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Assessing the change of ambient air quality patterns in Jiangsu Province of China pre-to post-COVID-19

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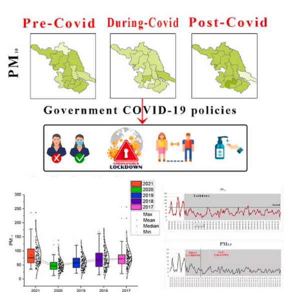
HIGHLIGHTS

- First study to highlight change in air quality pattern from pre-to post Covid in 13 cities of Jiangsu province of China.
- PM_{10} and NO_2 records an increase in 23% and 16% in post-Covid period while Ozone(O_3) decrease by 20% in post-Covid period.
- Metrological factors such as minimum temperature, and humidity show a positive correlation with COVID-19 cases.
- AQI increased by 3% in post-Covid highlighting pollution is increasing.
- Lockdown brings an abrupt drop in air quality patterns.

GRAPHICAL ABSTRACT



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ABSTRACT

Following the outbreak of the novel coronavirus in early 2020, to effectively prevent the spread of the disease, major cities across China suspended work and production. While the rest of the world struggles to control COVID-19, China has managed to control the pandemic rapidly and effectively with strong lockdown policies. This study investigates the change in air pollution (focusing on the air quality index (AQI), six ambient air pollutants nitrogen dioxide (NO_2), ozone (O_3), sulphur dioxide (SO_2), carbon monoxide (CO), particulate matter with aerodynamic diameters ≤10 μm (PM_{10}) and ≤2.5 μm ($PM_{2.5}$)) patterns for three periods: pre-COVID (from 1 January to May 30, 2019), active COVID (from 1 January to May 30, 2020) and post-COVID (from 1 January to May 30, 2021) in the Jiangsu province of China. Our findings reveal that the change in air pollution from pre-COVID to active COVID was greater than in previous years due to the government's lockdown policies. Post-COVID, air pollutant concentration is increasing. Mean change $PM_{2.5}$ from pre-COVID to active COVID decreased by 18%; post-COVID it has only decreased by 2%. PM_{10} decreased by 19% from pre-COVID to active COVID, but post-COVID pollutant concentration has seen a 23% increase. Air pollutants show a positive correlation with COVID-19 cases among which $PM_{2.5}$, PM_{10} and NO_2 show a strong correlation during active COVID-19 cases. Metrological factors such as minimum temperature, average temperature and humidity show a positive

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correlation with COVID-19 cases while maximum temperature, wind speed and air pressure show no strong positive correlation. Although the COVID-19 pandemic had numerous negative effects on human health and the global economy, the reduction in air pollution and significant improvement in ambient air quality likely had substantial short-term health benefits; the government must implement policies to control post-COVID environmental issues.

1. Introduction

In December 2019, a new type of coronavirus pneumonia (Coronavirus disease 2019, COVID-19) broke out in Wuhan City, Hubei Province (Chinazzi, 2020). On January 23, 2020, Wuhan City announced a lockdown and implemented various strong prevention and control measures (Singh, 2020). Governments around the world have also imposed lockdowns to prevent the spread of COVID-19 (Mandal, 2020); the resulting slowdown in personal travel and economic activity led to a significant reduction in air pollution within a few months (Chen, 2021). Despite the various drawbacks of COVID-19, the increase in cases has had a positive impact on air quality. The ongoing pandemic has brought millions of people around the world indoors in an attempt to limit their activity and exposure to highly infectious viruses. These behavioural changes and containment measures, which are mandatory in some places, have also had a dramatic and sudden impact on the planet (Liu, 2021a, 2021b).

Liu Fei et al. used satellite sensing technology to detect tropospheric nitrogen dioxide (NO_2), mainly emitted by fossil fuel consumption, over China during active COVID. Due to factory shutdowns during the holiday period, NO_2 emissions at this time are relatively low compared to other times of the year. On the contrary, after the provinces announced the first case of COVID-19, the concentration of NO_2 dropped by an average of 16%; after the implementation of the lockdown policy (within four days after the announcement), the concentration further dropped by 15%. During a period of 30–50 days, China's NO_2 pollution was reduced by about 20% in total (Liu, 2020). $PM_{2.5}$ decreases to 39 μgm^{-3} after lockdown and also prevent haze occurrence in Wuhan(Yao et al., 2021).

Guojun et al. evaluated the air quality index (AQI) and particulate matter ($PM_{2.5}$) of 95 blocked cities in China (the author defines a blockade as the prohibition of gatherings and non-essential commercial activity and restrictions on travel). Compared with 229 unblocked cities ('control' cities), both the AQI and $PM_{2.5}$ dropped by 17%, indicating that the air was cleaner. However, even in the control cities, these indicators slightly improved after the Spring Festival. However, $PM_{2.5}$ in blocked cities was still four times higher than the 'safe' level recommended by the World Health Organization (WHO). The main reason for that air quality change is the use of coal-fired central heating in some cities (He, 2020).

Zangari et al. observed a similar impact on air quality due to COVID-19; decreases in $PM_{2.5}$ (36%) and NO_2 (51%) concentrations were observed shortly after the shutdown took place (Zangari, 2020). On March 24, 2020, India enforced stringent lockdown measures to tackle COVID-19, resulting in a 17% decrease in the ambient AQI and an increase in ozone (O_3) concentration. This also reflects a positive correlation with the increase in COVID-19 cases due to poor air quality and indicates a correlation between COVID-19-vulnerable regions and AQI hotspots, thereby suggesting that air pollution may exacerbate clinical manifestations of the disease (Naqvi, 2021). Liu et al. observed a decrease of 8% CO_2 emissions in 2020 as compare to year 2019(Liu et al., 2020). Daniella et al. highlight reduced $PM_{2.5}$ across 50 countries post-COVID, with the highest decreases recorded in America, Asia and Africa (Rodríguez-Urrego, 2020). Dimitris et al. observed the air quality impact post-COVID in a medium-sized urban area in Thailand and found a 33.7% decrease in NO_2 concentration just three weeks after lockdown. Similar results were observed for other pollutants ($PM_{2.5}$, particulate matter with aerodynamic diameters $\leq$10 μm (PM_{10}) and O_3, which decreased by 21.8%, 22.9% and 12.5% respectively) (Stratoulias, 2020).

Studies have shown that air pollution poses a major threat to human health. Prolonged exposure to high concentrations of $PM_{2.5}$ and O_3 causes a number of problems (Kim, 2015; Akhbarizadeh, 2021; Xu, 2020). Epidemiological studies have found that fine particulate matter is closely related to cancer, cardiovascular disease and lung disease (Coleman, 2021; Khan, 2020). Additionally, air pollutants cause many premature deaths. In 2010, air pollution caused 1.36 million premature deaths in China (Bai, 2021), nearly 40% of the global total. Ambient air pollution accounts for an estimated 4.2 million deaths per year due to stroke, heart disease, lung cancer and chronic respiratory diseases. Around 91% of the world's population lives in places where air quality levels exceed WHO limits (Tan et al., 2021). Population growth and aging increase the burden of disease caused by O_3 exposure; strict emission reductions may carry key public health benefits (Rafaj, 2021).

COVID-19 had a positive environmental impact due to improved air quality (POLEDNIK, 2021). Therefore, the period of epidemic prevention and control is a good time to further explore the main factors affecting urban air quality changes. Different studies compared air quality before and during active COVID (Hasnain, 2021). In this study, the AQI and six ambient air pollutants (NO_2, O_3, sulphur dioxide (SO_2), carbon monoxide (CO), PM_{10}, and $PM_{2.5}$) were monitored before, during and after the 2020 COVID-19 lockdown in the Jiangsu province of China. The period between January and May 2020 was selected because strict lockdown was observed in all 13 cities of Jiangsu Province. Additionally, the AQI and pollutant concentrations during the same period in the prior two years (2017–18) were assessed. The relationships between the AQI and air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3) in each city were also observed with spatio-temporal change analysis. This exercise sought to improve the understanding of changing air quality patterns in each city pre-, during active and post-COVID. Furthermore, correlation analyses between the six air pollutants and the AQI during the three periods were performed to ascertain the sources of air pollutants during and after lockdown. Different studies have already revealed different air quality patterns during active and post-COVID (Pal, 2021; Li, 2021). Till August 26, 2021, total doses of COVID-19 vaccination doses administered reach 2 billion and some new cases are still reported in Guangdong, Yunnan, Shanghai, Henan, Tianjin, Liaoning, Heilongjiang, Hubei, and Sichuan in 2021(Baidu, 2021). In Jiangsu, there have been no prior reports focusing on pre-, active and post-COVID periods or on changes in the AQI with six ambient air quality patterns ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO and O_3). This study is the first to assess the relationships between the concentrations of the six named pollutants and the AQI before, during and after the Jiangsu COVID-19 lockdown. These results would help to identify effective control measures in mitigating air pollution in Jiangsu and China post-COVID.

2. Methods

2.1. Study area monitoring stations

Jiangsu is a provincial-level administrative region of the People's Republic of China. Nanjing, the provincial capital, is in the Yangtze River Delta region on the eastern coast of mainland China, spanning 30°45' ~ 35°08′ north latitude and 116°21' ~ 121°56′ east longitude; it borders on Shanghai, Zhejiang Province, Anhui Province and Shandong Province. The total area of Jiangsu Province is 107,200 square kilometres. As of November 1, 2020, the permanent population of Jiangsu Province is 84,748,016, with a total of 13 national historical and cultural sites. There are 72 selected air quality monitoring stations in Jiangsu Province; the details of each station with their coordinates and city are attached in Table S1. Fig. 1 shows the complete Jiangsu Province with black dots marking the station locations. Due to continuous development of air quality monitoring stations every year, it would be difficult to select all stations of latest year because of non-availability of data of new stations in previous year, so we same monitoring stations of each year. The monitoring stations are changed yearly; currently there are more than 110. To maintain data integrity and consistency over time, we selected the monitoring stations that remained the same every year (Table S2).

2.2. COVID data

Daily case data for COVID-19 were obtained from the websites of the Bureau of Health and the People's Government of Jiangsu Province (Ai, 2021; Dong, 2020). The geographical distribution of the cases is shown in Figure S1. On January 22, 2020, the first confirmed case of COVID-19 was found in Jiangsu Province (Ji, 2021), resulting in a strict lockdown from January to May. The most overall cases were recorded in Nanjing (93), followed by Suzhou (87), Xuzhou (79), Huaiyin (66), Wuxi (55), Changzhou (51), Lianyungang (48), Nantong (40), Taizhou (37), Yancheng (27), Yangzhou (23), Suqian (13) and Zhenjiang (12). Due to strict lockdown, no new cases were recorded after February 20, 2020. However, strict COVID-19 protocols (wearing a mask, maintaining social distance, washing hands, no public gatherings, etc.) were implemented, resulting in no new cases until May.

2.3. Air pollutant data

This paper primarily takes the daily average datasets of air pollutants from different stations. The mass concentration data of the AQI and ambient atmospheric pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3,CO) come from the weather post report (http://www.tianqihoubao.com/). Meteorological data extracted from website of climate data for the daily changes humidity, temperature and other factors (Climate Data, 2021). At each monitoring station, ambient $PM_{2.5}$, PM_{10}, NO_2, CO, SO_2, and O_3 concentrations were detected hourly, then provincial daily average and station average per 13 administrative cities were computed from those values.

2.4. Statistical analysis

This study mainly focuses on analysing the impact of COVID-19 on air pollution. Therefore, the six air pollutants were examined during the three consecutive periods: pre-COVID (from 1 January to May 30, 2019), active COVID (from 1 January to May 30, 2020) and post-COVID (from 1 January to May 30, 2021). 2019 was selected as the pre-COVID period in order to compare all four seasons rather than only winter, since air pollutant patterns change with the seasons (Marangon, 2021). For further assessment, we compared our results from 2017 (AQ-2017) and 2018 (AQ-2018) to better evaluate the impact of the changes in air pollutant patterns. Further, to show regional variation of air pollution levels, graphic maps were developed with a geographic information system using ArcGIS (version 10.5) (Draxler, 2003).

2.5. Trajectory analysis

This study used a hybrid single-particle Lagrange Integrated Trajectory Model (HYSPLIT 4.9 version), developed jointly by the National Oceanic and Atmospheric Administration's Air Resources Laboratory and the Australian Bureau of Meteorology (https://ready.arl.noaa.gov/HYSPLIT.php), to calculate the backward trajectory of the air flow to Jiangsu's cities. The model's meteorological information comes from the Global Data Assimilation System (GDAS) data from the National Centre for Environmental Prediction (NCEP) with a spatial resolution of $1^\circ \times 1^\circ$. It is a comprehensive model for calculating air flow trajectories and complex transmission, dispersion, chemical transformation and deposition simulations, enabling the visual application of air mass trajectories.

3. Results

Air pollution has a negative impact on environmental quality and global climate change, which requires almost every country to make policies to improve air quality. The problem of air pollution has become an important issue that urgently needs to be solved and has attracted the

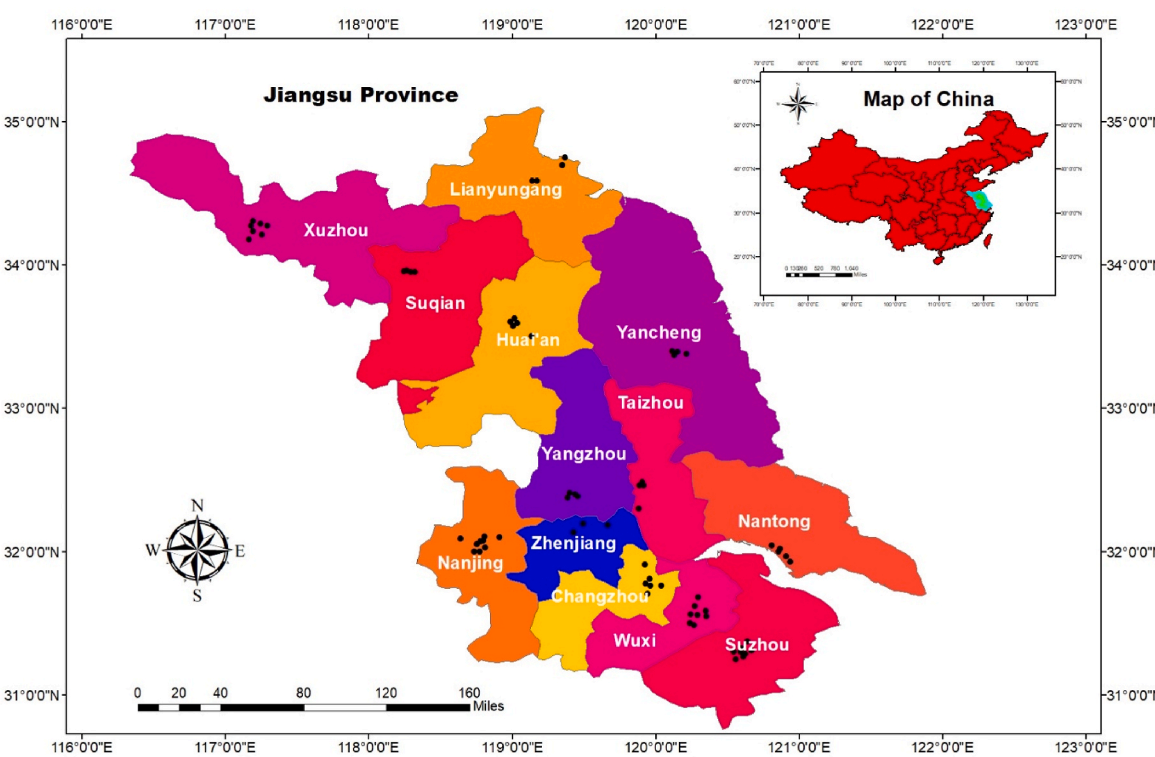

Fig. 1. Study area of Jiangsu with locations of monitoring stations in each city.

attention of both the government and society (Jiaxin, 2021). This study is an effort to highlight the pattern changes of the AQI and air pollutants post-COVID.

3.1. Daily change in air pollution during active COVID

According to the factual development process of the new coronavirus epidemic in early 2020 (active COVID), to understand the impact of the most stringent control measures on Jiangsu's air quality, we highlighted the three periods of COVID-19 according to governmental lockdown policy. The first period was from 1 January to January 22, 2020, in which COVID cases were rising in China but no cases were reported in Jiangsu. The second period is the strict lockdown period (a total of 17 days) from 25 January to 10 February. The most stringent control measures of 'no resumption of work' were implemented throughout the country during this period (Shen, 2020). After 11 February, lockdown conditions were less strict, allowing moderate traffic movement and the return of teachers to school. However, students were still not allowed to return even though the government had eased the lockdown (He, 2020). The daily average change in pollutants is shown in Fig. 2; we can observe that after the implementation of strict lockdown, all the pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO) decreased gradually and met the National Ambient Air Quality Standard (NAAQS) of China (shown by the green line in Fig. 2). During the first week of lockdown, CO decreased by 28%, NO_2 by 22%, PM_{10} by 72%, $PM_{2.5}$ by 56% and SO_2 by 39%. Only ground level O_3 saw an increase (21% during the first week of lockdown). The AQI achieved the standard value between 0 and 100 (Good to Moderate) during the strict lockdown as well as after. Other studies have revealed similar patterns of change, in which NO_2 levels in China and northern Italy have also fallen sharply due to reduced car travel and industrial activity (Zoran, 2020).

NO_2 is a powerful secondary pollutant that causes global warming. As the aviation industry stagnates and thousands of people work from home, emissions in many countries may follow the same downward trend (Liu, 2021a, 2021b). Air pollutants such as NO_2 and $PM_{2.5}$ are a direct result of human activity, but O_3 is a secondary pollutant generated by a variety of air pollutants through complex chemical reactions. Therefore, the impact of environmental changes on O_3 pollution is more difficult to predict. The product of this complex chemical reaction is not only O_3, but also NO, which quickly reacts with O_3 and decomposes it. So, since O_3 is quickly consumed after it is generated, how does it accumulate in the air? This is mainly because volatile organic compounds (VOC) can react with NO to prevent it from decomposing, and at the same time can promote the production of O_3 (Zhang, 2020).

Another study found similar results of changes in air quality patterns due to lockdown policy across China. The study reveals the impact of COVID-19 lockdown on urban air pollution in China: all cities that adopted lockdown measures to curb COVID-19 saw their AQI and $PM_{2.5}$ drop by 19.84% and 17% respectively. Since the strict lockdown, air pollutants achieved all-time lows while the O_3 level increased significantly (Semple, 2020).

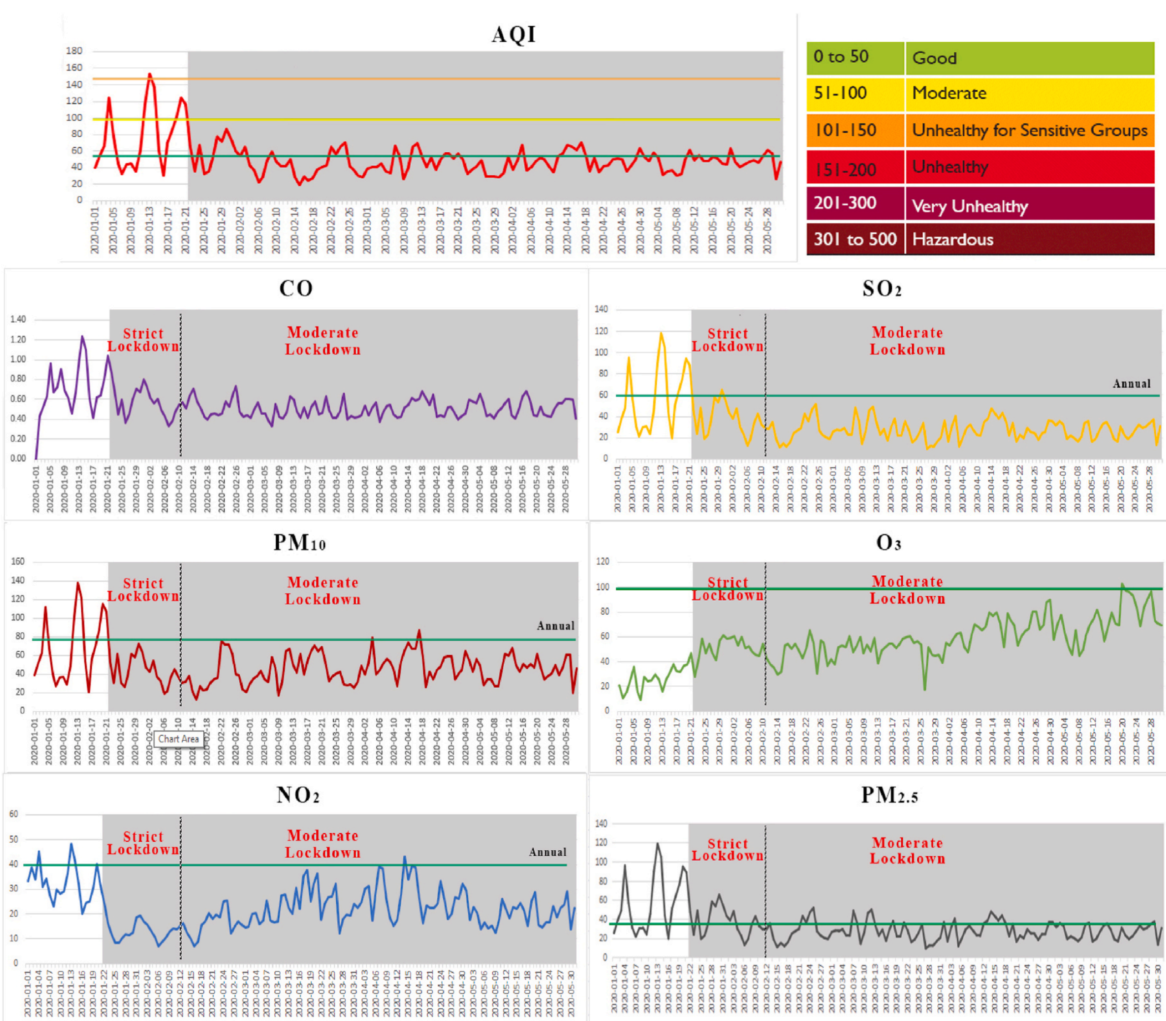

Fig. 2. Daily change in air pollutants and AQI during COVID-19.

3.2. City-wise change in air pollutants pre-, during active and post-COVID

Pre-, active and post-COVID variations show a clear change in air pollutant patterns, as shown in Fig. 3. The average concentration of $PM_{2.5}$ was high in the pre-COVID period in almost all the cities of Jiangsu, but during active COVID and post-COVID it reached the target set by the NAAQS of China (Annexure B, Table B1 and B2 standards of China air quality) (Wu, 2018). NO_2 concentration had a similar pattern, but its levels increased post-COVID. The decrease of NO_2 during active COVID is related to the Spring Festival in China. The power industry, which emits various exhaust gases every day, causes the NO_2 in the air to increase, but during the lockdown the NO_2 concentration was low compared to the pre-COVID period. The second cause of decreased NO_2 is the limited movement of motor vehicles, as worsening traffic has a huge impact on the concentration of NO_2 in the urban air. According to estimates, about 54% of the NO_2 pollution in Beijing's air comes from motor vehicle exhaust (Lv, 2020). Post-COVID, factories resumed production and the number of motor vehicles increased; according to the Jiangsu Bureau of Statistics, the province's industrial size increased by 23.8% this year and the two-year average growth rate was 10.9%, which was 5.7% higher than the same period in 2019. From an industry perspective, the value-added growth rate of the 10 key industries from January to May is over 15%, of which the electrical, automotive, special equipment, general equipment and metal product manufacturing industries all exceed 30%, 36.5%, 33.4%, 33.1% and 32.5% respectively. In May 2021, the output of new energy vehicles, rare earth magnetic materials, integrated circuits, urban rail vehicles and carbon fibre and its composite materials increased by 261.2%, 179%, 50.4%, 44.1%, and 40.6%, respectively, year-on-year (Wang, 2020). These factors are major results of the change in air pollutant patterns post-COVID.

The acceleration of the industrialisation process has improved the level of social productivity, but the use of fossil fuel has also brought about serious air pollution problems. Among these problems, SO_2 has a huge impact on human health and the ecosystem and must be given

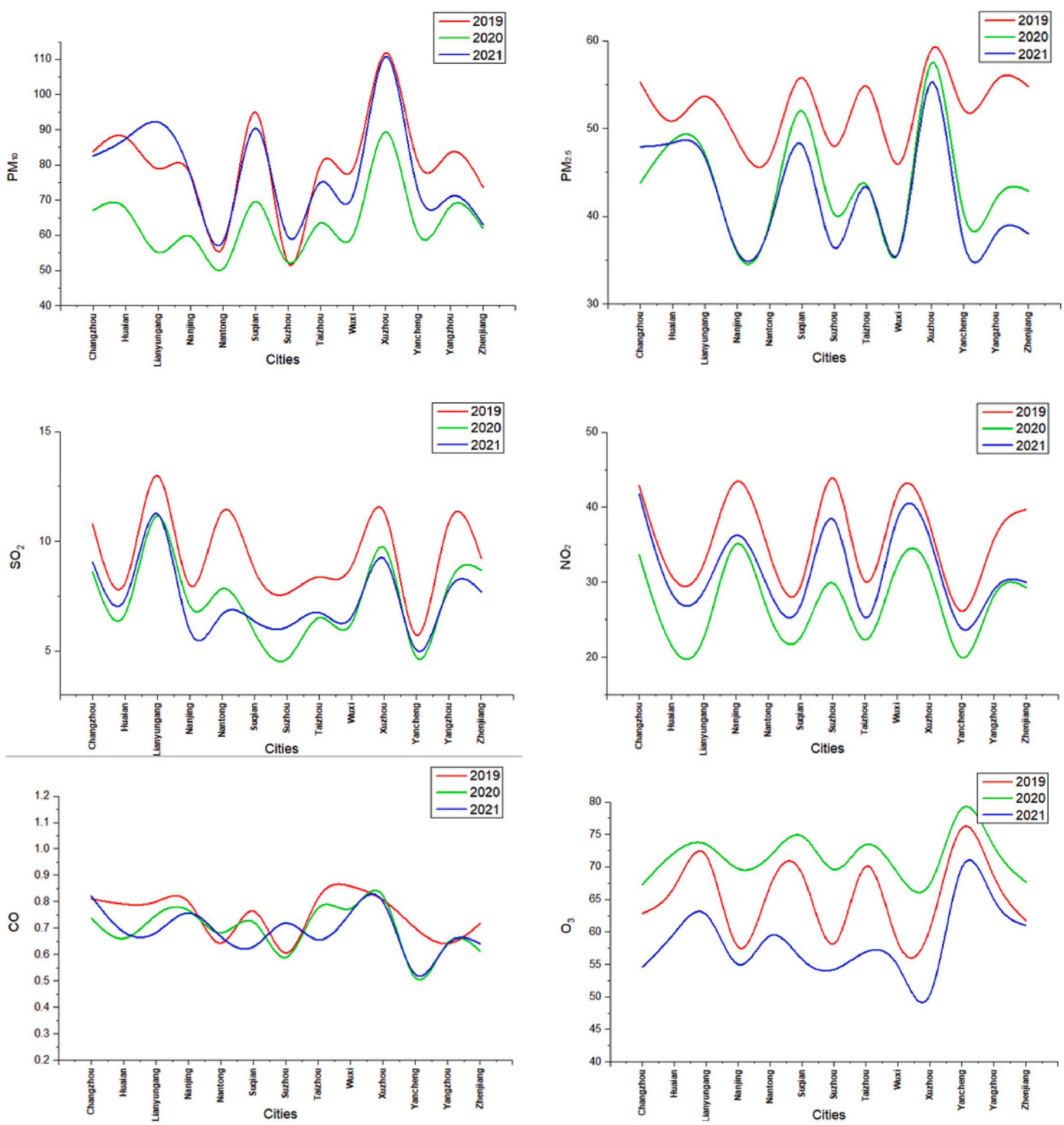

Fig. 3. City-wise comparison of air pollutants and AQI (pre-COVID, active COVID, post-COVID).

sufficient attention (Grennfelt, 2020). SO_2 causes environmental problems (such as acid rain) and if consumed excessively may also cause allergic reactions, breathing difficulties, vomiting and other symptoms. The concentration of SO_2 pre-COVID was remarkably high; during active COVID it dropped in almost all Jiangsu's cities, but due to current industrial growth SO_2 levels are rising again, which leads to alarming conditions for the government to address. Similar patterns of CO concentration as a result of road transportation, which emits large amounts of pollutants, and coal-based energy production have been recorded. These are the main reasons for the relatively high CO concentration (Dong, 2021). In addition, in Jiangsu, the population is relatively large, distribution is concentrated, the amount of coal consumed is large and the emission of smoke and dust is more than three times the national average (Fu, 2020), especially during autumn and winter, when the demand for coal is even greater. So far, these factors were reduced during active COVID and post-COVID because of strong measures taken by the government. The AQI of all the cities in Jiangsu is increasing due to growth and development in the province post-COVID (Rana, 2021), which is a clear indication that air quality will decrease in the coming months.

3.3. Yearly change in concentration pattern of air pollutants 2017–2021

Fig. 4 and Table S6 shows air pollution decreasing gradually from 2017 until the pre-COVID period (2019). The change from pre-COVID to active COVID is larger than previous years due to the government's lockdown policy. Post-COVID, the pattern of air pollutant concentration is increasing. The mean change of $PM_{2.5}$ from pre-COVID to active COVID decreased by 18%; post-COVID the decrease is only 2%. PM_{10} decreased by 19% from pre-COVID to active COVID, but post-COVID a 23% increase pollutant concentration was recorded. NO_2 decreased by 24% pre-COVID to active COVID; post-COVID it increased by 16%. CO levels went down by 7% from pre-COVID to active COVID but rose to 1% post-COVID. O_3 recorded an increase of 11% from pre-COVID to active COVID and a decrease of 20% from active COVID to post-COVID.

3.4. Correlation analysis

The correlations among the AQI and other air pollutants in Jiangsu during the three periods are presented in Fig. 5 (Table S5). For the pre-COVID period, the AQI concentrations were highly correlated with CO concentrations (r^2 = 0.906**), PM_{10} (r^2 = 0.928**) and $PM_{2.5}$ (r^2 = 0.976**), had medium correlation with NO_2 (r^2 = 0.685**) and SO_2 (r^2 = 0.531**) and were not correlated with O_3. In the active COVID period, the AQI concentrations were highly correlated with CO (r^2 = 0.857**), PM_{10} (r^2 = 0.944**) and $PM_{2.5}$ (r^2 = 0.971**) and had medium correlation with NO_2 (r^2 = 0.589**) and SO_2 (r^2 = 0.431**) and were not correlated with O_3. During active COVID, the overall r^2 value reduce expect PM_{10} have little increase. Post-COVID, the AQI concentrations were highly correlated with PM_{10} (r^2 = 0.952**) and $PM_{2.5}$ (r^2 = 0.861**), had medium correlation with CO (r^2 = 0.580**) and NO_2 (r^2 = 0.465**), low correlation with SO_2 (r^2 = 0.303**) and were not correlated with O_3.

For the pre-COVID period, the CO concentrations were highly correlated with PM_{10} (r^2 = 0.769**), PM2.5 (r^2 = 0.945**), had medium correlation with NO_2 (r^2 = 0.634**), low correlation with SO_2 (r^2 = 0.531**) and were not correlated with O_3 During active COVID, CO concentrations were highly correlated with PM_{10} (r^2 = 0.749**) and $PM_{2.5}$ (r^2 = 0.887**), had medium correlation with NO_2 (r^2 = 0.541**), low correlation with SO_2 (r^2 = 0.290**) and were not correlated with O_3.

Pre-COVID period, $PM_{2.5}$ concentrations had medium correlation

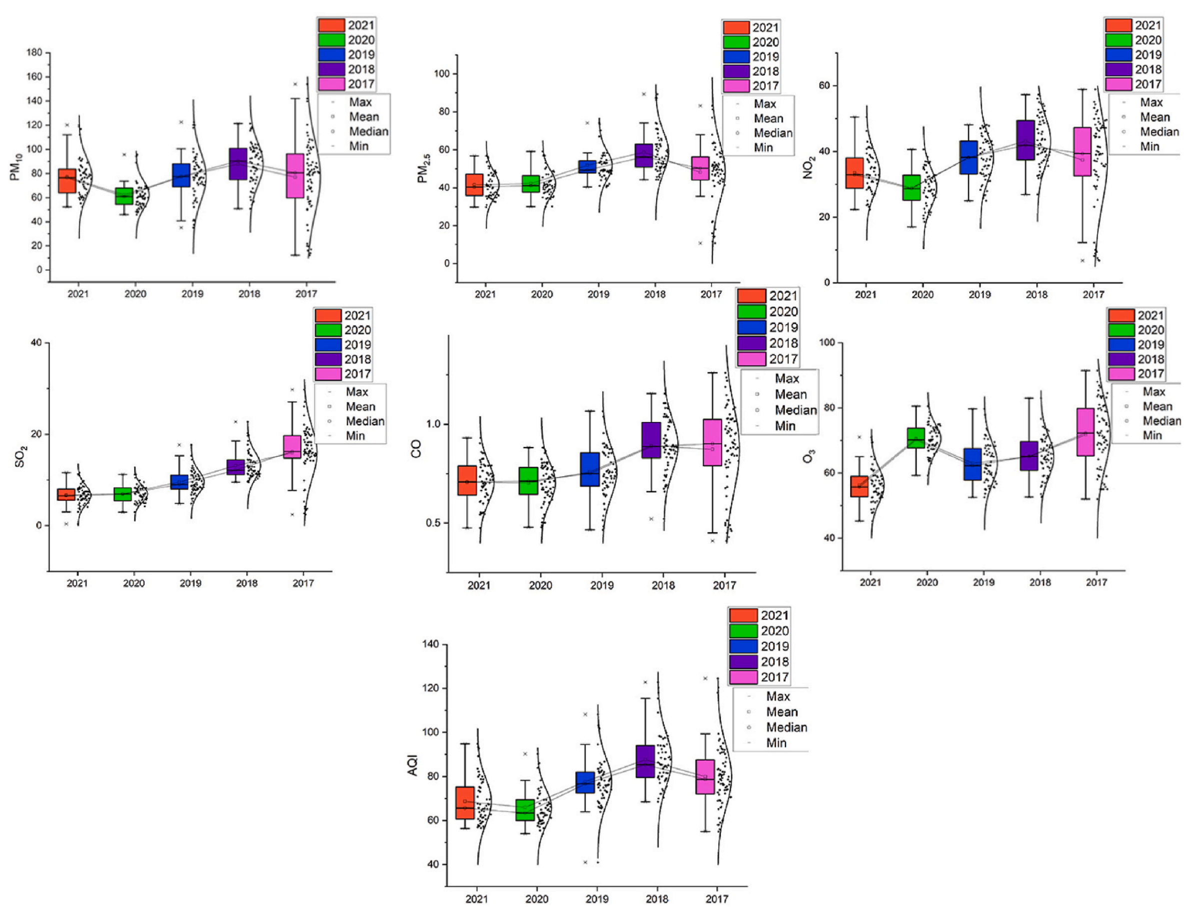

Fig. 4. Yearly change in the concentration of pollutants 2017–2021.

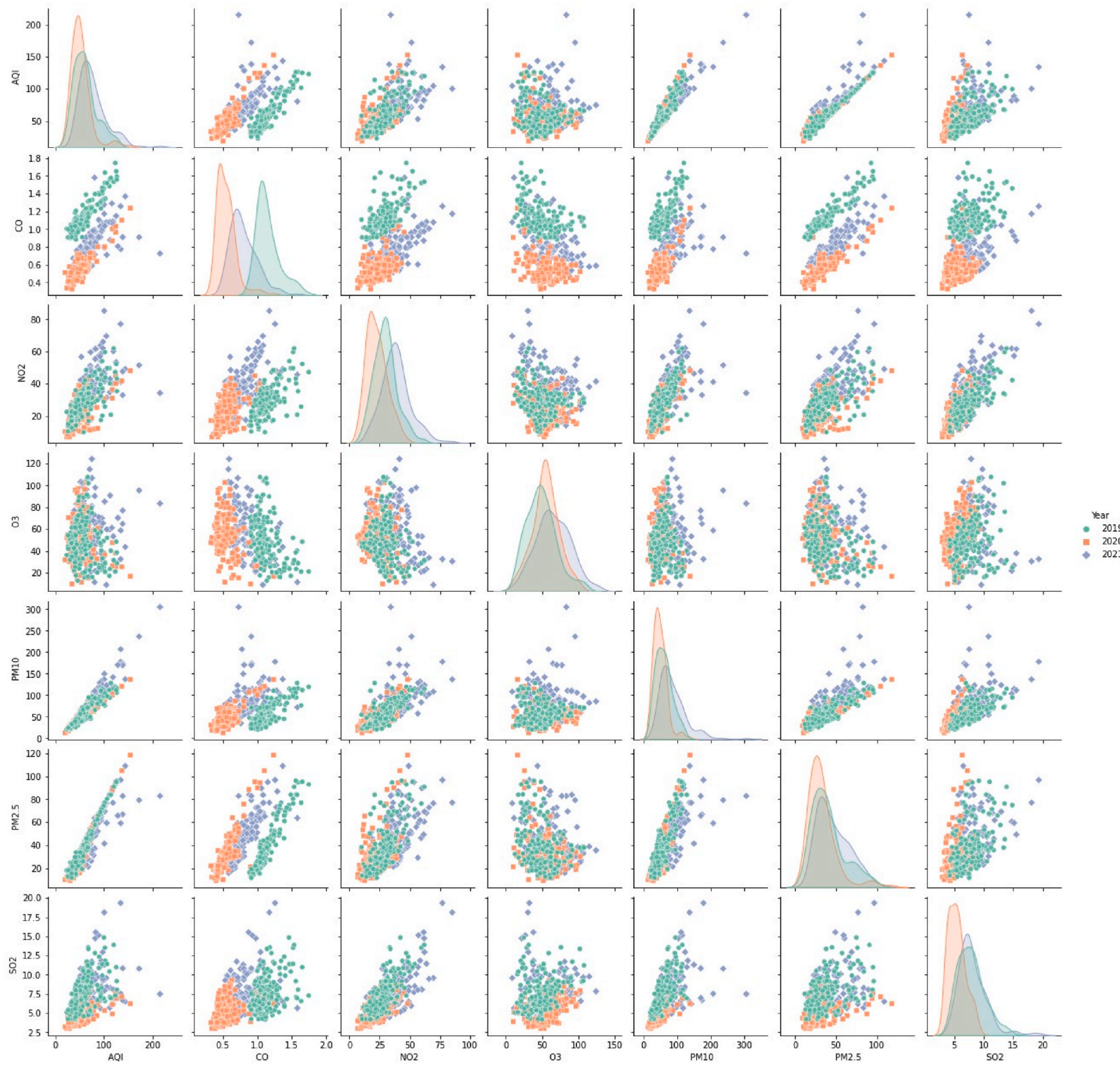

Fig. 5. Correlation between AQI and air pollutants pre-COVID (2019), during active COVID (2020) and post-COVID (2021).

with SO_2 ($r^2 = 0.440^{**}$). During active COVID, $PM_{2.5}$ concentrations had low correlation with SO_2 ($r^2 = 0.286^{**}$). Post-COVID, $PM_{2.5}$ concentrations had low correlation with SO_2 ($r^2 = 0.271^{**}$). The analysis of these gaseous pollutants agrees with previous evidence that, in urban microenvironments, the pollution mainly comes from emissions induced by local heavy human activity (Pirjola, 2012; Li, 2019). Smooth building surfaces and efficient floor plans may help to eliminate air pollution via wind ventilation, which accelerates dispersion.

3.5. *Correlation analysis of meteorological parameters with COVID-19 cases and air pollutants*

Further, we find the correlation between the 6 pollutants and COVID-19 cases (Active COVID-19 duration), with the monthly average values of 4 meteorological factors in the ambient air of Jiangsu (Table S7). The monthly averages of SO_2 and CO concentrations are not significantly related to the four meteorological factors. The correlation coefficient between the monthly mean value of NO_2 concentration and the air temperature is -0.863, which has a very significant negative correlation ($p<0.01$), and the correlation coefficient with the air pressure is 0.830, with a very significant positive correlation ($p<0.01$), low correlation with humidity and wind speed ($p > 0.05$); the correlation coefficient between the monthly mean PM_{10} concentration and wind speed is -0.603, which has a significant negative correlation ($p > 0.05$), low correlation with temperature, humidity, and air pressure ($p > 0.05$); The monthly mean value of $PM_{2.5}$ has a very significant negative correlation with temperature ($p<0.01$), It has a significant negative correlation with wind speed ($p<0.01$), low correlation with humidity ($p<0.01$), the correlation coefficients are -0.602 and-0.758, and the correlation coefficient with temperature is 0.738, which has a very significant positive correlation ($p<0.01$), and low correlation with humidity ($p > 0.05$). A strong correlation is observed among air pollutants and COVID-19 total cases while other studies show similar results of the strong relationship between air pollutants COVID-19 cases (Table S7) (Sahoo, 2021). $PM_{2.5}$, PM_{10} and NO_2 show a strong correlation with COVID19 cases and O_3 observed a negative correlation with COVID-19 cases.

Temperature (T), an important factor in the human living environment, can play an important role in public health concerning epidemic development, prevention, and control. During the active COVID-19 period, average temperature and minimum temperature have a positive correlation with COVID-19 active cases (correlation value is 0.48) as well as total cases (correlation value is 0.52). However, a negative correlation is observed with maximum temperature for active cases (correlation value is -0.342) and with total cases, a negative correlation is -0.362. Air pressure and wind speed show a low positive correlation with the value of active COVID-19 cases and total COVID-19 cases.

Humidity shows a strong positive correlation with active COVID-19 cases and total COVID-19 cases (Table S8).

4. Discussion

To the best of our knowledge, this is the first in-depth provincial study that analyses air quality patterns pre-, during active and post-COVID. Another study focused on Wuhan City compared the periods before, during and after lockdown to identify the relationship between air quality patterns and meteorological factors (Sulaymon, 2021). COVID-19 and its economic impact have severely damaged the development of every country and affected more than 180 million people (Zheng, 2021). This study suggests that the government's policies regarding the spread of COVID-19 provided a positive effect on air pollution levels through decreased human activity, lower traffic and the closure of factories. A complete change in air pollutants patterns in Jiangsu province is shown in Fig. 6. This study also highlighted the alarming signals that pollutant concentration post-COVID is rising to the same levels as the pre-COVID period. There is a strong indication for the need to implement environmental improvement policies to halt this increase (Beig, 2021). O_3 is the only pollutant that increased during active COVID but decreased by 20% post-COVID due to government monitoring. O_3in the stratosphere protects the earth, but a high concentration of O_3 near the ground endangers human health. O_3 pollution is not as visible as $PM_{2.5}$ pollution; its harm to human health is mainly reflected by irritation and damage to the eyes and respiratory tract (Betancourt-Odio,2021; Higham, 2021; Wang, 2021). O_3 near the ground originates from vertical transport in the stratosphere, while in the troposphere it is composed of precursors such as nitrogen oxides (NO_x), CO and VOCs. Tropospheric ozone is mainly generated by the photochemical reaction of NOx, CO and VOCs under sunlight(Szep et al., 2016). Methane is also an important precursor of O_3, and its concentration has been changing in COVID-19. The global background value of ozone is mainly contributed by carbon monoxide and methane. In most cases near cities and human activities, the contribution of methane and carbon monoxide to ozone generation can often be ignored, so only non-methane total hydrocarbons (Non-Methane VOC, NMVOC) can be considered. In the troposphere, O_3, NO and NO_2 react quickly to form an approximately steady-state equilibrium:

$$O_3 + NO \rightarrow NO_2 + O_2$$

$$NO_2 + hv \rightarrow NO + O$$

$$O + O2 \rightarrow O_3$$

This reaction cycle does not have a net environmental ozone generation effect. But in the presence of CO and VOCs, more ozone will be produced. The CO–O_3 formation reaction is firstly produced by the reaction of OH radicals to form radical HO_2, which further reacts with NO to form NO_2, and the photolysis of NO_2 produces a new ozone:

$$HO_2^{\bullet} + NO \rightarrow {}^{\bullet}OH + NO_2$$

$$NO_2 + h\nu \rightarrow NO + O(^3P)$$

$$O(^3P) + O_2 \rightarrow O_3$$

The net effect of the above reaction can be expressed as:

$$CO + 2O_2 + h\nu \rightarrow CO_2 + O_3$$

The generation of ozone in the troposphere is almost entirely the result of the oxidation of VOCs. The atmospheric photochemical reaction involving VOCs is much more complicated than the process of CO oxidation to O_3, but the oxidation process of NO by peroxy radicals is still the key reaction of ozone formation(Tan et al., 2018). Taking methane as an example, the oxidation process of methane and intermediate products by HOx provides a way to convert NO into NO_2 without losing O_3:

$$CH_4 + OH + O_2 \rightarrow CH_3OO + H_2O$$

$$CH_3OO + NO \rightarrow CH_3O + NO_2$$

$$CH_3O + O_2 \rightarrow HCHO + HO_2$$

$$HO_2 + NO \rightarrow OH + NO_2$$

Similarly, consider the photolysis of NO_2:

$$2NO_2 + hv \rightarrow 2NO + 2O$$

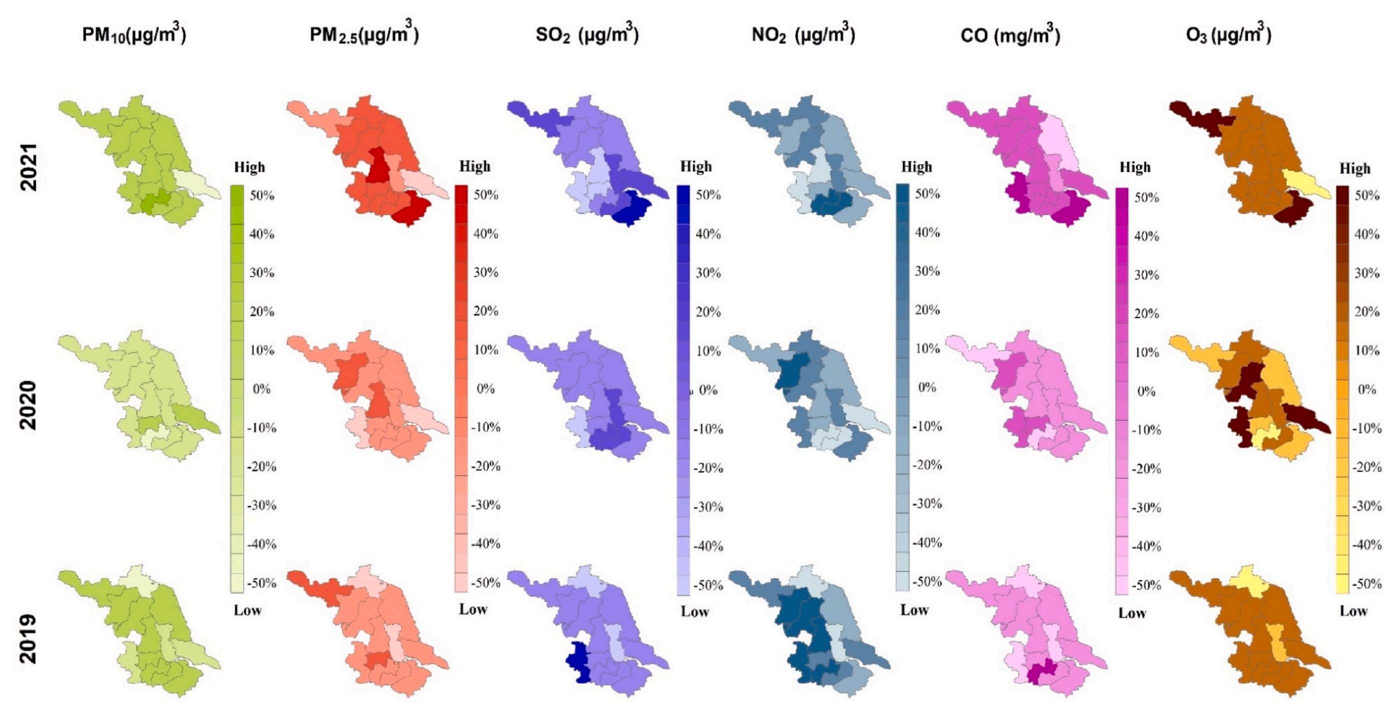

Fig. 6. Change of air quality pattern of AQI and pollutants pre-COVID (2019), active COVID (2020) and post-COVID (2021).

$$2O + 2O_2 \rightarrow 2O_3$$

The net reaction of the oxidation of one methane molecule forms 2 ozone molecules:

$$CH_4 + 4O_2 \rightarrow HCHO + H_2O + 2O_3$$

There are many types of non-methane volatile organic compounds in the troposphere, including alkanes, alkenes, aromatics the atmospheric chemical mechanism of aromatic hydrocarbons, oxygenated organic matter and ozone emitted from natural sources is very complicated. Figure S3 shows the daily changes in the mass concentration of O_3 and precursors NO, NO_2, NOx, and VOCs in different seasons of 2020. The variation of the precursor concentration is inversely related to O_3, and the overall performance is characterized by a decrease in the concentration during the day and an increase in the concentration at night.

Government should analyze the source of ozone pollution in ambient air which can clarify the causes of ozone pollution in cities and monitor the flow of pollutants as shown in Fig S4. Key points to remain focused on are:

(1) Clarify the temporal and spatial distribution of ozone concentration, and analyze the temporal and spatial evolution characteristics of ozone pollution in combination with the change of source intensity and the distribution of main pollution sources.
(2) Analyze the main atmospheric physical and chemical processes of high-concentration ozone formation, estimate the contribution of each main ozone precursor emission source to ambient air ozone in the typical ozone pollution process and diagnose the source contribution of the typical ozone pollution process.
(3) Analyze the sensitivity of ozone and its precursor emissions, diagnose the cause of ozone pollution, and determine the direction of ozone pollution precursor control.
(4) Determine the control targets for the key pollution sources and NOx emission sources of NOx in the ambient air.
(6) Clarify the concentration levels and temporal and spatial distribution characteristics of different types of VOCs in the ambient air, determine the key control species, key control industries and key control sources of VOCs, and clarify the control targets of the VOCs emission source category.

With the development of the urban economy, expansion of scale and the increase of exhaust emissions from motor vehicles, urban photochemical pollution with O_3 as a product is increasing day by day (Briz-Redón, 2021). Studies have shown that air pollution in China has gradually transitioned from traditional soot-type pollution to regional composite air pollution characterized by high concentrations of $PM_{2.5}$ and O_3 (Wang, 2021). (Zhu, 2011) believe that the formation of complex air pollution patterns is mainly due to the concentrated emission of many pollutants into the atmosphere; multiple high-concentration pollutants co-exist and have complex physical and chemical interactions. In terms of pollution, it manifests as significantly reduced atmospheric visibility, significantly enhanced atmospheric oxidisability and a trend of environmental deterioration spreading to the entire region.

Many other countries enacted strict policies to control the impact of COVID-19. For example, Spain controlled the spread of COVID-19 after just two weeks of lockdown and recorded a sudden change in air quality pattern (Briz-Redón, 2021). European countries also observed air pollution changes during the lockdown and noted that the means of urban background PM_{10} and traffic NO_2 decreased by 28% and 51% during the two weeks of lockdown after comparison with the pre-COVID period. A sharp reduction in NO_2 emissions in European countries, including Spain as well as France, Germany and Italy, were found via European Space Agency satellite monitoring. Similarly, there is evidence of air pollution changes post-COVID in non-European countries, including the U.S., Brazil and Morocco (Beloconi, 2021).

5. Conclusion

This study shows many benefits in terms of highlighting the changes in air quality patterns due to COVID-19:

(1) First, it included 13 cities with differing COVID-19 numbers and air pollutant levels, which enabled us to observe the potential association between air pollution and COVID-19.
(2) Second, this is one of few efforts in China to focus on the effect of air pollution in three stages of COVID-19 (pre-COVID, active COVID and post-COVID). Third, we used different methods to reflect exposure level, including average pollutant concentration and other factors of the environment, which capture the average level of air pollution as well as abnormal changes in the air pollution level.

In the future, this study can be extended by finding a relationship with socio-economic indicators to get a better impact on economic growth and find the real impact of COVID-19 on human life.

Authors contribution

Uzair Aslam Bhatti: Validation, Methodology, Investigation, Formal analysis, Writing – original draft. Linwang Yuan: Methodology, Writing – review & editing. Zhaoyuan Yu: Writing – review & editing. Sibghatullah Bazai: Conceptualization, Supervision, Funding acquisition, Writing – review & editing. Mir Muhammad Nizamani: Conceptualization, Supervision, Funding acquisition, Writing – review & editing. Zeeshan: Methodology, Investigation, Formal analysis, Writing – original draft.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2021.132569.

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