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Global air quality change during COVID-19: a synthetic analysis of satellite, reanalysis and ground station data

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Abstract

Coronavirus disease 2019 (COVID-19) pandemic has led to a rare reduction in human activities. In such a background, data from ground-based environmental stations, satellites, and reanalysis materials are utilized to conduct a comprehensive analysis of the global air quality changes during the COVID-19 outbreak. The results showed that under the impact of the COVID-19 outbreak, a significant decrease in particulate matter (PM_x) and nitrogen dioxide (NO_2) occurred in more than 40% of the world's land area, with NO_2 (PM_x) decreasing by ∼30% (∼20%). The mobility, meteorological factors, and the response speed to COVID-19 outbreaks were examined. It was further found that in quick-response cities, lockdowns produced a sharp decline in mobility and had a dominant impact on air quality. In contrast, in slow-response cities, mobility dropped gradually since the confirmation of the first COVID-19 case (FCC) and he impact of the FCC, lockdowns, and meteorological factors were comparable.

1. Introduction

During the past several decades, worldwide monitoring has provided concrete evidence that human activities, such as fossil fuel combustion, biomass burning, and changes in land use, are causing serious atmospheric pollution (Klepeis *et al* 2001, Ezzati *et al* 2004), which is a major environmental risk to human health (Brunekreef and Holgate 2002, Cohen *et al* 2017, WHO 2020a). With air pollution exerting heavy pressure on the environment, scientists around the world have conducted many studies that explore how to reduce air pollution by making human activities cleaner and greener (Akimoto 2003). However, there has seldom been a chance to directly observe how such changes will affect the global air quality.

The coronavirus disease 2019 (COVID-19) (Guan *et al* 2020, Zhu *et al* 2020), which has had successive outbreaks in cities around the world (Mizumoto *et al* 2020, Remuzzi and Remuzzi 2020), has caused unprecedented suffering (Anderson *et al* 2020, Sohrabi *et al* 2020, Wu and McGoogan 2020, WHO 2020b, 2020c). People around the world have started to change their usual lifestyles to reduce the risk of infection, and countries and regions have begun to adopt various restriction measures to slow down the spread of the novel coronavirus (Chinazzi *et al* 2020, Tian *et al* 2020). Hence, there has been a rare large-scale slowdown of human activities all over the world. How the global air quality will change under such a situation remains an interesting question (He *et al* 2020a, Rosenbloom and Markard 2020, Saraswat and Saraswat 2020).

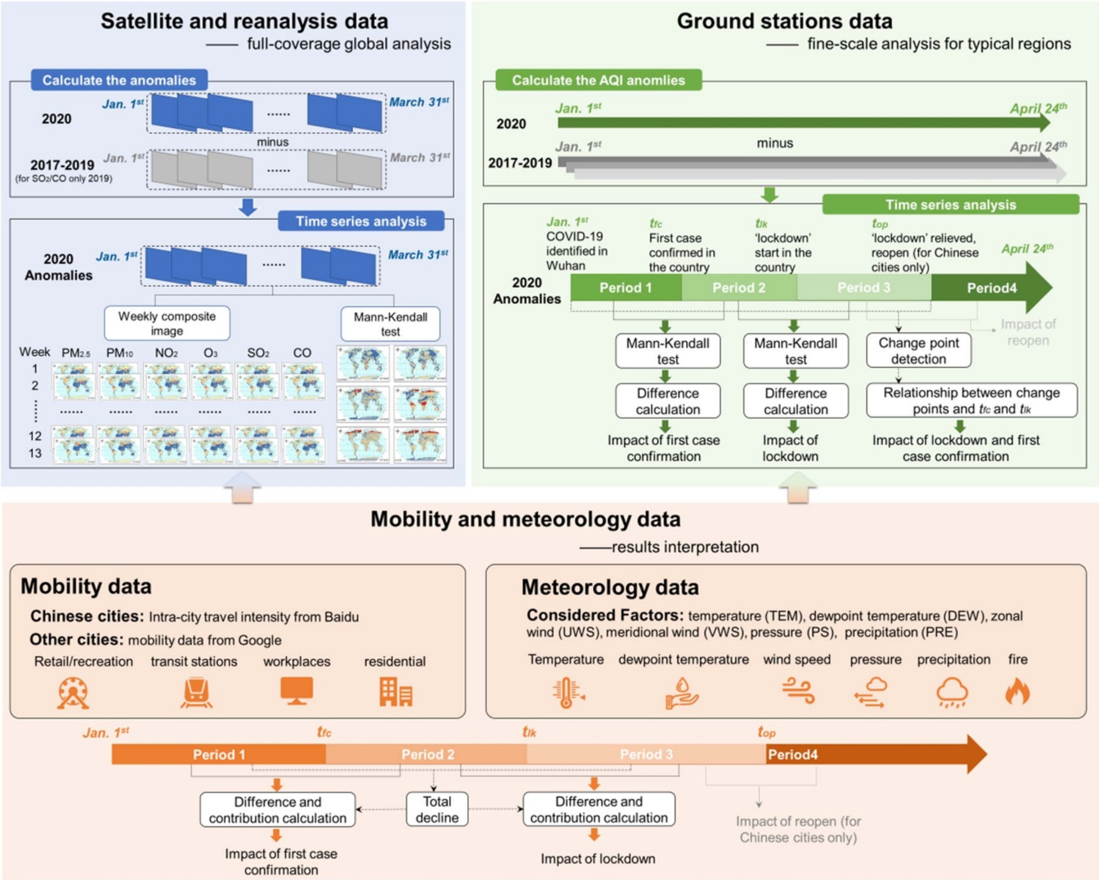

Figure 1. Flowchart of the work (symbols for different places and meteorological factors are provided by iSlide).

Currently, there are a number of studies researching the impact of the lockdowns on air quality changes (Mahato *et al* 2020, Wang and Su 2020). While most of the studies are either confined to local regions (Huang *et al* 2020, Mahato *et al* 2020, Sharma *et al* 2020, Shi and Brasseur 2020, Wang and Su 2020) or certain types of air pollutants (Bauwens *et al* 2020, Chen *et al* 2020a, Rodriguez-Urrego and Rodriguez-Urrego 2020, Shi and Brasseur 2020, Barua and Nath 2021), there are some studies analyzing the air quality changes at the global scale and from a synthetic perspective (Diffenbaugh *et al* 2020, Venter *et al* 2020, Zhang *et al* 2020, Liu *et al* 2021). However, there are still several limitations of these global studies. Firstly, the current studies have concentrated on the impact of the lockdowns on air quality. COVID-19 affects human activities not only through lockdowns, but also in other aspects, such as the confirmation of the first COVID-19 case (FCC), which was merely mentioned in several local studies (He *et al* 2020a) and was not paid enough attention in global studies. Secondly, the impact of COVID-19 on air quality can vary with cities if the city make response to the COVID-19 pandemic in different ways. How will the response speed influence the relationship between air pollution and human activities change brought by COVID-19 remains an interesting but unclear question. Hence, a comprehensive investigation on how COVID-19 outbreak affects air quality at the global scale with consideration of the FCC and city response speed is still urgently required.

In this study, the air quality changes during the time since the COVID-19 outbreak began are investigated at the global scale. In addition, the impacts of the FCCs and lockdowns on air quality are investigated using satellite products, reanalysis data, and station measurements, and these data are analyzed in relationship to mobility changes and meteorology variations. A workflow schematic is shown in figure 1.

2. Materials and methods

2.1. Datasets

The global satellite-based concentration data for NO_2, O_3, SO_2, and CO were obtained from tropospheric monitoring instrument (TROPOMI) (Veefkind *et al* 2012, He *et al* 2020b) and ozone monitoring instrument (Levelt *et al* 2006). The global $PM_{2.5}$ and PM_{10} (PM_x) concentration data were provided by the Copernicus Atmosphere Monitoring Service (CAMS) reanalysis dataset (Inness *et al* 2019). These two products provide a large-extent and planar monitoring of the global air quality. However, the drawsbacks are that they cannot reflect the ground-level variations and are less accurate compared with the ground-station measurements. Therefore, for a more accurate analysis of the ground-level air quality change, data from ground environmental monitoring stations was also collected. We selected 26 cities from different continents and countries as study object. The ground-level air quality index (AQI) data for $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2, and CO (Wang *et al* 2014) in these cities was provided by the World Air Quality Index project, which collected the official air quality data from each country's respective Environmental Protection Agency and aimed to provide transparent air quality information in the global extent.

Auxiliary data including transportation and meteorological data. Transportation data comes from the Baidu map and Google Community Mobility Reports. The global meteorological data were collected from CAMS. The considered factors included temperature (TEM), dewpoint temperature (DEW), zonal wind (UWS), meridional wind (VWS), precipitation (PRE), and pressure (PS) (Fan *et al* 2020). The composite wind speed (WS) was calculated from UWS and VWS (text S3). For more details, please refer to the supporting information (SI) available online at stacks.iop.org/ERL/16/074052/mmedia.

2.2. Methodology

Before analysis, we preprocessed the data and calculated the anomalies using observations of previous years as baselines (Berman and Ebisu 2020, Chen *et al* 2020b, Le *et al* 2020, Liu *et al* 2020, Tian *et al* 2020). For the satellite data, the pixel-level Mann–Kendall (MK) test (Yue *et al* 2002) was conducted using the anomalies from 1 January to 31 March 2020 to show the variation tendency. For the ground station data, two time nodes were researched (time of FCC and lockdown) and one time node was considered (time of reopening). Firstly, we quantified the percentile changes in air quality after the FCC and lockdowns. Then, the relationship between air quality change and COVID-19 pandemic were also quantified. The time point when the tendency of time series began to change was detected, and the Pearson correlation coefficients between the detected change point, FCC time, and lockdown time were then calculated. Mobility and meteorological data were processed in similar method for the explanation of the air quality change. For more details about the methodology, please refer to the SI (texts S2 and S3).

3. Results

3.1. Global air quality changes based on satellite and reanalysis data

Satellite and reanalysis data were utilized to reflect the global full-coverage air quality variations. The variation tendencies of the anomalies of six kinds of pollutants detected using MK test (text S3) are depicted in figure 2. The anomalies of $PM_{2.5}$, PM_{10}, and NO_2 significantly declined in general, while the other pollutants showed an uptrend or insignificant tendency. Specifically, the percentages of areas showing significant downtrends (uptrends) during the COVID-19 epidemic were 42.32% (1.49%), 40.32% (1.21%), and 45.26% (9.52%) for the $PM_{2.5}$, PM_{10}, and NO_2 anomalies, respectively. However, for the O_3, SO_2 and CO anomalies, the percentages were 30.45% (15.88%), 23.15% (12.68%), and 30.15% (16.07%), respectively. The spatial distribution of the regions where air quality improved varied with the pollutant types. Regions where $PM_{2.5}$ declined significantly were primarily located in the northern hemisphere and eastern Australia. The spatial distribution of the PM_{10} variation tendency was similar to that of $PM_{2.5}$ in general. NO_2 anomalies declined in most areas except for near the Arctic Circle. O_3 anomalies decreased significantly in the US, Canada, and northern Africa, but they increased in regions around the equator, possibly because of the stronger solar radiation and higher temperatures there, which can promote photochemical reactions and thus produce more O_3 (Hashem *et al* 1997). However, anomalies of SO_2 and CO showed increases or nonsignificant tendencies across the world. In addition, it is worth noting that the positive tendencies of four gas pollutants in the polar region (figures 2(C)–(F)) might be inaccurate due to the great number of missing values here, which does not affect the discovery and conclusion for other areas. To demonstrate the detailed variations in air quality, China, Europe, the Contiguous United States (CONUS), and Brazil (figure S1) were focused on, where COVID-19 was the most prevalent (Saglietto *et al* 2020, Wu and McGoogan 2020).

PM_x anomalies decreased significantly in northwestern China, central and northeastern CONUS, and most parts in Europe and Brazil. The PM_x anomalies remained negative in most regions of China during COVID-19. While in Europe, the signs of $PM_{2.5}$ anomalies did not display a uniform pattern prior to week 4, and then the values remained negative in most areas until week 12 (figure S2). Although there were no compulsory measures declared by the local governments then, it was found that people were likely to spontaneously reduce their outing activities after the COVID-19 pandemic began to be prevalent (figure S3). Therefore, this caused a decline in $PM_{2.5}$. The variations in the anomalies of PM_{10} was similar to $PM_{2.5}$ in most areas of Europe, except the southwest portion (figure S4). In the northeastern CONUS, the anomalies of $PM_{2.5}$ were negative in week 11. This was close to the time (19 March 2020) that the number of CONUS cases exceeded 10 000, and 40% of them were in New York State. The spatiotemporal pattern of the anomalies of PM_x and CO in Brazil were similar. Both of these pollutants decreased in most of the area, but they were unexpectedly increased in the eastern coastal area and in the countries southwest of Brazil.

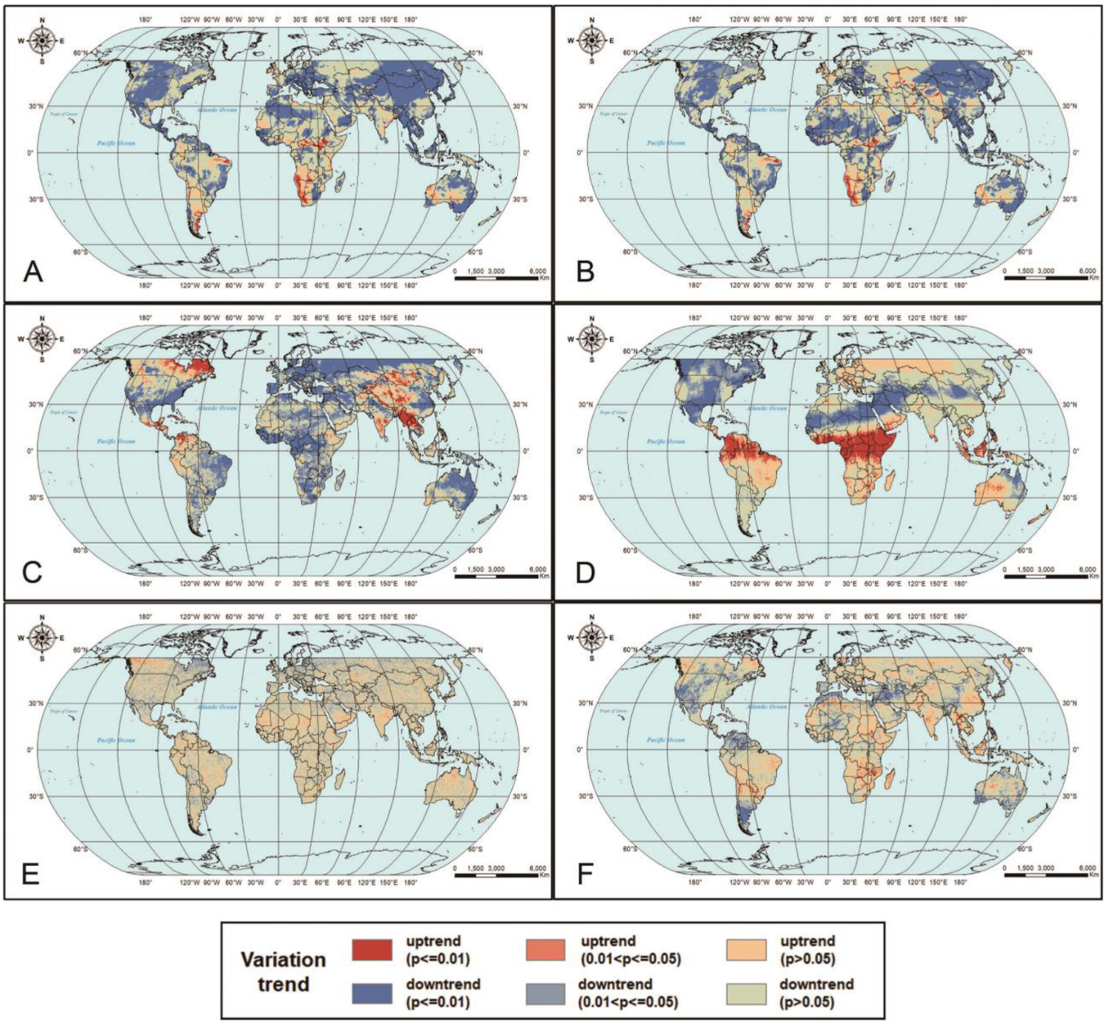

Figure 2. Variation tendencies and the significance of six pollutant anomalies. Figures (A)–(F) represent the results for $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2, and CO, respectively.

Figure S5 shows that the zonal wind (UWS, positive represent eastward wind) in the eastern coastal areas of Brazil showed positive anomalies. Considering that westward wind prevails in eastern Brazil from January to March, the positive UWS anomalies could have indicated a decrease in the westward wind speed, which were likely to lead to an accumulation of pollutants. Therefore, the anomalies of PM_x concentration showed an uptrend in the east with time. For other regions in Brazil where the meteorological data did not significantly change, the concentration of PM_x still declined under the impact of the COVID-19 lockdown. As for the PM_x and CO increases in the countries southwest of Brazil, it was inferred this might have been a result of the wildfires. These areas witnessed an increase in wildfire frequency in 2020 compared with 2019, especially since March (figure S6), thus leading to an increase in PM_x and CO.

For NO_2, the anomalies primarily had a significant downward tendency in central and northern China (figure S7), which was most probably related to the restrictive measures issued by the government (Kupferschmidt and Cohen 2020). Specifically, the anomalies experienced a −129% fractional change after lockdown started. The anomalies of NO_2 typically fluctuated in central and eastern China prior to the outbreak of COVID-19 (figure S7). During the lockdown period which started on 23 January 2020 in Wuhan, the NO_2 anomalies remained negative in most areas of central and eastern China until week 12. The next week, due to work resumptions, the anomalies of NO_2 turned positive. Compared to China, the timing of the changes in the NO_2 anomalies in Europe showed a certain delay due to the difference in the COVID-19 outbreak time (figure S7). The anomalies of NO_2 turned negative in most areas after week 11 when the local governments declared their restrictions to deal with the COVID-19 epidemic. In the eastern CONUS, the values turned negative in week 8. Although the values fluctuated in week 12 in some areas, they remained negative in areas with severe epidemic, such as New York. The anomalies in NO_2 showed a significant downtrend in urban areas in east

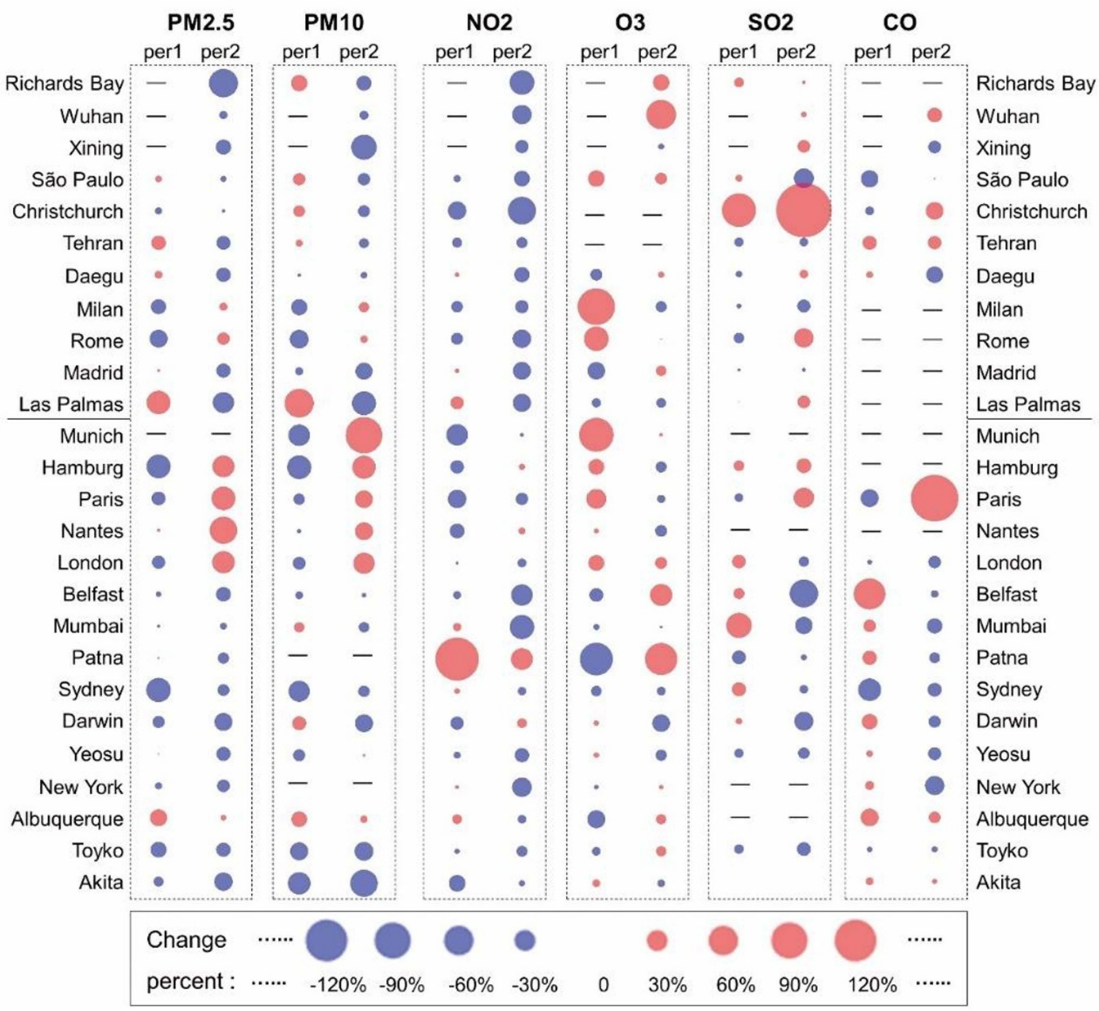

Figure 3. The percentage change in the AQI after FCC/lockdown (per1/per2) for six pollutants in 26 cities, specific definition of per1/per2 can be found in text S3. The dash lines in the rectangles stand for missing data. Cities above the black lines are the quick-response cities and below the lines are the slow-response cities.

Brazil. However, the concentration of NO_2 in Brazil were less serious than in the other three places, so the weekly variations in the anomalies (figure S7) were unobvious from a satellite perspective relative to other regions.

For the other three pollutants, the variation tendencies were not as significant as PM_x and NO_2, but the turning points of the time series were related to the COVID-19 lockdown time. The turning point of the O_3 anomalies in the CONUS was observed at the 11th week, and the anomalies of SO_2 and CO also turned at approximately week 12, all close to the lockdown time in the CONUS. The turning point of the SO_2 anomalies in Europe was week 9, which was near to most of the European countries' lockdown times. As demonstrated above, the satellite and reanalysis data showed that the global air quality significantly improved during COVID-19, and the turning points of pollutants variations were closely related to lockdown times.

3.2. Ground-based air quality changes in typical cities

To better reflect near-surface pollution variations in typical cities, the ground-based monitoring data were collected for further analysis. The distribution of cities and the key time nodes (FCC, lockdown, and reopen time) of each are shown in figure S8. The cities were divided into two groups according to the time difference between the FCC and the lockdown. Cities with a time difference of fewer than 50 d (figure S9) were defined as quick-response cities. The others were defined as slow-response cities. For each city, the change curves of the daily AQI during the study period are displayed in figure S10, and the percentile change (text S3 in SI) since the FCC/lockdown are shown in figure 3 and table S1.

The results showed that both the FCCs and lockdowns brought a large reduction in NO_2 in most cities, with lockdowns typically bringing larger changes (22% [95% confidence interval: 14%, 30%]) than the FCCs (9% [3%, 16%]). However, in Europe,

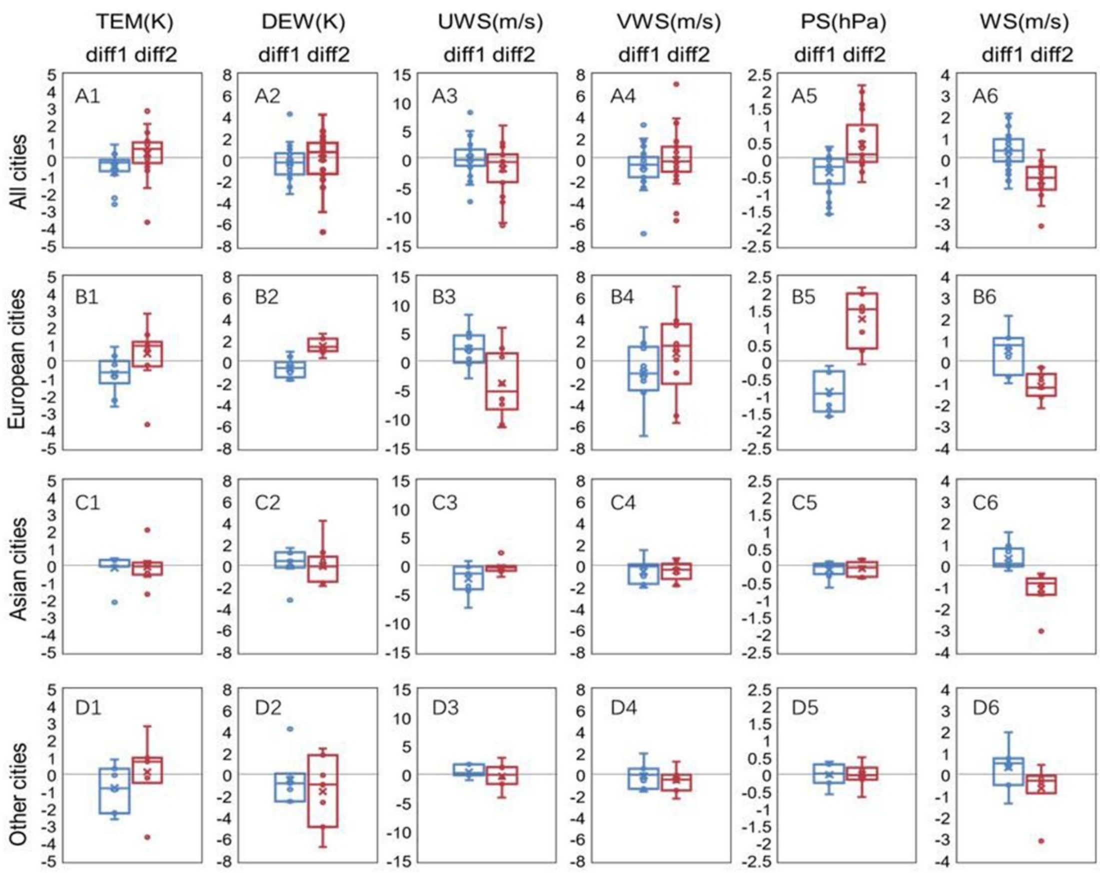

Figure 4. The boxplot for the changes in the meteorological anomalies after the FCC/lockdowns (diff1/diff2) in the different groups of cities. The blue box plots represent diff1, and the red represent diff2.

the changes in NO_2 caused by the FCCs and lockdowns were similar (16% [7%, 26%] for the FCCs and 16% [5%, 26%] for the lockdowns). An exception occurred in Patna, India, where the AQI anomalies of NO_2 increased greatly after the FCC (180%) and the lockdown (46%). Patna was a heavily polluted (Arif *et al* 2018, Kota *et al* 2018) and lightly infected city. Transportation data showed that mobility in Patna did not decrease during the COVID-19 outbreak (figure S3, row 1 column 5), while in Mumbai, India, mobility decreased significantly (figure S3, row 1 column 4). In addition, O_3 in Patna decreased 103.96% since the FCC (figure 3, table S1), which was the largest among all of the 26 cities. Previous studies had shown that an inverse relationship existed between O_3 and NO_2 (Ripperton *et al* 1970, Wang *et al* 2001, Han *et al* 2011), which was also detected by the analysis results of this study (figure S10). Based on the above points, it was inferred that the ongoing human activities and the interactions between air pollutants led to the increase in NO_2 concentration in Patna.

Additionally, PM_x also decreased by a large amount after the FCCs and lockdowns. Specifically, the lockdowns caused a decline of 24% (10%, 39%) in Asian and Africa and 12% (4%, 16%) in the cities of North America, South America, and Australia. In contrast, the FCCs brought little changes to PM_x in these regions. An interesting phenomenon appeared in cities in Europe (Rome, Milan, Paris, Nantes, Hamburg, London). PM_x declined by 20% (14%, 32%) after the FCC, but increased greatly (28% [3%, 53%]) during the European lockdowns. The meteorological data showed that European cities experienced extremely unfavorable meteorological conditions during the lockdowns (figures S11 and S12). To be specific, compared with other cities, the European cities witnessed large increases in pressures and dewpoint temperatures and a decrease in wind speeds since the lockdowns began (figure 4). It can be inferred that the high-humidity, high-pressure, and low-wind-speed conditions offset the improvements in the PM_x pollution caused by the COVID-19 lockdowns. Asian cities and other cities have also experienced small declines in wind speed, but generally, the overall meteorological conditions did not change significantly compared with the period prior to the lockdowns.

The changes in the other three atmospheric pollutants were not as obvious as for NO_2 and PM_x. Among them, O_3 showed an increase in some cities after the FCCs and lockdowns, which has been paid

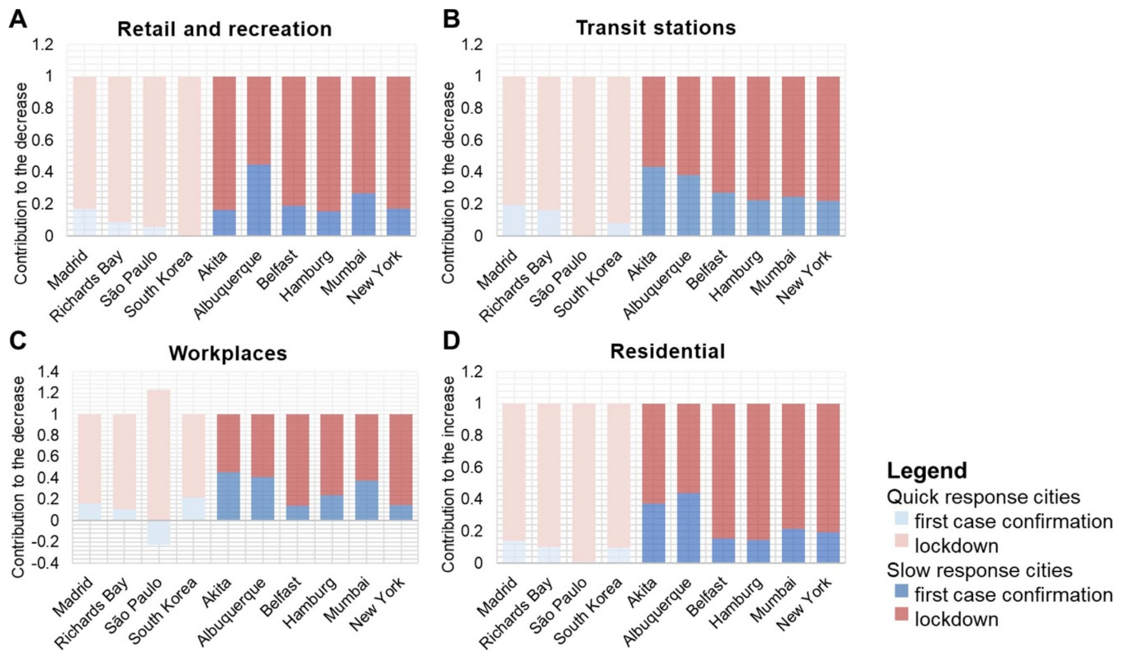

Figure 5. The contribution of the FCCs/lockdowns to the total mobility declines (increase for (C)) in different places.

special attention by some researchers (Hashim *et al* 2020, Le *et al* 2020). It was inferred to be a result of a nonlinear production chemistry of ozone in the atmosphere, and reduced nitrogen oxides resulted in ozone enhancement (Le *et al* 2020). CO showed a mild increase after the FCCs and a mild decrease during lockdown in most regions. As for SO_2, the variation tendency showed strong spatial heterogeneity.

The impact of the FCCs and lockdowns on air quality varied with cities. In the quick-response cities (the upper portion of figure 3), the lockdowns typically caused a larger decline than the FCCs, but in the slow-response cities (the lower portion of figure 3), the case was more complicated, and it was likely that the effect of the FCCs and lockdowns were comparable. In some of the slow-response cities (not all), people may have already tried to avoid going out since the appearance of the first case. The changes in human activities caused by the COVID-19 pandemic happened gradually in a relatively long period of time, rather than changing sharply in a short time like in the quick-response cities. Therefore, the changes in air quality were not dominated by the lockdown, but they could have been affected by multiple factors, such as the FCCs and meteorological factors. When analyzing the mobility data, we also found that lockdown contribute more to the mobility change in quick-response cities than in the slow-response cities (figure 5), which can serve as an evidence for the above inference. An interesting phenomenon in figure 3 also demonstrates this opinion. It has been discussed that unfavorable meteorological conditions have offset the impact of the lockdowns and caused increase in PM_x in European cities. Then it was found in figure 3 that the offset effect was more obvious in the slow-response cities than in the quick-response cities.

3.3. Correlation between the FCC/lockdown and air quality changes

The above analysis revealed the relationships between air quality changes and human activity slowdowns caused by the COVID-19 pandemic. We tried to further quantify these relationships. The time when the variation tendency of daily air quality anomalies began to change (referred to as the change point hereafter) was detected using a time series analysis approach. The results showed that these change points were highly correlated with the time of the FCC/lockdowns (figure 6(A) and table S2). Generally, the change point of NO_2 had the highest correlation with the FCC/lockdown time, with correlation coefficients, r, of 0.69 ($p < 0.05$) and 0.58 ($p < 0.05$), respectively. O_3 had r of 0.56 ($p < 0.05$) and 0.51 ($p < 0.05$) for lockdown time and the FCC time, respectively. In addition, the change point of the $PM_{2.5}$ AQI anomalies had a high correlation with the time of the FCC ($r = 0.53$, $p < 0.05$), but it had a relatively low correlation ($r = 0.26$, $p = 0.21$) with the lockdown time. The r values for the other three pollutants ranged from 0.23 to 0.48.

A comparison was also conducted between the quick- and slow-response cities. In the quick-response cities, the change points were very close to the lockdown time and then got closer to the FCC time in slow-response cities (figure 6(A)). In addition, in the quick-response cities, the correlations between the change points and the FCC/lockdown

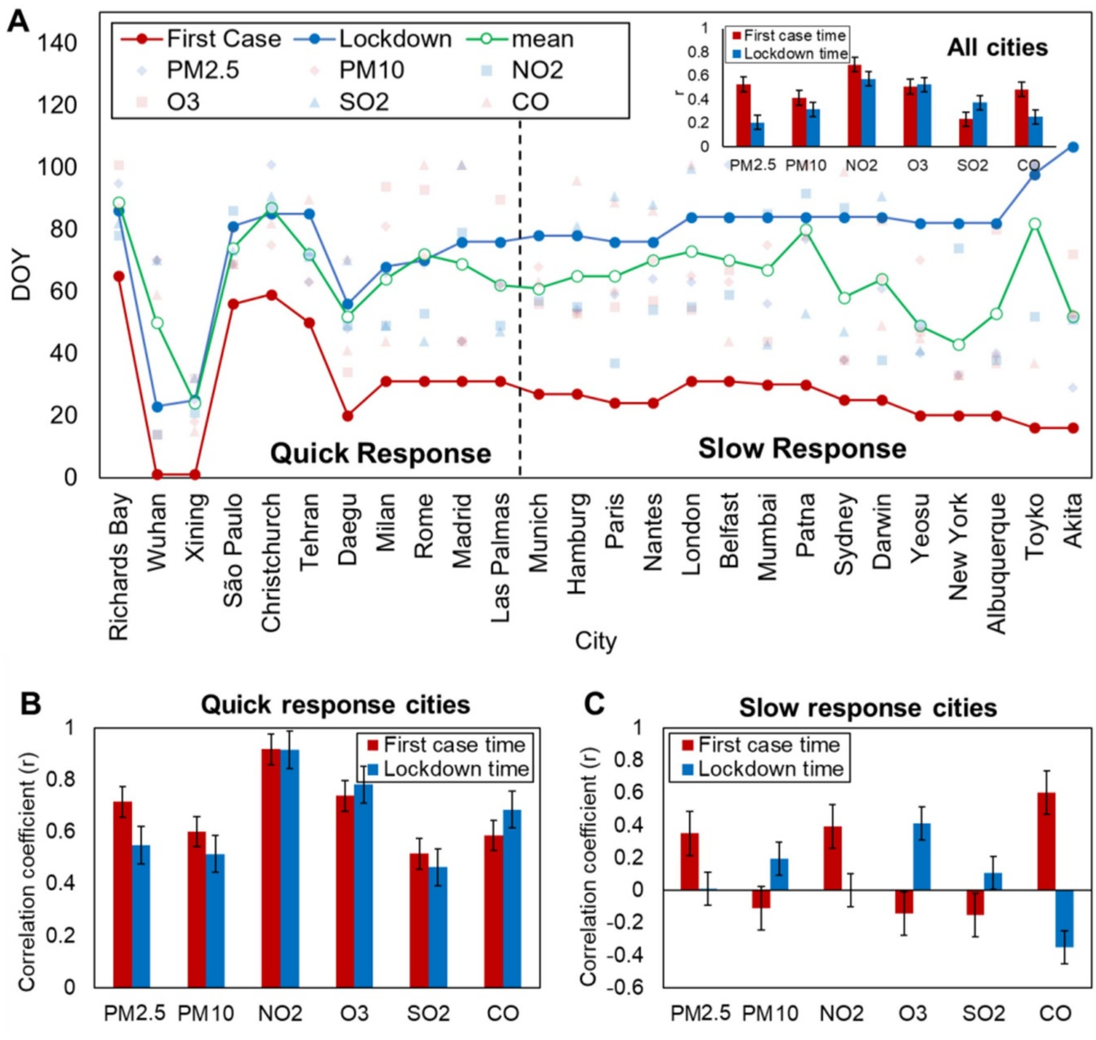

Figure 6. The relationship between the change point and the time of the FCC/lockdown. (A) The detected change point and the FCC/lockdown times in the 26 cities for 6 pollutants. DOY represents the day of year. The green line is the mean time of the change points of the six pollutants. The histogram in the upright corner displays the correlation between them. (B) The correlations between the change point times and the FCC/lockdown times in the quick-response cities and (C) slow-response cities.

times (r ranges from 0.48 to 0.92) were much higher than that in the slow-response cities (r ranges from −0.38 to 0.58) (figures 6(B) and (C)). As has mentioned before, COVID-19 caused air quality changes primarily due to alterations in human activities. The human activities changing patterns were different in quick- and slow-response cities, therefore, making the air quality in quick-response cities dominant by lockdown while air quality in slow-response cities equally affected by lockdowns, FCCs, and meteorology. This could be the reason for the correlation difference between air quality change points and the lockdown/FCC times in the quick- and slow-response cities.

4. Conclusion

Industrial development has been accused of being the primary cause of air pollution in the past several decades. The breakout of the COVID-19 pandemic has provided a special test foundation to investigate the relationship between them. In this study, multisource data were utilized to quantify the air quality changes and the impacts of COVID-19 FCCs and lockdowns on air quality changes. The results showed that the COVID-19-related human activity slowdowns resulted in the greatest reduction in NO_2 pollution, which dropped by approximately 30% since the COVID-19 breakout on the global scale. Then the $PM_{2.5}$ and PM_{10}. Most cities witnessed a percentage decline of approximately 20%, except for cities in Europe. Unfavorable meteorological conditions since the end of March in European cities offset the influence of the lockdowns. The changes in O_3, SO_2, and CO pollution were not as obvious as for PM_x and NO_2, but indications of ozone enhancement and CO decreases were seen in some areas. While most current studies have focused only on the impact of lockdowns and have concluded that lockdowns are followed by air quality improvements, this study found that this was not always the case. In those cities with a relatively quick responses to the outbreak of the COVID-19 pandemic, the effect of lockdowns on air quality was typically significant, but for the slow-response cities, the effect of FCCs and meteorological parameters on air quality was found also to be important.

Our study reveals the interactions between air pollution and human activities with meteorology considered and deepens our understanding on pollution formation and control. But there are also some limitations. The used reanalysis data can contain uncertainties since the emission inventories were not updated in a timely manner. In the future, we will pay more attention to the satellite retrieved $PM_{2.5}$ and PM_{10} product and the reconstructed full-coverage satellites product. In addition, many studies have tried to investigate the relationships between meteorology and air quality change during COVID-19 pandemic through introducing model simulations or complex statistical models (Yang *et al* 2020). In our study, we eliminate the impact of periodic intra-year meteorological changes through calculating the anomalies. And the impact of inter-annual meteorological variations was analyzed qualitatively rather than quantitatively. Introducing a more rigorous and accurate model for a further research is worthy of attention. Finally, as some studies have proposed (Diffenbaugh *et al* 2020, Gillingham *et al* 2020), COVID-19 can have a long-run impact on the earth system. In the future, long-term and continuous observations will be collected for a further exploration.

Data availability statement

Satellite products were download from https://disc.gsfc.nasa.gov/. Reanalysis products are accessible at https://apps.ecmwf.int/datasets/data/cams-nrealtime/levtype=sfc/. Global air quality index data are accessible at https://aqicn.org/. Transportation data of China was supported by the Baidu migration dataset (https://qianxi.baidu.com), while those of other countries were provided by Google mobility reports (www.google.com/covid19/mobility/).

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no competing financial interests.

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