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Impact of lockdown during the COVID-19 outbreak on multi-scale air quality

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HIGHLIGHTS

• Global NO$_2$ column observations were reduced by approximately 9.19% (March) and 9.57% (April) due to COVID 19 lockdown.
• Most monitoring sites in Europe, USA, China, and India showed declines in pollutant concentrations during analysis.
• Four major cities case studies also shown a similar reduction trends and an increase in ozone concentration.

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ABSTRACT

One of the multi-facet impacts of lockdowns during the unprecedented COVID-19 pandemic was restricted economic and transport activities. This has resulted in the reduction of air pollution concentrations observed globally. This study is aimed at examining the concentration changes in air pollutants (i.e., carbon monoxide (CO), nitrogen dioxide (NO$_2$), sulfur dioxide (SO$_2$), ozone (O$_3$), and particulate matters (PM$_{2.5}$ and PM$_{10}$)) during the period March–April 2020. Data from both satellite observations (for NO$_2$) and ground-based measurements (for all other pollutants) were utilized to analyze the changes when compared against the same months between 2015 and 2019. Globally, space borne NO$_2$ column observations observed by satellite (OMI on Aura) were reduced by approximately 9.19% and 9.57%, in March and April 2020, respectively because of public health measures enforced to contain the coronavirus disease outbreak (COVID-19). On a regional scale and after accounting for the effects of meteorological variability, most monitoring sites in Europe, USA, China, and India showed declines in CO, NO$_2$, SO$_2$, PM$_{2.5}$, and PM$_{10}$ concentrations during the period of analysis. An increase in O$_3$ concentrations occurred during the same period. Meanwhile, four major cities case studies i.e. in New York City (USA), Milan (Italy), Wuhan (China), and New Delhi (India) have also shown a similar reduction trends as observed on the regional scale, and an increase in ozone concentration. This study highlights that the reductions in air pollutant concentrations have overall improved global air quality likely driven in part by economic slowdowns resulting from the global pandemic.

1. Introduction

The rapid spread of Coronavirus Disease (2019) (COVID-19) is having profound human health, environmental, social, and economic impacts worldwide. On March 11, 2020, the World Health Organization (WHO) declared the COVID-19 outbreak a pandemic, and by December 31, 2020 there were over 112 million cases globally, and over 2.49million people had lost their lives (Johns Hopkins University and Medicine, 2020). The novel coronavirus that causes COVID-19 has been linked to animals and was reportedly transmitted to humans in Wuhan, China, in December 2019 (Chen et al., 2020).

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countries have locked down to prevent the spread of Coronavirus (Venter et al., 2020); but ozone mean concentrations increased at urban stations compared to the same period (Sicard et al., 2020; Aluì et al., 2021). However, COVID-19’s impact on the global atmospheric environment needs examining. This will allow linking air quality changes to human health. The impact of reduced air pollution and greenhouse gas emissions and energy consumption will be temporary unless governments adopt new approaches to development that protect both the health of the planet and those that inhabit it. This will require more stringent regulations and, ultimately, the transition to clean energy (e.g. supporting renewables and energy efficiency).

Air pollution is known to weaken the immune system, compromising people’s ability to fight off infection, thus severely adversely effecting COVID-19 impact (The European Public Health Alliance, 2020). The SARS outbreak in China (2003), infected patients in areas with higher air pollution were 84% more likely to die than in less polluted areas (Cui et al., 2020). The COVID-19 impact (The European Public Health Alliance, 2020). The SARS outbreak in China (2003), infected patients in areas with higher air pollution were 84% more likely to die than in less polluted areas (Cui et al., 2020). The research in the US suggests that air pollution has significantly worsened the COVID-19 outbreak and led to more deaths than if pollution-free skies were the norm. Moreover, recent research suggests that atmospheric transport of air pollution (i.e. fine particulate matter (PM$_{2.5}$) particles) may be acting as vehicles for viral transmission. For example, an increase of just 1 μg per cubic meter of PM$_{2.5}$ is associated with an 8% increase in the COVID-19 death rate (Wu et al., 2020) as well as 9.4 more COVID-19 cases, 3.0 more hospital admissions, and 2.3 more deaths (Cole et al., 2020). WHO data shows that 9 out of 10 people are exposed to elevated concentrations of pollutants, therefore, the WHO is working with countries to monitor air pollution and improve air quality.

As countries scale up responses to COVID-19, an opportunity exists to align with the proposed redefined values of development, which embrace a safer planet and a promise of improved health and environment for all. As we become more aware of our dependence on the environment, governments must focus on effective science-policy interface or changes in policy, which is informed by science. Once we emerge from lockdown it will be into a new and uncertain world with a serious need for air pollution and climate change curve still to flatten. We thus need policies not for the short term, but for the long term. Possible solutions include raising fuel efficiency standards for the transport sector and supporting zero-emission vehicles; promote mass transit in urban areas as well as cycling and pedestrian activities; reducing air pollution and greenhouse gas emissions in the electricity and agricultural sectors by supporting renewables and energy and nutrient use efficiencies and adopt a suite of other policies in the manufacturing, industrial, and agricultural sectors that also reduce both air pollution and greenhouse gases.

Surface measurements made at more than 800 monitoring stations show that the mean levels of fine particulate matter (PM$_{2.5}$) and nitrogen dioxide (NO$_2$) in northern China have decreased by approximately $29 \pm 22\%$ and $53 \pm 10\%$, respectively, after the lockdown following the COVID-19 outbreak of early 2020; while simultaneously, the ozone (O$_3$) concentration, a secondary pollutant responsible for severe health problems, has increased by a factor 1.5–2 (Shi and Brasseur, 2020). Satellite NO$_2$ data show substantial decreases by 40% on average over Chinese cities due to lockdown measures against the coronavirus outbreak; while Western Europe and U.S. display robust NO$_2$ decreases in 2020, 20–38% relative to the same period in 2019 (Bauwens et al., 2020). Venter et al. (2020) provide similar results (after accounting for the effects of meteorological variability) for reductions in tropospheric and ground-level air pollution concentrations, using satellite data and a network of >10,000 air quality stations (in 34 countries). Elsewhere, Dantas et al. (2020) and Siciliano et al. (2020) indicated a reduction of carbon monoxide (CO) and NO$_2$ in Rio de Janeiro and São Paulo, Brazil during the partial lockdown. Their study also found that in the same period O$_3$ concentrations increased. The reduction between 9% and 69% in CO, NO$_2$, and PM were also observed in Northern South America (Mendez-Espinosa et al., 2020). In Saudi Arabia, Anil and Alagha (2020) conducted their study on air pollutant concentrations before and after the lockdown. They found that, excluding O$_3$, air pollutant concentrations reduced between 6% and 86%. Tobias et al. (2020) looked at the changes of NO$_2$, black carbon (BC), PM$_{10}$, and O$_3$ concentrations during the lockdown in Barcelona, Spain, and found a similar pattern observed in other locations, i.e., reduction in all but O$_3$ concentrations. Moreover, daily global CO$_2$ emissions decreased by $-17\% (-11$ to $-25\%$ for $\pm 1\sigma$) by early April 2020 compared with the mean 2019 levels (Le Quéré et al., 2020). Kumari and Toshniwal (2020) examined the global impact of COVID-19 on the air quality based on ground-based data from 162 monitoring stations from 12 cities across the globe. The concentration of PM$_{2.5}$, PM$_{10}$ and NO$_2$ were reduced by 20–34%, 24–47% and 32–64%, respectively, owing to restriction on anthropogenic emission sources during lockdown. However, SO$_2$ concentration level showed a mixed trend during the lockdown phase. For few cities like Lima, Madrid, Moscow, Rome, Sao Paulo and Wuhan, SO$_2$ concentration remained unchanged in lockdown phase as the main emission source of SO$_2$ is power plants, which remained operational at most of the location.

The main objective of this study is to determine the impact on air quality (after accounting for meteorological variations) due to the measures taken globally related to the coronavirus- COVID-19 -outbreak using both satellite and ground-based measurements in the United States, India, and Europe. Furthermore, city-wide case studies for New York City (USA), Milan (Italy), Wuhan (China) and New Delhi (India) were also conducted. Satellite and ground-based measurements were analyzed for March and April 2020, with data from China also being analyzed for February 2020, then compared against ground-based measurements and satellite retrieval data for the same data from China also being analyzed for February 2020, then compared against ground-based measurements and satellite retrieval data for the same months from 2015 to 2019. The compared five-year period was used as the baseline for air quality not influenced by the lockdowns. The purpose of the inclusion of this period is two-fold: (1) to normalize the impacts of meteorological factors to the atmospheric concentrations of air pollutants; (2) to narrow down the case studies to locations that have long-term measurements and data-series. By means of normalizing the meteorological influences and narrowing down the case studies, this study attempts to corroborate a closer examination on the lockdown effect rather than to generalize the findings by incorporating multiple locations with a shorter data coverage.

Satellite measurements revealed how air pollution has fallen dramatically in cities across the world due to COVID-19 lockdown measures. Ground level measurements confirm these observations.

2. Data & methodology

Changes in CO, O$_3$, PM$_{2.5}$, and PM$_{10}$ were analyzed using ground-based measurements. Changes in NO$_2$ were evaluated using a combination of ground-based measurements and satellite-based measurements. For the purposes of the current study, NO$_2$ concentrations were particularly amenable to analysis using satellite data, since motor vehicle emissions of NO$_2$ were affected by the shutdowns and also amenable to detection on a regional scale. SO$_2$ is also measured by satellite, but emissions of this gas are primarily from point sources, industrial factories and electric power generation stations. Elevated concentrations of SO$_2$ are localized around these sources, and the sources were not as strongly affected by the shutdowns as motor vehicles. Satellite measurements of O$_3$ measure a combination of stratospheric and tropospheric O$_3$. Variations in stratospheric O$_3$ make it difficult to evaluate changes in tropospheric O$_3$. Satellites are also used to measure aerosol optical depth (AOD), which is often used as a surrogate for particulate matter. However, AOD represents a combination of natural and anthropogenic sources, and transport. Therefore, only NO$_2$ was evaluated using satellite data.

Satellite data for NO$_2$ were obtained from the OMI/Aura NO$_2$ Cloud-Screened Total and Tropospheric Column Level 3 (https://disc.gsfc.nasa.gov/datasets/OMNO2d.003/summary). The daily data have a 0.25 ° x 0.25 ° resolution with a global spatial coverage, while the temporal
coverage for this data is from January 2015 to April 2020. Based on the temporal average, this dataset is divided into two timeframes. The 2015–2019 timeframe is the reference period and the 2020 timeframe are designated as the analyzed period. All daily data in the 2015–2019 timeframe were averaged to generate a single baseline as the reference period. For the analyzed period, the 2020 timeframe was averaged by each month in the timeframe (i.e., January, February, March, and April 2020) and was compared to the reference period (for the same months) to determine the change of NO2.

Ground-based measurements data from Europe were obtained from the European Environment Agency (https://discomap.eea.europa.eu/map/time/AirQualityExport.htm) for the same coverage period as the NO2 satellite dataset. The pollutants of interest are CO, NO2, O3, PM2.5, PM10, and sulfur dioxide (SO2). For uniformity, European countries that are contributing to the dataset must follow a reporting template. However, the data availability for each country is subject to the type of instruments or measurements used in collecting the data. The data for ground-based measurements from India were downloaded from the Central Control Room for Air Quality Management, the Indian Ministry of Environment, Forest, and Climate Change (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing) and the Coordinated Clean Air Status Report – 2019 (Figs. 1 A and B, the major global contributors for NOx are China, India, USA, and Europe, where most highly urbanized areas are located (Bechle et al., 2011). When these concentrations are compared against the 5-year average loadings for the respective month (Fig. 1C and D), these regions indicate a reduction of at least 10%. Depending on when the lockdowns were implemented; and the magnitudes of reduction vary from one region to another. In China, massive reduction of NO2 concentrations in March 2020 was observed primarily in the eastern part of the country. In April 2020, however, much of this region saw an increase in NO2 after the lockdown measures were relaxed. Elsewhere, western, southern, and central Europe featured with NO2 reduction in both March and April 2020. The reduction occurred more prominently in April 2020 when most European countries-imposed lockdowns and travel restrictions.

Table 1

| Region          | Change (%) |
|-----------------|------------|
| Europe          | 9.57       |
| USA             | 9.57       |
| China           | 9.57       |
| India           | 9.57       |

3.2. Regional air pollutants concentrations during lockdowns (Europe, USA, China, and India)

When comparing ambient concentrations of pollutants across Europe for March and April 2020 against the average concentrations of each respective month for 2015–2019 (Figs. 2–3), ambient concentrations of NO2, PM2.5, particulate matter (PM10) and carbon monoxide (CO) were all below average in both March and April (Table 2). Ambient concentrations and satellite retrievals of NO2 were, on average, 32% and 22% lower, respectively, then average in March 2020; and 34% and 26% lower than average in April 2020. PM2.5 concentrations in March 2020 were 15% lower than average, when compared against ambient concentrations in March 2015–2019, but then by April, PM2.5 concentrations in Europe were only 6% lower than normal, suggesting an increase in emission sources. Similarly, PM10 and CO concentrations went from 10% below average in March to 2% and 4%, respectively, below average in April 2020. Ambient concentrations of SO2 were 10% lower in March 2020 than in March 2015–2019 but then ambient concentrations in April 2020 were 0.4% higher than average when compared against previous years. The drastic reductions, particularly in March 2020, can likely be attributed to the mandatory stay at home orders that began in March. However, O3 concentrations were 5% and 7% above average in March and April, respectively, when compared against concentrations from 2015 to 2019. Scard et al. (2020) observed the daily O3 mean concentrations increased at urban stations in Europe by 24% in Nice, 14% in Rome, 27% in Turin, 2.4% in Valencia. The reduction in NO2, PM and CO can likely be primarily attributed to the reductions in automotive traffic and industrial activity associated with lockdown measures taken to contain COVID-19. Because SO2 is a product of the combustion of coal and diesel combustion, it is possible these activities were
Fig. 1. Global tropospheric NO$_2$ column loadings with 30% cloud screened, presented in μmol m$^{-2}$ during March and April 2020. Top panel figures show NO$_2$ observed in (A) March 2020, and (B) April 2020. Figures on the bottom panel illustrate the difference of NO$_2$ loadings in (C) March 2020, and (D) April 2020 when compared against the average loadings for the respective month in the period 2015–2019.
considered essential, and therefore changes in these activities were slight.

In Europe (Habibi et al., 2020) showed that the NO$_2$ response was site-specific; Lyon-France (−46% in April), followed by Milan-Italy (−18% in April); however, Berlin-Germany (−1% in March and April) had the lowest reduction levels during these three months. Milan-Italy, one of the worst COVID-19-hit European cities, had a moderate reduction in NO$_2$ (−18%) compared to Lyon-France. The increase in O$_3$ is believed to be attributable to the complex relationships among O$_3$ precursors and meteorological conditions. O$_3$ is a secondary photochemical pollutant, produced by reactions of nitrogen oxides (NO$_X$), including NO$_2$ and nitric oxide (NO), volatile organic compounds (VOCs) and other precursors. We have shown that NO$_2$ emissions were decreased during the study period. Any change in NO$_2$ emissions is accompanied with a similar change in NO, as the two are emitted together. In fact, NO emissions comprise the bulk, 90–95%, of NO$_X$ emissions (EPA inventory documentation). In the short term, NO can destroy ozone, while in the longer term, NO is converted to NO$_2$ and catalyzes O$_3$ production. This rate of production of O$_3$ process is dependent on the magnitudes of NO and NO$_2$ in comparison with VOCs and other O$_3$ precursors. Therefore, this increase in O$_3$ concentrations is mainly explained by an unprecedented reduction in NO$_X$ emissions leading to a lower O$_3$ titration by NO. Ozone concentration is also strongly dependent on meteorological conditions, with O$_3$ formation enhanced by higher temperatures. Thus, O$_3$ concentrations are generally higher in summer than in spring. It is not known whether NO$_X$ emission reductions would have increased O$_3$ concentrations in Europe if these reductions had occurred in summer rather than in Spring.

In the US, the average concentrations of NO$_2$, PM$_{2.5}$, CO, SO$_2$ and O$_3$ for March and April 2020 were compared against that average

Fig. 2. Percent changes of gaseous pollutants in March 2020 (left figures) and April 2020 (right figures) measured over ground-based monitoring stations in Europe. The pollutants are (A, B) carbon monoxide (CO); (C, D) nitrogen dioxide (NO$_2$); (E, F) ozone (O$_3$); and (G, H) sulfur dioxide (SO$_2$). The changes are based on the concentration difference between the period 2015–2019 and 2020 for respective month.
concentrations for the respective months in 2015–2019. NO\textsubscript{2}, both from measurements and from satellite observations were 22% and 15% lower, respectively, than average in 2020 (Goldberg et al., 2020). Similarly, concentrations of SO\textsubscript{2} and PM\textsubscript{2.5} were 35% and 6% lower, respectively, when compared against previous years. In contrast to this, concentrations of CO and O\textsubscript{3} were, on average, 7% and 11% higher than the average concentrations from 2015 to 2019 (Fig. 4). By April 2020, satellite observations of NO\textsubscript{2} were 19% lower than average while concentrations of PM\textsubscript{2.5} and O\textsubscript{3} were 3% and 15% above average. Like Europe, these changes in ambient concentrations are likely due to lockdown measures taken during mid-March across the US. The observed increase in ozone, shown in Fig. 4, is slightly more prominent in the US than in Europe due to the southern areas of the US observing much warmer temperatures in March and April, which is favorable for ozone formation.

Satellite observations of NO\textsubscript{2} were also observed at a continental scale. Europe saw the largest reduction in NO\textsubscript{2} column loading in April (18%) when compared against the base years, while South America saw the smallest reduction (0.79%) in March. The average reduction of NO\textsubscript{2} over all continents except Antarctica was about 14–15% in March and April. This is consistent with the reduction in CO\textsubscript{2} emissions from combustion estimated by Le Qu\textsuperscript{´}er et al. (2020) during this period. While there was an overall global reduction, the magnitude of the reductions can likely be attributed to restrictions placed upon each country during this period. Because COVID-19 did not reach South America until late February (compared with December 2019 in the US and January 2020 in Europe), restrictions were not as strict during this study period when compared against other continents and countries. For example, Sao Paulo, Brazil, is the largest city in Latin America, with a population of 12,252,023 people. Nakada and Urban (2020) study during similar time period, indicated the pollution of the megacity Sao Paula observed averaged concentrations of PM\textsubscript{10} increased and PM\textsubscript{2.5} decreased by about 9% and 0.3% respectively; while gaseous pollutants between pre and during lockdown reduced by about NO\textsubscript{2} (−22%), CO (−30%). The maximum concentration of O\textsubscript{3} increased about (+11% overall variation).

A study by Shi and Brasseur (2020) using data collected from ground-based monitoring stations during lockdowns in China found that PM\textsubscript{2.5} and NO\textsubscript{2} concentrations have decreased by about 35% and 60%, respectively. Similarly, a study by Venter et al. (2020) using a network of >10,000 air quality stations in 34 countries found that PM\textsubscript{2.5} and NO\textsubscript{2}...
concentrations decreased by about 31% and 60%, respectively. These reductions were attributed to the reduced economic and transport activities in major cities. Like the US and Europe, their study also observed an increase by a factor 1.5–2 in O$_3$ concentrations during the same period.

In India, Sharma et al. (2020) investigated the changes in air pollutant concentrations in 22 cities during the period March 16 to April 14, 2020. Their finding indicated reductions in PM$_{2.5}$, PM$_{10}$, CO, and NO$_2$ by 43%, 31%, 10%, and 18%, respectively. An increase in O$_3$ by 17% was observed in their analysis, suggesting these cities underwent
the same pathway of $O_3$ production and its precursors (explained earlier). Moreover, Mahato et al. (2020) study during similar time period, indicated the pollution of the megacity Delhi observed substantial reduction of the particulate matter pollutants averaged concentrations for PM$_{10}$ and PM$_{2.5}$ by about $-52\%$ and $-53\%$ respectively; while gaseous pollutants between pre and during lockdown reduced by about NO$_2$ ($-53\%$), CO ($-30\%$), SO$_2$ ($-18\%$), and NH$_3$ ($-12\%$). However, the 8 h average daily maximum concentration of O$_3$ increased about ($-1\%$ overall variation).

3.3. Case studies on changes of pollutant concentrations at city level

The change in pollutants, both satellite measurements of NO$_2$ and ground measurements of PM$_{2.5}$, PM$_{10}$, CO, NO$_2$, SO$_2$ and O$_3$, at the city level were also examined. Four major cities were chosen in this analysis: New York City (USA), Milan (Italy), Wuhan (China), and New Delhi (India). Fig. 5A shows the concentrations of pollutants in New York as a fraction of the average concentration of the base period (2015–2019) on a monthly temporal scale. The monthly analysis shows concentrations of PM$_{2.5}$, NO$_2$, SO$_2$ and CO declining (90 ± 5\%, 36 ± 8\%, 40 ± 35\%, and 10 ± 3\%, respectively) in the study period. In New York, NO$_2$ satellite observations were 51\% and 28\% lower, on average, in March and April 2020, respectively, when compared with the baseline average column loadings for the given month from 2015 to 2020. In contrast, ambient measurements of SO$_2$ show concentrations increasing by 10 ± 10\% during the period. In Milan, concentrations of PM, NO$_2$, CO, and SO$_2$ all drastically declined (22 ± 19\%, 40 ± 10\%, 30 ± 30\%, and 30 ± 30\%, respectively) between January and February before increasing through the end of the study period (Fig. 5B). In contrast, O$_3$ concentrations were above average (18 ± 8\%) compared with previous years. In Milan, NO$_2$ satellite observations were 55\% and 49\% lower, on average, in March and April 2020, respectively, when compared with the baseline average column loadings for the given month from 2015 to 2020. The concentrations of pollutants from January to April of 2020 as a fraction of the average concentration in the base period for Wuhan, China, were also observed on a monthly scale (Fig. 5C). On a monthly scale, the concentrations of CO declined through the period, while concentrations of NO$_2$ and O$_3$ steadily increased. In contrast to this, PM and NO$_2$ concentrations initially decreased before starting to increase in March/ April. In Wuhan, NO$_2$ satellite observations were 62\%, 50\% and 18\% lower, on average, in February, March and April 2020, respectively, when compared with the baseline average column loadings for the given month from 2015 to 2020. The concentrations of pollutants from January to April of 2020 as a fraction of the average concentration in the base period for New Delhi, India, were also observed on a monthly scale (Fig. 5D). The average monthly concentrations of CO increased through March before dropping in April, while concentrations of NO$_2$, PM and O$_3$ all peaked in February before declining, with all pollutants, except SO$_2$, at a minimum in April. In New Delhi, India, NO$_2$ satellite observations were 24\% and 54\% lower, on average, in March and April 2020, respectively, when compared with the baseline average column loadings for the given month from 2015 to 2020. The reduction in CO, PM and NO$_2$ concentrations can likely be primarily attributed to the mandatory shutdown of non-essential personnel. Because the timings of the mandatory quarantine periods varied city to city, the timelines for changes in the concentrations also vary. The increase in O$_3$ can be attributed to the reduction of NO emissions from automobiles and industrial activities. Similarly, the increase in NO$_2$ and decrease in O$_3$ concentrations toward the end of the study period can be attributed to the likely increase in NO emissions which then react with the O$_3$ to create NO$_2$. SO$_2$ concentrations sharply increase through the period toward the end of the study period. A potential cause for this sharp increase in emissions could potentially be from an increase in truck and air traffic associated with shipping. As stores remained closed through the lockdown process, online sales skyrocketed.

Fig. 6 provides the relationship for New Delhi, India, and Milan, Italy, between the NO$_2$ observations during maximum photochemical activity (11:00 a.m.–6:00 p.m.) versus maximum O$_3$ concentrations during the same time window (also reflecting maximum photochemical activity) for March and April for 2015 to 2019 (before lockdown i.e. Fig. 6 A and C), and 2020 (during and after lockdown i.e. Fig. 6 B and D). Before the lockdown in New Delhi (Fig. 6 A), the ozone concentration increases with increasing NO$_2$ (the information on the emissions of VOCs is not available) (NRC 1991). However, in Milan (Fig. 6 C) the concentration of surface ozone decreases with increased concentration of NO$_2$. When the nitric oxide (NO) concentrations are large, NO released in the atmosphere from fossil fuel combustion reacts with ozone to form NO$_2$. After lockdown, Fig. 6 B and D we observe a reduction in NO$_2$ leads to an increase of the ozone concentration. When the lockdown kicked in New Delhi and Milan, nitrogen dioxide levels plummeted as the automotive traffic reduced, but ozone levels rose. Nitric oxide, which is also in traffic exhaust reacts with ozone to produce NO$_2$ ($NO + O_3 \rightarrow NO_2 + O_2$). This happens almost instantaneously. In effect ozone is being “converted” into nitrogen dioxide in equal measure, so that the total of both gases (“O$_x$”) remains about the same (Sillman et al., 1990; Monks et al., 2015; Shi and Brasseur, 2020). However, it is important to note that there is a lot of variability and uncertainty in the data because of the influence of other variables (e.g. measurement uncertainty, meteorology, transport of background ozone and its precursors, etc.).

4. Conclusions

We incorporate 5-years of data into our calculation of the baseline prior to the COVID-19 lockdowns. The compared five-year period was used as the baseline for air quality not influenced by the lockdowns provides a more robust analysis. The purpose of the inclusion of this period is two-fold: (1) to normalize the impacts of meteorological factors to the atmospheric concentrations of air pollutants; (2) to narrow down the case studies to locations that have long-term measurements and data-series. By means of normalizing the meteorological influences and narrowing down the case studies, this study attempts to corroborate a closer examination on the lockdown effect rather than to generalize the findings by incorporating more locations with a shorter data coverage. Moreover, incorporating a short baseline period may result in a bias inherited from prevalent meteorological conditions during that period. By introducing a longer baseline period, this bias may be minimized. This is evident from the suggested examination of meteorological effects on air pollutant concentrations that indicates meteorology has a small influence on the changes of air quality during the lockdowns (–1\%–3\% across all species). Ground based measurements of SO$_2$, CO, PM$_{2.5}$, PM$_{10}$, O$_3$ and NO$_2$ were examined across Europe and for four major cities: Milan (Italy), Wuhan (China), New York City (USA) and New Delhi (India). Ground based measurements of PM$_{2.5}$ and O$_3$ concentrations in the continental United States were also analyzed for study period; and satellite measurements of NO$_2$ column density were examined at a global and regional scale. The results of this study (based on satellite observations) showed that NO$_2$ column loadings were generally lower than normal on both a city-wide, regional, and national scale. Ambient concentrations of CO, NO$_2$, PM$_{2.5}$ and PM$_{10}$ were generally lower than normal to normal, with certain cities observing higher than normal conditions in Europe over the study period. In contrast to this, O$_3$ concentrations were generally higher than normal, which can be attributed to lower than normal emissions of NO due to restrictions placed on industrial activities and travel. Therefore, this increase in O$_3$ concentrations is mainly explained by an unprecedented reduction in NO$_2$ emissions leading to a lower O$_3$ titration by NO. Similarly, PM$_{2.5}$ concentrations in the United States were primarily below average or around average for much of the US while O$_3$ concentrations were slightly above average.

Ambient concentrations of each pollutant were also examined on a city-wide scale. Ambient concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$ and CO in each city generally declined in association with quarantine orders.
placed upon the states, while SO\textsubscript{2} and O\textsubscript{3} concentrations generally increased. The only city that did not see an increase in O\textsubscript{3} concentrations through the study period, which can potentially be attributed to meteorological conditions in New Delhi. These changes in the concentrations of these pollutants can likely be, in part, attributed to the reductions in traffic and industrial activity associated with lockdown measures taken to contain COVID-19. The increase in O\textsubscript{3} concentrations can likely be attributed to a reduction in NO emissions, which thus reduces the reaction of NO with O\textsubscript{3} to form NO\textsubscript{2}. In some regions (e.g. India and China), SO\textsubscript{2} concentrations increased through the period which can likely, in part, be attributed to an increase in the combustion of coal to heat houses and electricity production.

Based on the results of this study as well as the results of Shi and Brasseur (2020), Venter et al. (2020), and Bauwens et al. (2020), it is evident the lockdown orders associated with COVID-19 have had a profound impact on our atmospheric environment. With the reduction in industrial activities and residential automobile activity, the ambient concentrations of PM, CO, NO\textsubscript{2} and, in some cases, SO\textsubscript{2} were much lower than they normally are likely due to a combination of lower emissions and meteorological conditions. In contrast to this, O\textsubscript{3} concentrations were higher than normal due to the reduction in emissions from traffic. It is important to note that these changes in ambient concentrations are not permanent and it is not possible at this time to determine any long-term impacts of this reduction in emissions on air quality at a global, regional and urban scales. However, lack of preparedness for the coronavirus only highlights the need for a long-term air pollution and climate change strategy requiring transitioning to clean-energy (i.e. supporting renewables and energy efficiency). Additionally, this does not mean poor air quality should return. It too, should be made history.

CRediT authorship contribution statement

Casey D. Bray: initial draft preparation, reviewing and editing. Alberth Nahas: Data curation, Formal analysis. William H. Battye:
Data curation, Formal analysis, reviewing and editing. Viney P. Aneja: response to reviewers, reviewing and 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.

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Appendix A. Supplementary data

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