, from daily variations of PM$_{2.5}$ level, we could also find that reduction in PM$_{2.5}$, which was more significant in China, India, South Korea, Italy, Spain, Chile, and Australia compared to other regions, was related to lockdown status. The sudden and early drop in Chinese emissions corresponds to the initial outbreak of COVID-19 and to the country’s strict lockdown measures, which were gradually relaxed in March (Fig. 7). Monthly relative differences in China between 2020 and the baseline were −26.4% in February, −32.2% in March, and −15.5% in April, further indicating that China’s PM$_{2.5}$ emissions recovered gradually post-lockdown. In other countries, PM$_{2.5}$ concentration also showed a significant decrease in January and February, but this trend was not caused

Fig. 7. Daily mean PM$_{2.5}$ concentrations across all national stations from the January 1, 2020 (Day of the Year, DOY = 1) to the June 28, 2020 (DOY = 180). The red lines indicate the concentration of pollutants in 2020, while the blue lines indicate the average concentration of pollutants in the baseline (2015–2019), with standard deviations in the baseline in light blue. Gray rectangles show the duration of lockdown in each of the 12 study countries. The numbers in parentheses indicate the relative rate of change (ROC) of daily mean PM$_{2.5}$ concentration after the COVID-19 lockdown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
by lockdowns. In January and February, PM$_{2.5}$ concentration decreased by 16.9–28.6% in India, 19.7–23.3% in Japan, and 10.5–19.7% in South Korea (Fig. S1). Following the outbreak of COVID-19, the observed drop was coincident with the spread of the virus and onset of lockdowns, with greater decreases in March (Japan: –35.3%, India: –38.8%, South Korea: –39.3%, Italy: –26.1%, Chile: –31.8%, and Australia: –31.5%) than in February (Japan: –19.7%, India: –16.9%, South Korea: –16.1%, Italy: –12.3%, Chile: –18.9%, and Australia: –1.3%). In some countries, decreases in emissions were the highest in May (UK: –41.7%, US: –19.4, and Canada: –35.0%; Fig. S1).

The daily variations of ground-level NO$_2$ concentrations before and after lockdown in 2020 compared with the baseline are presented in Fig. 6. It was clear from time series graphs that daily NO$_2$ level before the lockdown period in 2020 was showing a similar trend of fluctuation as it was in the baseline condition (2015–2019), while after the lockdown was carried out, time series of mean NO$_2$ began to drop down compared to the baseline level due to strict lockdown measures. Specifically, all selected countries except Italy (1.9%) and Australia (3.5%) have shown a lower decline in ground-level daily NO$_2$ concentrations before the lockdown was implemented. During the lockdown, all countries showed a significant reduction in daily mean NO$_2$ concentration compared to the baseline, except Australia, which showed a moderate decline (–3.6%; Fig. 8). The most significant declines occurred in Spain (–103.5%, –5.6% before lockdown), Italy (–93.7%, 1.9%), France (–93.1%, –21.1%), and the UK (–81.2%, –42.4%) followed by India (–79.4%, –23.2%), China (–57.0%, –15.2%), and Chile (–54.7%, –21.9%). In addition, Japan (–33.6%, –17.7%), South Korea (–33.3%, –12.0%), the US (–36.1%, –8.4%), and Canada (–23.7%, –9.2%) showed notable declines (Fig. 8 and Table S6). It can be seen from Table S6 that the national ground-level NO$_2$ concentrations after the lockdown was less than that before the lockdown. Compared with before the COVID-19 lockdown, daily mean ROC of ground-level NO$_2$ concentration changed after COVID-19 lockdown by –97.9% in Spain, –95.6% in Italy, –72.1% in France, –38.8% in the UK, –56.3% in India, –41.8% in China and –35.9% in Chile. Since May 2020, lockdown restrictions in many countries have begun to ease and emissions deficits have decreased (China: –25.4% in May and –26.1% in June, India: –73.1% in May and –52.1% in June, Japan: –21.3% in June, UK: –47.9% in June, Italy: –103.2% in June, Spain: –72.4% in May and –46.6% in June, France: –52.7% in May and –29.6% in June).

Similarly, compared with baseline conditions, a significant reduction in NO$_2$ concentration was observed in all countries except Italy and Australia from January to June 2020 (Fig. 8 and Fig. S2). Meanwhile, all study countries except China showed a large reduction in NO$_2$ concentration in April and May 2020 compared with baseline conditions. In February 2020, the maximum reduction was observed in China (–82.4%). In April, the maximum decline was seen in Spain (–116.4%), followed by India (–93.4%), the UK (–93.1%), and France (–94.1%). Similarly, in May, Italy (–112.2%) followed by South Korea (–47.7%), Canada (–41.4%), the US (–39.2%), Japan (–37.0%), and Australia (–12.9%) showed the highest reductions in NO$_2$ concentration compared with the baseline (Fig. S2).

Generally, by comparing data of for the 12 countries, a mixed trend was observed for monthly mean O$_3$ concentration. Compared to the baseline, 7 countries in January, 8 countries in February, 7 countries in March, 9 countries in April, and 5 countries in May showed higher ground-level O$_3$ concentrations in 2020 (Fig. S3). On the other hand, reductions were seen in some countries during some months, such as India (–30.4%), the US (–15.3%), and Canada (–2.3%) in March; Japan (–9.4%) and South Korea (–8.5%) in May; and China (–9.6%) and France (–7.4%) in June (Fig. S3). Increases were observed in China (18.1% in January and 14.7% in February), Japan (7.9% in April), South Korea (9.1% in January, 3.3% in March, 14.0% in April, and 4.2% in Jun), the UK (13.5–24.1% from January to June), Italy (8.1% in February and 5.3% in April), France (19.3% in February, 7.6% in March, and 7.5% in April), Canada (7.2% in January and 0.4% in March), Chile (2.8–15.8% from January to June), and Australia (11.4–18.0% from January to June; Fig. S3).

Fig. 9 exhibits the daily variations of ground-level O$_3$ concentrations compared with the baseline level during 2015–2019 before and after lockdown in 2020. Before the lockdown, the daily O$_3$ mean concentrations were similar to the same period averaged over 2015–2019 in Japan.

![Fig. 8. Daily mean NO$_2$ concentrations across all national stations from the January 1, 2020 (Day of the Year, DOY = 1) to the June 28, 2020 (DOY = 180). The red lines indicate the concentration of pollutants in 2020, while the blue lines indicate the average concentration of pollutants in the baseline (2015–2019), with standard deviations in the baseline in light blue. Gray rectangles show the duration of lockdown in each of the 12 study countries. The numbers in parentheses indicate the relative rate of change (ROC) of daily mean NO$_2$ concentration after the COVID-19 lockdown. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)](image-url)
(−3.6%), South Korea (4.8%), Italy (−7.1%), France (8.4%), the US (−5.1%) and Canada (2.7%), while the O3 concentrations were much lower in India (−22.6%) and Spain (−11.4%), and much higher in China (12.9%), the UK (17.1%), Chile (12.1%) and Australia (14.1%). Compared to baseline conditions, daily O3 mean concentration increased during the lockdown by 10% in China, 15.6% in the UK, 11.1% in Chile, and 15.9% in Australia, while daily O3 mean concentration decreased by 22.5% in India and 11.9% in the US. After the COVID-19 lockdown, daily O3 mean concentrations showed small changes compared to the baseline in Japan (2.6%), South Korea (3.3%), Italy (3.5%), Spain (−2.1%), France (5.1%), and Canada (−0.4%; Fig. 9).

4. Discussion

Long-term exposure to air pollution (e.g., PM$_{2.5}$, NO$_2$, and O$_3$) has become a major public health issue globally (van Donkelaar et al., 2016; Klimont et al., 2017). The COVID-19 pandemic has presented an opportunity to quantify pollutant emission changes and assess how their concentrations can be reduced. In this study, we analyzed global air quality at different scales under the influence of COVID-19 lockdowns in the first half of 2020. Overall, PM$_{2.5}$ and NO$_2$ concentrations showed a significant decline in 80% of study cities during the enforcement of lockdowns (mostly in March to May 2020) compared to the 5-year baseline (2015–2019). However, O$_3$ have shown a mixed trends in March, April and May of 2020 as compared to the 5-year baseline (2015–2019).

Reductions in PM$_{2.5}$ and NO$_2$ concentrations could be explained by a number of factors. First, the global economic downturn may have played a role. PM$_{2.5}$ and NO$_2$ are the main pollutants of the atmospheric environment, mainly derived from coal combustion (Wang et al., 2018), industrial and domestic sources (Klimont et al., 2017), regional transport (Lei et al., 2015), and urban construction. These two air pollutants show significant correlations with the economy, including import and export trade (Liu et al., 2019). As COVID-19 became a global pandemic, COVID-19 containment measures weighed heavily on economic activities in the second quarter of 2020, with unprecedented falls in real gross domestic product (GDP) in most countries, except China (+3.2%). GDP fell most dramatically by −23.5%, in India, followed by the UK (−21.7%), France (−18.9%), Italy (−17.7%), Canada (−13.0%), the US (−9.1%), Japan (−10.1%), and Australia (−6.3% (Fig. 5a). Export values significantly declined in March, April, and May 2020 compared to the baseline (2015–2019) in the 12 study countries, except for China (Fig. S5).

The main reason for this discrepancy may be the timing of lockdowns. The prevalence of COVID-19 led to a temporary contraction of the global economy and trade and reduced the transfer and flow of pollutants in global trade. Previous studies have shown that during the 2007–2009 global economic recession, Chinese NO$_x$ emissions declined by −20% (Lin et al., 2013). Although the exports of goods and services as a percentage of GDP decreased from 32% in 2008 to 20% in 2018, the decreasing demand from other countries would nevertheless impact Chinese businesses focusing on exports, as well as domestic suppliers (The World Bank, 2020).

Second, under the impact of an unprecedented reduction in human activities, Zhang et al. (2020a,b) and Bauwens et al. (2020) found that the decline in global air pollutants was mainly attributable to lockdowns, which caused sharp reductions in human activities, especially transportation and industry. The strict restrictions had a strong impact on the transport sector, the industrial sector, commerce, institutions, and households (Venter et al., 2020). These were dominant sectors contributing to air pollution in most countries pre-COVID-19 (Klimont et al., 2017). Prior to the COVID-19 lockdowns in Europe, the transport sector was the largest contributor to NO$_x$ emissions (road transport: 39% and non-road transport: 8%) and represented 13% of PM emissions (EEA, 2019). Fuel and biomass combustion in the “commercial, institutional and households” (i.e., domestic heating) sector was the largest contributor to PM$_{2.5}$ and PM$_{10}$ emissions (56% and 39%, respectively) and represented 14% of NO$_x$ emissions. On the other hand, 46% of non-methane volatile organic compounds (VOCs) and 8% of NO$_x$ were...
emitted by the industrial sector (EEA, 2019). However, during the COVID-19 lockdowns, stronger reductions were observed at traffic stations for NO (−78%) and NO$_2$ (−65%) in European countries, where the road transport sector was the largest contributor to NO$_x$ emissions (Sicard et al., 2020). The magnitude of changes in NO$_2$ levels was similar between Chinese cities (−29% to −47%) and Delhi in India (−52.68%), where automobile exhausts are the major source of NO$_x$ (Li et al., 2020).

To further study changes in human activities during the COVID-19 lockdowns, we used the Google Community Mobility Reports dataset to quantitatively illustrate changes in mobility for different human activities in 9 of the 12 study countries (Fig. 56). The Google Mobility Index divides usual mobility activities into different categories, such as retail and recreation, grocery and pharmacy, transit stations, workplaces, residential, and park usage. From country-specific data (Fig. 56), we can see that activities such as transport, industries, social places, and educational sectors experienced large decreases, while the mobility index for residential activities increased during COVID-19 lockdowns. The highest reductions in the mobility index were observed in retail and recreation, transit stations, and workplaces, with Italy, Spain, France, and India exhibiting the largest drops in activities. These contextual data may explain why PM$_{2.5}$ and NO$_2$ concentrations in these countries declined sharply during COVID-19 lockdown.

Third, changes in PM$_{2.5}$ and NO$_2$ during the COVID-19 lockdowns may be linked to declines in global industrial production. In many countries, air pollutants mainly originate from industrial production, especially PM$_{2.5}$ and NO$_2$ (Zhao et al., 2019). As shown in Fig. 54b, COVID-19 containment measures severely limited industrial production in the second quarter of 2020, with unprecedented falls in real industrial production in most study countries. China was the only study country recording growth in the second quarter of 2020 (3.3%), reflecting the earlier onset of the pandemic in this country and subsequent recovery. Industrial production contracted by an average of −15.35% in the other study economies in the second quarter of 2020, when the effects of the pandemic began to feel more widely. The most pronounced declines in industrial production occurred in Italy (−25.9%), Spain (−24.4%), and France (−23.2%). Industrial production also dropped in Japan (−19.4%), the UK (−18.7%), Canada (−17.2%), and the US (−14.2%). The contraction was less pronounced in South Korea (−4.2%), Chile (−4.1%), and Australia (−2.1%). In China, the number of operating vents of key polluting enterprises decreased by −24.68% and the standardized NO$_{x}$/vent·day decreased by an average of −9.54 ± 6.00% due to COVID-19 (He et al., 2021). Similar patterns have been observed in Italy, Spain, France, and India (Sharma et al., 2020; Sicard et al., 2020).

Finally, meteorological factors may have influenced our results. Meteorological conditions are the primary factor causing daily variation in pollutant concentrations (He et al., 2017). Previous research has revealed that both emissions and meteorological variation dominate the long-term pollutant concentration trend (Wang et al., 2015). The unprecedented change in major global air pollutants in the first half of 2020 may be attributable, in part, to meteorological variability. For example, O$_3$ concentration decreases in countries such as Spain and the US may be explained by low and constant temperatures during lockdowns, hence O$_3$ concentrations could not increase. In addition, Spain and the US exhibited high humidity during the study time frame (Fig. 57). Generally, O$_3$ production is limited during cool or rainy weather (Kwak et al., 2017).

Compared with the significant decrease in PM$_{2.5}$ and NO$_2$ concentrations, O$_3$ concentration showed mixed trends during COVID-19 lockdowns compared to the baseline period. This may be explained by the fact that, first, O$_3$ is a secondary pollutant that depends on the local availability of its precursors (i.e., NOx and VOCs), where the reduction in emission of its precursors can increase O$_3$ concentration in the atmosphere (Lu et al., 2020). Our study also shows that changes in mean O$_3$ concentration at the global scale were associated with a strong decline in ground-level daily mean NO$_2$ concentration compared to baseline conditions. Second, NO consumes O$_3$ under the titration process: $\text{NO} + \text{O}_3 = \text{NO}_2 + \text{O}_2$. The O$_3$ titration effect is relevant locally and within the planetary boundary layer, whereas, further downwind, photochemical O$_3$ formation with the catalytic role of NO$_x$ is a more important factor (Venter et al., 2020).

5. Conclusions

Our results reveal the impact of stringent COVID-19 lockdown measures on global changes in PM$_{2.5}$, NO$_2$, and O$_3$ concentrations from March to June 2020. We observed declines in ground-level global PM$_{2.5}$ (−16.1%) and NO$_2$ (−45.7%) concentrations during COVID-19 lockdowns compared to the baseline (2015−2019). In contrast, O$_3$ increased by 5.4% globally. Over all continents, concentrations of PM$_{2.5}$ and NO$_2$ substantially dropped in 2020 during the lockdown period, with a maximum reduction of 20.4% for PM$_{2.5}$ in East Asia and 42.5% for NO$_2$ in Europe. Highly polluting countries such as India, China, South Korea, Italy, and Spain witnessed a notable decline in air pollution during the COVID-19 lockdown period, with PM$_{2.5}$ levels decreasing by −11.5% to −50.8% compared to the baseline in these countries. Higher declines (from −33.3% to −103.5%) were observed for NO$_2$ in these countries. O$_3$ concentration showed mixed trends during lockdown and an increasing trend in many countries, which may be due to the reduction of NO$_x$ consumption in the titration process and changes to meteorological conditions.

In conclusion, this analysis of air quality data shows that the strict implementation of lockdown measures by various countries during COVID-19 (and associated reductions in transport and industrial activities) contributed to the improvement of global air quality. Observed variations and improvements in air quality were temporary as the concentrations of study pollutants increased again in cities where lockdowns were lifted. Nonetheless, observed improvements in air pollution may catalyze governments and authorities to implement strict air quality policies and emission control strategies to improve environmental conditions and human health.

Credit author statement

Chao He: conceived the idea of the study and designed research, wrote the paper, discussed the results and revised the manuscript; Song Hong: conceived the idea of the study and designed research, discussed the results and revised the manuscript; Lu Zhang: interpreted the results, discussed the results and revised the manuscript; Hang Mu: analyzed the data, discussed the results and revised the manuscript; Yiqi Zhou: analyzed the data, discussed the results and revised the manuscript; Feng Deng: reviewed the results and revised the manuscript; Junjie Gu: reviewed the results and revised the manuscript; Hong: conceived the idea of the study and designed research, discussed the results and revised the manuscript; Ya Tian: discussed the results and revised the manuscript; Nanjian Liu: analyzed the data, discussed the results and revised the manuscript; Hang Mu: discussed the results and revised the manuscript; Lu Yang: conceived the idea of the study and designed research, interpreted the results, wrote the paper, discussed the results and revised the manuscript.

Declaration of competing interest

We have no conflict of interests for the paper titled: Global, continental, and national variation in PM$_{2.5}$, O$_3$, and NO$_2$ concentrations during the early 2020 COVID-19 lockdown.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apr.2021.02.002.
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