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Spatial and temporal variation characteristics of atmospheric NO_2 and SO_2 in the Beijing-Tianjin-Hebei region before and after the COVID-19 outbreak

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Abstract

Emergency response mechanisms were activated throughout China during the COVID-19 outbreak. It is different from the temporary, partial, and limited pollution control measures taken to ensure the regional environmental quality during several important events such as the 2008 Beijing Olympic Games and the 2014 Asia-Pacific Economic Cooperation (APEC). During the COVID-19 epidemic period, extensive movement of people and almost all unnecessary industrial production (necessary industrial production refers to the production of food, epidemic prevention materials, etc.) have been severely restricted, so transportation and industrial production have been greatly reduced. This is a rare extreme emission reduction scenario that presents a unique opportunity for atmospheric research. In this study, based on hourly mass concentration data of NO_2 and SO_2 from atmospheric monitoring sites in the Beijing-Tianjin-Hebei (BTH) region during the COVID-19 epidemic period, the changes in transportation and industrial production in the region, data statistics, and spatial analysis were used to analyze the pollution changes and their causes. The results indicate that the NO_2 and SO_2 concentrations in the BTH region decreased significantly during the epidemic period. The spatial distribution pattern of NO_2 pollution in the BTH region was "high in the southeast and low in the northwest," and SO_2 pollution in the BTH region was high in the southern and eastern parts of Hebei. The initiation of emergency response level 1 had an obvious effect on reducing NO_2 and SO_2 pollution in the region, while the impact of emergency response level 2 and below was limited. Compared with the single traffic control, the comprehensive control, similar to the emergency response, had a better effect on reducing NO_2 pollution in the region. The control of major large cities in the region also had a certain effect on alleviating NO_2 and SO_2 pollution in the entire region. Moreover, for activities under short-term control, it is particularly important to guard against the "retaliatory growth" after the control is lifted. By reducing and controlling some polluting industries in industrial production, the degree of NO_2 and SO_2 pollution in the region can be effectively reduced. The manufacturing industry of chemical raw materials and the chemical products and non-metallic mineral products industry made a great contribution to the change in industrial source pollution emissions in the BTH region during the COVID-19 epidemic. Road traffic emissions remained an important source of NO_2 emissions in the BTH region during this period. NO_2 emission reduction can be effectively achieved by controlling road traffic and transportation.

Keywords COVID-19 · NO_2 · SO_2 · Variation characteristics · Beijing-Tianjin-Hebei region

Introduction

Rapid urbanization and industrialization in many cities have resulted in higher concentrations of air pollutants, which affect population health and have become a key environmental issue (Oh et al. 2021). Gaseous pollutants not only affect human health but also have important impacts on the regional ecological environment and global climate change (Jenkin 2004). The World Health Organization (WHO) and the European Environmental Agency (EEA) outline three major outdoor air pollutants that are most detrimental to health, two of which are nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) (EEA

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2019; WHO 2005). NO_2 and SO_2 are also routine monitoring items of air pollution in China (Ministry of Environmental Protection of the People's Republic of China, and General Administration of Quality Supervision, Inspection and Quarantine 2012).

As China's main economic, population, and industrial circles, there has long since been concern regarding air pollution in the Beijing-Tianjin-Hebei (BTH) region, where scholars have conducted extensive studies on air pollution characteristics, temporal and spatial distribution, and short-term control and emission reduction effects on air pollution in recent years (Wang et al. 2018; Qi et al. 2017; Hou et al. 2019; Hou et al. 2018; Zhao et al. 2020). Wang et al. (2018) studied the characteristics of SO_2 pollution in the BTH region from 2006 to 2017 based on ozone monitoring instrument (OMI) remote sensing inversion data and found that SO_2 pollution was closely related to the industrial pattern, population distribution, and terrain and surface coverage and that rapid SO_2 reductions generally correlate well with sharp reductions in industrial activity. Qi et al. (2017) established a high-resolution air pollutant emission inventory for the BTH region and found that the industry sector is the largest emission source of SO_2, NO_X, particulate matter with an aerodynamic diameter of < 2.5 μm ($PM_{2.5}$), particulate matter with an aerodynamic diameter of < 10 μm (PM_{10}), CO, and NMVOC. Zhao et al. (2020) analyzed the spatial and temporal distributions of six air pollutants in the BTH region from 2014 to 2018 and studied the population exposure of $PM_{2.5}$ and O_3.

The COVID-19 outbreak occurred in China in January 2020. Emergency response mechanisms were activated throughout China during the COVID-19 outbreak. It is different from the temporary, partial, and limited pollution control measures taken to ensure the regional environmental quality during several important events such as the 2008 Beijing Olympic Games and the 2014 Asia-Pacific Economic Cooperation (APEC) (Shen et al. 2011; Huang et al. 2015). Extensive movement of people and almost all unnecessary industrial production (necessary industrial production refers to the production of food, epidemic prevention materials, etc.) have been severely restricted during COVID-19 epidemic period, so transportation and industrial production have been greatly reduced. This is a rare extreme emission reduction scenario that presents a unique opportunity for atmospheric research. Therefore, this study was based on atmospheric NO_2 and SO_2 data in the six different stages before and after the COVID-19 outbreak in the BTH region. In contrast, data from the same period in 2019 was combined with the change of industrial production, transportation, and systematic analysis of the COVID-19 outbreak during different stages, and of NO_2 and SO_2 emission scenario variation characteristics, in order to determine the most effective control measures of atmospheric pollution and an air pollution control policy and to provide an effective reference.

Data and methods

Study area

The BTH region is located in the heart of the Bohai Rim. The urban agglomeration includes Beijing and Tianjin (i.e., two municipalities directly under the central government) and Shijiazhuang, Tangshan, Qinhuangdao, Langfang, Baoding, Zhangjiakou, Chengde, Cangzhou, Hengshui, Xingtai, and Handan in Hebei province. This region has the largest economic scale in northern China and has become a key area of air pollution prevention and control in China due to its high energy consumption and pollution discharge.

In this study, 88 ground air quality monitoring stations were selected in the BTH region, including 12 stations in Beijing, 20 stations in Tianjin, and 56 stations in Hebei, covering all cities above the prefecture level in the BTH region. The distribution of the monitoring stations is shown in Fig. 1.

Data sources and study time selection

The atmospheric NO_2 and SO_2 data used in this study were hourly monitoring data of 88 air quality ground monitoring stations in the BTH region issued by the national urban air quality real-time publishing platform of the China Environmental Monitoring General Station (http://106.37.208.233:20035/). The administrative boundary vector data were obtained from a national basic geographic database. Meteorological data are from the National Oceanic and Atmospheric Administration (NOAA) (https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily). The tropospheric NO_2 column concentration data used in this paper are from the OMI data inversion and tropospheric emission monitoring network service published by the Royal Netherlands Meteorology Institute (http://www.temis.nl). The output data of major industrial products above scale and the growth rate of industrial added value above scale in the BTH region were obtained from the Beijing Municipal Bureau of Statistics, Tianjin Bureau of Statistics, and Hebei Bureau of Statistics (http://tjj.beijing.gov.cn/tjsj_31433/yjdsj_31440/gy_31782/2020/index.html;http://stats.tj.gov.cn/TJTJJ434/SJCX629/; http://tjj.hebei.gov.cn/hetj/tjsj/sjcx/101583911125077.html). Transportation data were obtained from the Beijing Municipal Bureau of Statistics, Tianjin Transportation Commission, and Hebei Provincial Transportation Department (http://tjj.beijing.gov.cn/tjsj_31433/yjdsj_31440/ysyd_31830/2020/index.html;http://jtys.tj.gov.cn/Page/InfoListPage_index.aspx?NCode=1705;http://jtt.hebei.gov.cn/jtyst/zwgk/jcxxgk/jttj/zhtjfx/).

The study was conducted from January to June 2020. Six phases were selected, as shown in Table 1. According to the changes in the emergency response level during the epidemic, 2 weeks after, the beginning of each phase was selected as the

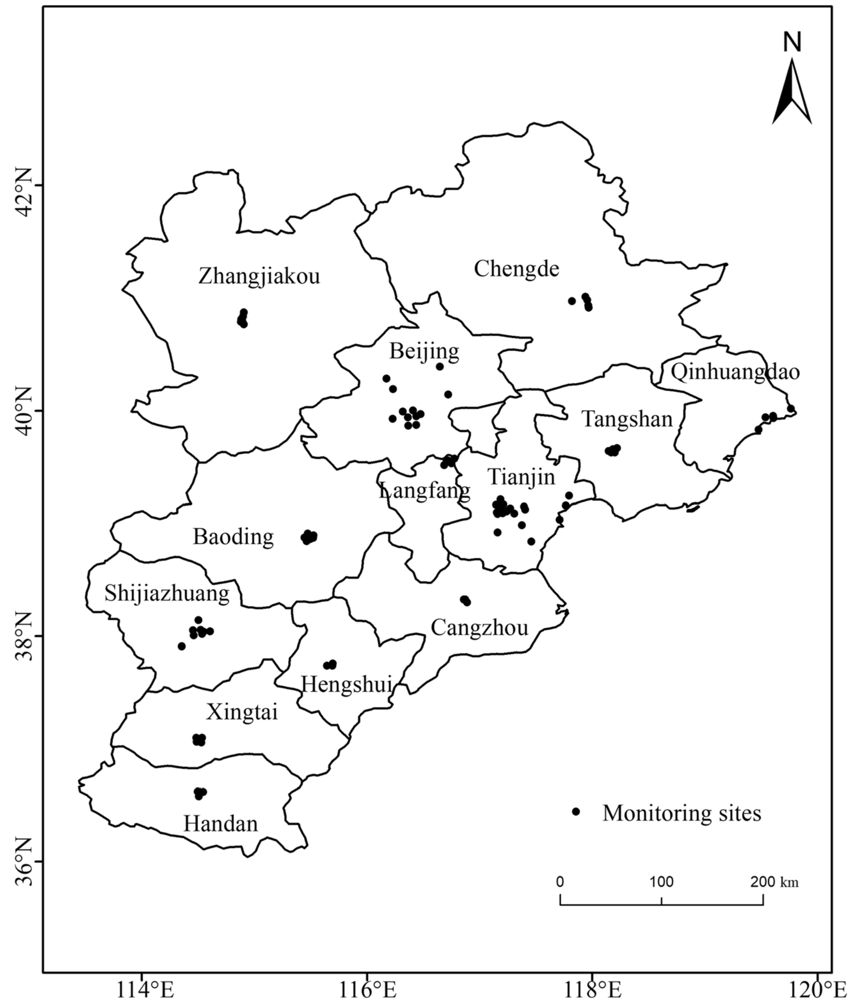

Fig. 1 Distribution of monitoring stations in the study area

research period, with a total of four stages. Emergency response level 1 was activated on January 24. However, considering the possible impact of the Spring Festival on the air pollution situation and to clarify the impact of the epidemic, the phase was selected from February 11 to 24. In addition, starting from the mutual recognition of health codes of the BTH region on April 18, as an important node for the resumption of work and production within the BTH region, the period from April 19 to 29 was selected as the research phase. Selecting January 6 to January 19 as the normal production phase. Data for the same period in 2019 served as a control group. The duration of each phase was approximately 2 weeks but varied slightly with the length of each phase. This ensured that not only did the obtained mean mass concentration not make the comparison not obvious because of the long time span, but the influence caused by severe pollution in a short time was also weakened to some extent. The results of monthly statistics were used for publicly released data, the output of major products of industries above a designated size, the growth rate of added value of industries above a designated size, and transportation statistical results.

Research methods

First, the mass concentration data of NO_2 and SO_2 in the BTH region during the study phase were counted and plotted using Origin2018 to analyze the variation trends of atmospheric NO_2 and SO_2 mass concentrations at each stage, which were

Table 1 Research stage division

Phase Year	Phase 1 (normal production phase)	Phase 2 (activation of emergency response level 1)	Phase 3 (area resume work and production)	Phase 4 (adjust to level 2 response)	Phase 5 (adjust to level 3 response)	Phase 6 (Beijing resumes level 2 response)
2020	January 6–19	February 11–24	April 19–29	April 30–May 13	June 6–15	June 16–29

then compared with the same period in 2019. Second, the meteorological conditions in the study area during COVID-19 and the same period in 2019 were compared to analyze the influence of the changes of meteorological conditions on the change of pollutant concentration. Third, based on the mass concentration data of NO_2 and SO_2 from 88 ground air quality monitoring stations in the BTH region, kriging interpolation analysis was carried out by applying a mathematical analysis method to discuss and analyze the spatial distribution changes of NO_2 and SO_2 in different stages and compare them with the same period in 2019. Furthermore, results from OMI satellite data were used to validate ground station data. Finally, we combined the output of major products of above-scale industries, the growth rate of industrial added value of above-scale industries, and the changes in traffic and transportation data in the BTH region, verified the data, and compared and discussed the mass concentration changes of NO_2 and SO_2 in the region.

Results and discussion

Analysis of mass concentration changes of NO_2 and SO_2 in different phases

During the COVID-19 epidemic, the NO_2 concentration in the BTH region tended to decrease, increase, and then decrease again (Fig. 2). From the emergency response level 1 (phase 2), the NO_2 mass concentration in all cities showed a significant downward trend, which was closely related to the reduction of industrial production in the emergency response level 1, strict traffic control, and people's lack of willingness to travel due to the epidemic. In phase 3, after relaxation of traffic control within the region, the mass concentration of NO_2 in most cities of the BTH region remained at a low level; however, that in the southern region of Hebei (namely Handan, Xingtai, and Hengshui) increased to a certain extent. This indicated that the control degree in the southern region far from the central core functional area (Beijing, Tianjin, Baoding, and Langfang) was relatively loose and that there were differences in the degrees of control within the BTH region. With the decrease in the emergency response level (phase 4), it can be seen that the NO_2 mass concentration in all cities in the BTH region (except in the three southern cities [Handan, Xingtai, and Hengshui]) increased to different degrees. This indicates that the emergency response mechanism (i.e., a comprehensive policy adjustment) had a more effective impact on NO_2 pollution in the region than changes in a single traffic control policy in the region. However, in the stage of improving the level of emergency response in Beijing (i.e., phase 6), the NO_2 pollution level in most cities in the BTH region declined to different degrees, which may have been related to the control in major cities in the region. By observing the changes of NO_2 in various stages at the same time in 2019 (Fig. 2), it can be seen that NO_2 in various stages at the same time in 2019 generally showed a continuous downward trend. This is because rainfall increases with seasonal changes, which leads to atmospheric NO_2 entering other environmental media under the influence of rainfall (Lee et al. 2012). The difference in atmospheric NO_2 pollution concentrations between 2020 and 2019 in the BTH region indicates that the emergency response mechanism caused by the COVID-19 epidemic was a significant factor in the change in the NO_2 concentration in the region. From a numerical perspective, the mass concentration of NO_2 in 2020 was lower than that in 2019 in both phase 2 and phase 3, and similar levels were gradually restored in phases 4 and 5. This indicates that the activation of emergency response level 1 had a significant reduction effect on the NO_2 mass concentration in the region.

It can be seen from Fig. 3 that in the northern winter heating season (i.e., phase 1 and phase 2), the SO_2 mass concentration was relatively high in the BTH region. In phase 3 (i.e., during emergency response level 1 and when people began to resume work), the mass concentration of SO_2 in the region remained at a low level, which was related to the end of heating activities in this stage and the reduction of industrial production. Studies have shown that the rapid decrease in the SO_2 mass concentration is often closely related to the sharp decrease in industrial activities (Wang et al. 2018). However, in phases 4 and 5, when the emergency response level dropped to level 2 or lower, the mass concentration of SO_2 in the region as a whole showed an upward trend, which was closely related to the general resumption of industrial production. It can be found that compared with other cities in the region, typical industrial cities (represented by Tangshan) experienced a greater increase in the SO_2 mass concentration, which also confirms the close relationship between the change in SO_2 mass concentration and industrial production. By comparing the changes of SO_2 in different phases at the same time in 2019 (Fig. 3), it can be seen that the SO_2 mass concentrations in the northern winter heating season (phases 1 and 2) were higher than those in the non-heating season, while the SO_2 mass concentration in phase 3 under normal production was generally higher than that in the same phase during the COVID-19 epidemic. This indicates that the shutdown during the COVID-19 epidemic had a significant impact on the reduction of the SO_2 concentration in the region. In addition, by comparing the SO_2 mass concentration in phase 4 of Tangshan city in 2019 and 2020, the SO_2 mass concentration in Tangshan city after the resumption of work in 2020 was significantly higher than that in the same period in 2019; this phenomenon belongs to the concept of "retaliatory growth."

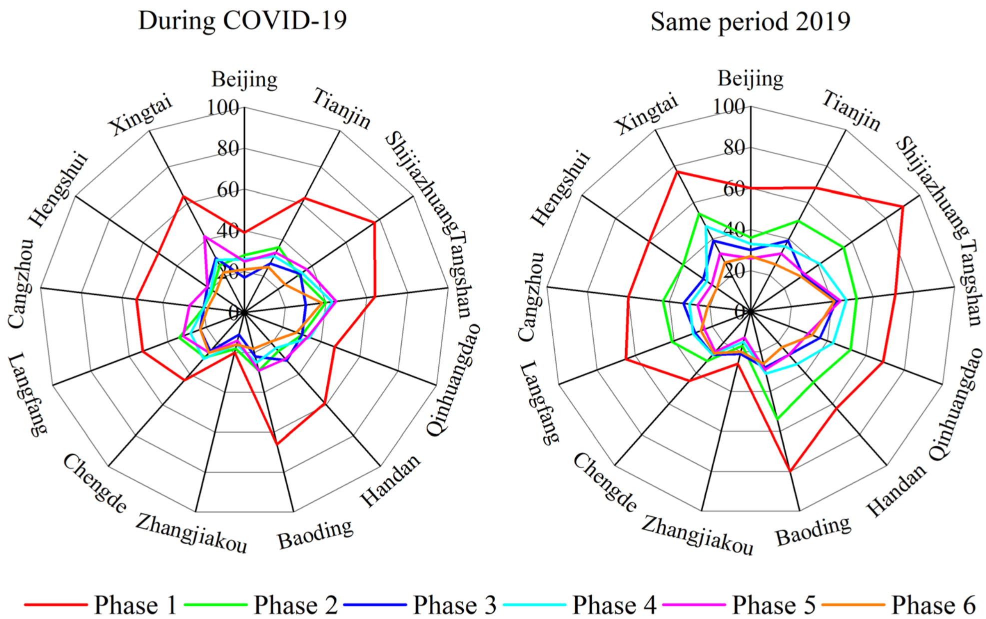

Fig. 2 NO_2 concentrations in the Beijing-Tianjin-Hebei (BTH) region during COVID-19 and the same period in 2019

Analysis of meteorological elements between COVID-19 and the same period in 2019

We collected the daily average wind speed, daily average temperature, and accumulated precipitation of several meteorological stations at different geographical locations in the BTH region during COVID-19 and the same period in 2019 (Fig. 4). The wind is a fundamental element for the dispersion, dilution, and orientation of pollutant plumes. Under high wind speed, the dispersion of the pollutant is greater, while in the lower wind speed is likely for air pollution accumulation (Sbai et al. 2021). High temperatures can function as catalysts for chemical processes of air pollutants (Wang et al. 2020). As can be seen from Fig. 4, the average wind speed and average temperature in each study phase during COVID-19 fluctuated somewhat compared with the same period in 2019, but the differences were not significant.

Air pollutants can be removed from the atmosphere by precipitation (Wang et al. 2020). By comparing the cumulative precipitation in the selected period during the 2 years, it can be found that the cumulative precipitation in 2020 is significantly higher than that in the same period in 2019. Increased precipitation is conducive to pollutant removal, so it is necessary to further clarify the contribution of increased precipitation to pollutant reduction during COVID-19. Table 2 lists the correlation coefficients between the daily precipitation and NO_2, SO_2 at each meteorological station during COVID-19 and the same period in 2019. It can be

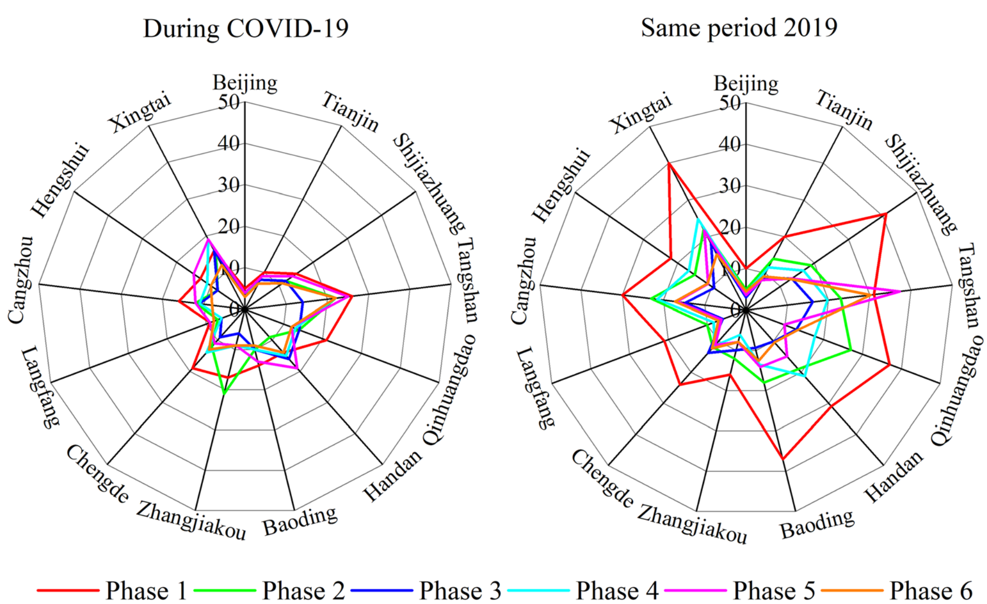

Fig. 3 SO_2 concentrations in the Beijing-Tianjin-Hebei (BTH) region during COVID-19 and the same period in 2019

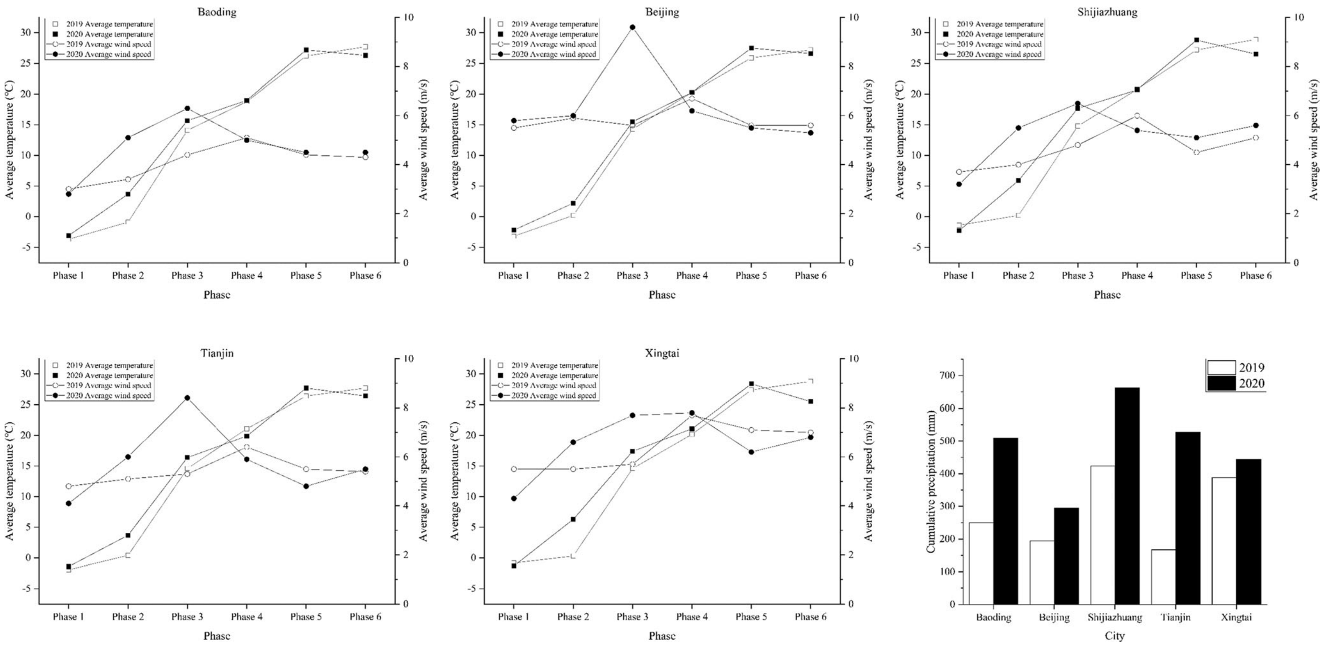

Fig. 4 Meteorological parameters in several meteorological stations at different geographical locations in the BTH region during COVID-19 and the same period in 2019

found that most of them are significantly negatively correlated, indicating that the concentration of NO_2 and SO_2 will decrease with the increase of precipitation. However, from the numerical point of view, the correlation coefficient is low and the correlation is weak. Compared with the significant decrease of NO_2 and SO_2 concentration during COVID-19, it can be said that the decrease of NO_2 and SO_2 concentration is related to the increase of precipitation to some extent, but the increase of precipitation is not the dominant factor.

Analysis of spatial distribution changes of NO_2 and SO_2 in different phases

The spatial distribution pattern of NO_2 pollution in the BTH region was characterized by being "high in the southeast and low in the northwest" in the six different phases during COVID-19, which is similar to the pollution distribution in the same period in 2019 (Fig. 5). The lowest value (4.2 $\mu g \cdot m^{-3}$) and the highest value (75.1 $\mu g \cdot m^{-3}$) of the NO_2 average mass concentration in phase 1 in 2020 were significantly lower than those in the same period in 2019 (22.9–89.6 $\mu g \cdot m^{-3}$). This is related to a series of actions that were taken to reduce NO_2 pollution in the region, such as phasing out of old cars, traffic restrictions, and the promotion of new energy vehicles. The average mass concentration of NO_2 in phase 2 of 2020 was significantly reduced, and the decrease was larger than that in the same period of 2019, indicating that the first-level emergency response control initiated by COVID-19 had a certain effect on reducing the mass concentration of atmospheric NO_2 in the region. Regarding the spatial distribution, there were less high-value pollution areas than during the same period 2019 and were mainly concentrated in coastal areas, indicating that transportation in most areas was significantly reduced at this stage and that the emergence of high-value pollution areas may be related to foreign trade transportation and small-scale industrial production. However, the average mass concentration of NO_2 in phase 3 (which is also under the first-level control of the emergency response) continued to decline, and the decline was larger than that in the same period of 2019, indicating that the relaxation of traffic control in the region under the first-level control of emergency response did not rapidly change the phenomenon, whereby the mass concentration of NO_2 in the region declined. From the spatial distribution of phase 3, the southern part of Hebei

Table 2 The correlation coefficients between the daily precipitation and SO_2 and NO_2 at each meteorological station during COVID-19 and the same period in 2019

City	Baoding		Beijing		Shijiazhuang		Tianjin		Xingtai	
Year	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
NO_2	−0.320**	−0.243*	−0.152	−0.041	−0.348**	−0.319**	−0.113	−0.211	−0.343**	−0.249*
SO_2	−0.260*	−0.318**	−0.212	−0.307**	−0.338**	−0.253*	−0.280*	−0.225*	−0.276*	−0.161

* At level 0.05(double tail), the correlation was significant. ** At level 0.01(double tail), the correlation was significant. n=77

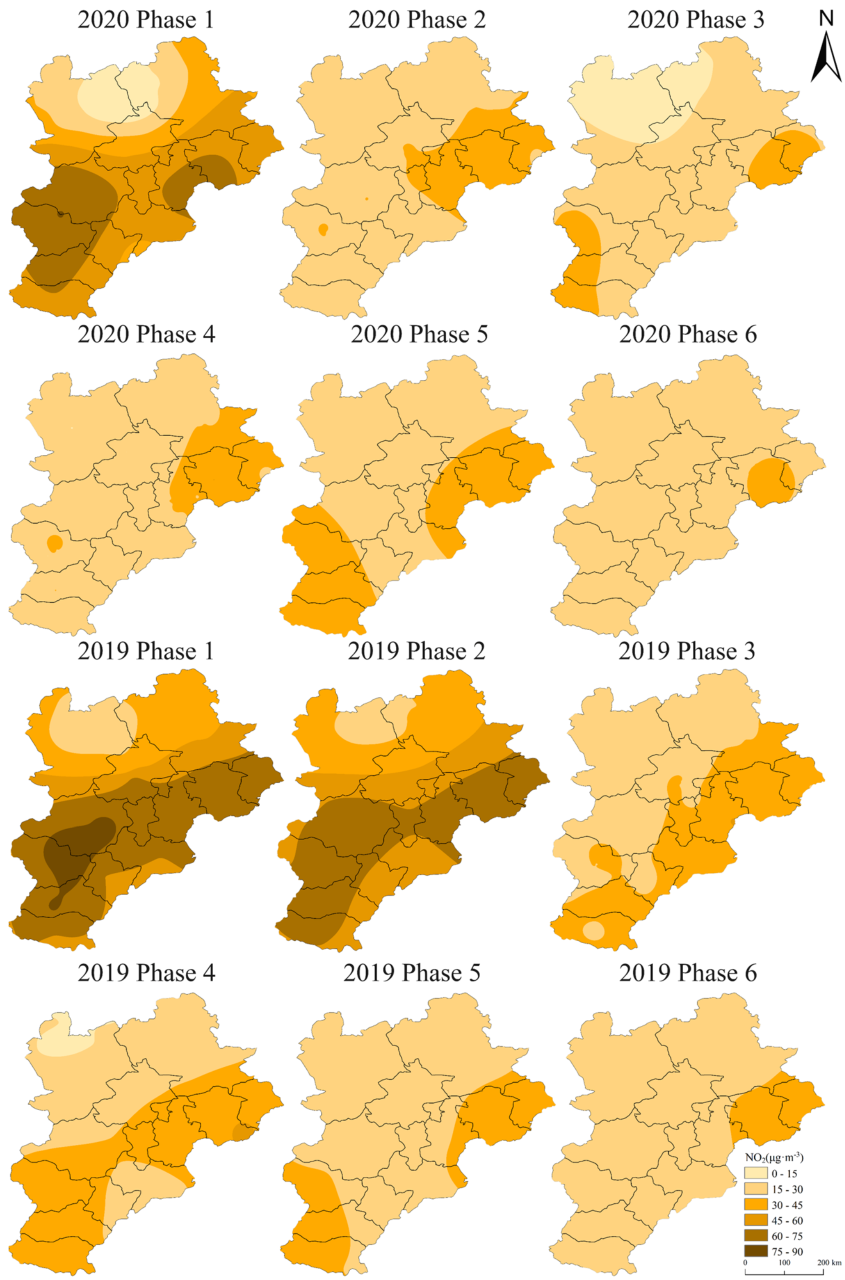

Fig. 5 Distribution of NO_2 pollution in the Beijing-Tianjin-Hebei (BTH) region during COVID-19 and the same period in 2019

also became a high-value region, which may be related to the relaxation of local control caused by the regional resumption of work and production.

Starting from phase 4, the NO_2 pollution mass concentration in the BTH region recovered to a level similar to that in the same period of 2019. However, combined with the difference in NO_2 mass concentration between 2020 and 2019 in phase 1, which was not affected by the epidemic, this indicated that the NO_2 mass concentration in phase 4 of 2020 in the BTH region increased abnormally. This change may be related to the “retaliatory” resumption of production and the relaxation of traffic control within the region. The difference in the NO_2 mass concentration in phases 5 and 6 over the 2 years was similar to that in phase 1 (which was not affected by the epidemic), indicating that secondary and lower emergency response mechanisms had limited influence on the change in the NO_2 pollution mass concentration in the region.

Figure 6 shows the change of the monthly average concentration of NO_2 column in the troposphere over the BTH region during COVID-19 and the same period in 2019 based on OMI satellite data. The black box in the figure indicates the location of the study area. It can be found that, similar to the monitoring results at ground stations, the concentration of NO_2 in the BTH region during COVID-19 was significantly lower than that in the same period in 2019 and recovered to a similar level after May.

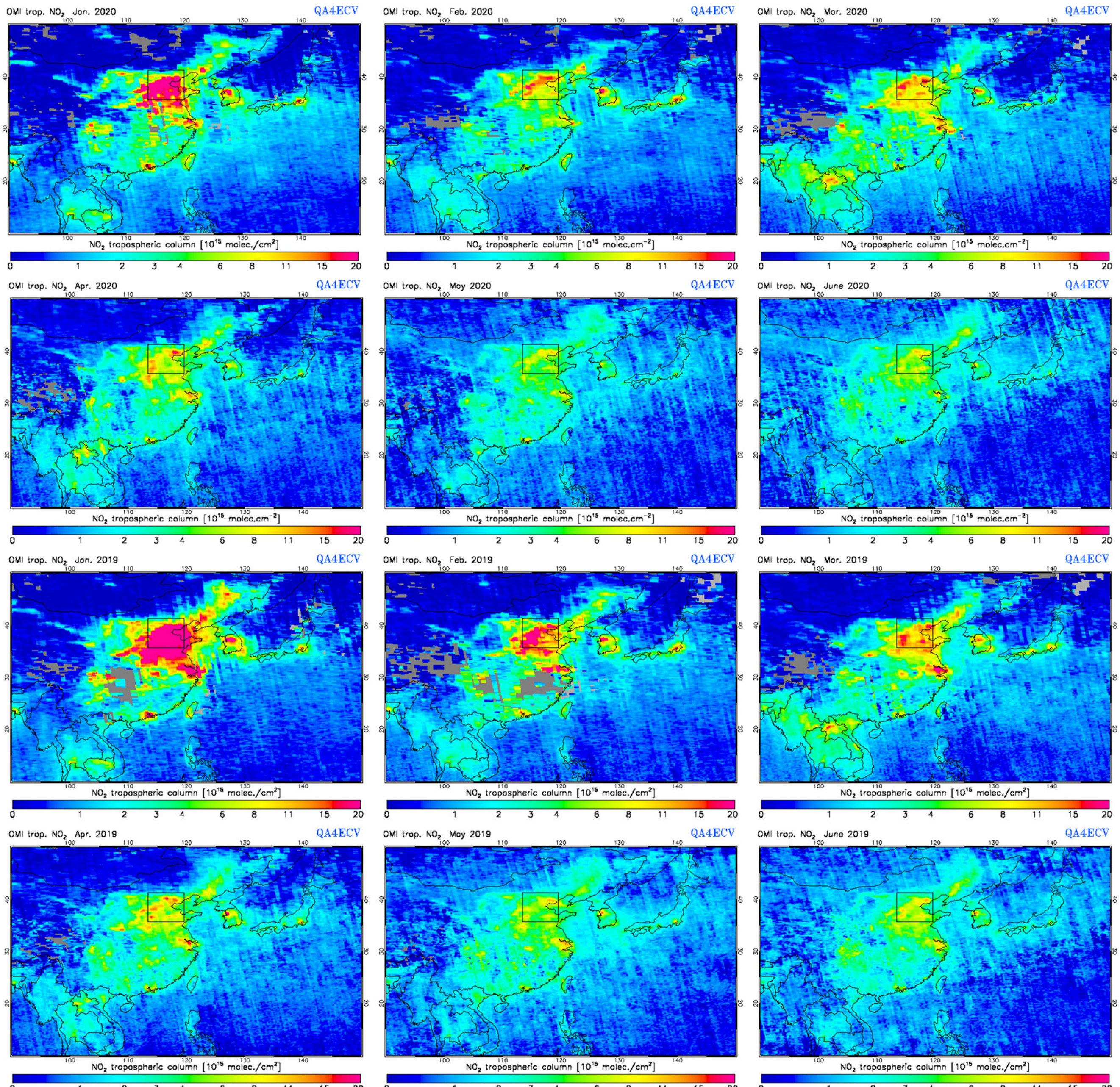

Fig. 6 Distribution of the monthly average concentration of NO_2 column in the troposphere over the BTH region during COVID-19 and the same period in 2019 based on OMI satellite data

In the six different phases during COVID-19, the focus of SO_2 pollution in the BTH region was the southern and eastern parts of Hebei, and the level of SO_2 pollution in the Beijing–Tianjin region remained at a low level, which was similar to the pollution distribution in the same period in 2019 (Fig. 7).

From a numerical perspective, compared with the same period in 2019, SO_2 pollution in phase 1 decreased, and high-value polluted areas significantly decreased, which was related to a series of pollution control, coal suppression, and sulfur control actions in the region. In phase 2, the pollution level of SO_2 decreased, and the difference between the same period of phase 2 and 2019 was smaller than that between the same period of phase 1 and 2019, indicating that the mass concentration of SO_2 pollution in the BTH region actually increased at this stage. Regarding the spatial distribution, the high-value pollution areas were more dispersed than in the same period 2019. In the second phase of the COVID-19 outbreak, when the Traditional Chinese Spring Festival was taking place, the first-level emergency

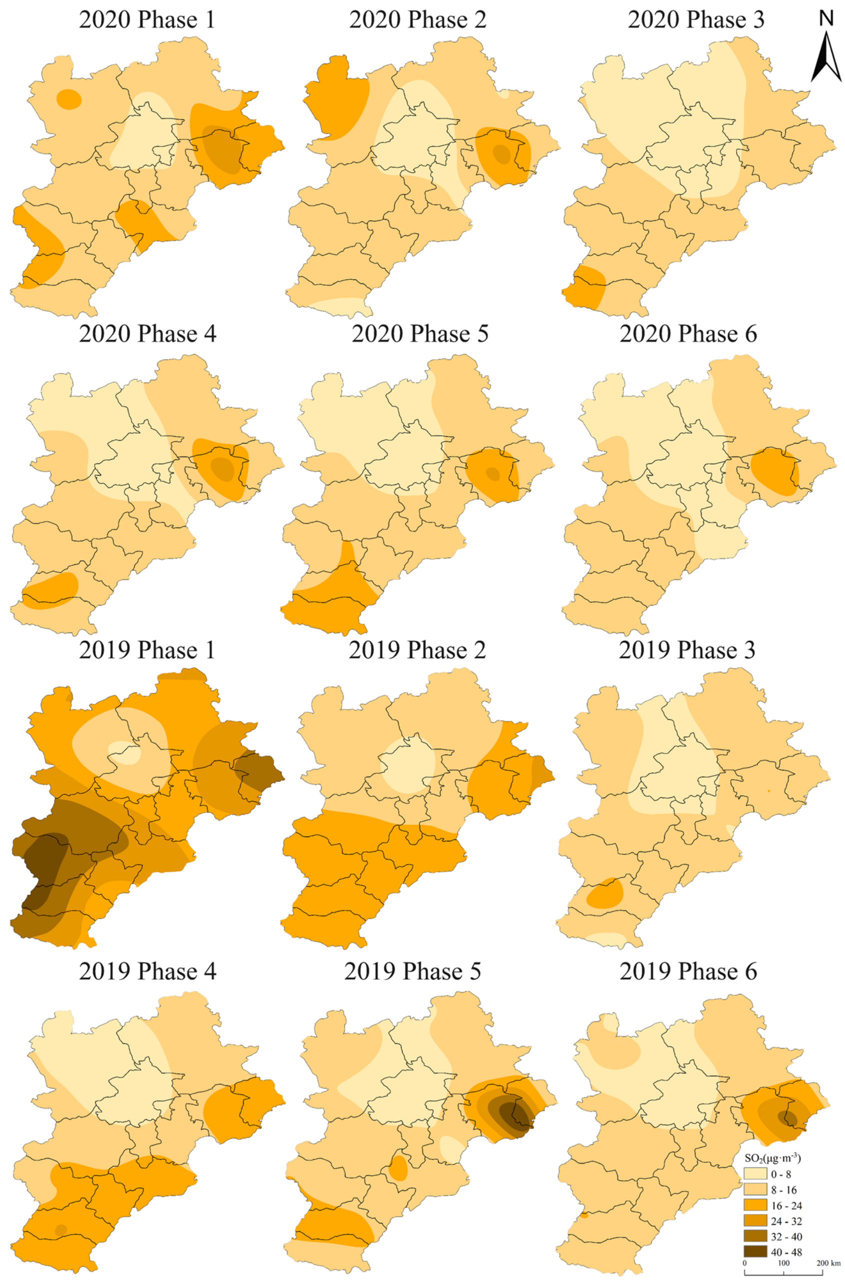

Fig. 7 Distribution of SO_2 pollution in the Beijing-Tianjin-Hebei (BTH) region during COVID-19 and the same period in 2019

response was launched in the BTH region. During this period, industrial production activities were significantly reduced. In this phase, the increase in SO_2 pollution may be inseparable from the increased emissions from living sources caused by people remaining at home due to the COVID-19 outbreak, such as the contribution of dispersed coal burning in urban and rural areas. Phases 3 to 6 were non-heating seasons, in which industrial production activities became the main contribution source of SO_2 in the region. In phase 3, the SO_2 pollution level continued to decline, indicating that industrial production activities in this stage remained low. In phase 4, SO_2 pollution increased significantly and was higher than that in the same period in 2019. With the reduction of the emergency response level and extensive resumption of work and production in this phase, a "retaliatory increase" was caused by the long-term shutdown of the epidemic. Comparing phases 3 and 4 also showed that the recovery effect of the change in the single traffic control policy on industrial production in the region was weaker than the adjustment of the comprehensive policy of the emergency response mechanism. Meanwhile, the SO_2 pollution concentrations in the BTH region in phases 5 and 6 also decreased and were significantly lower than that in the same period in 2019. The emergence of this phenomenon may be closely related to the decline in industrial production orders caused by the severe external epidemic.

Analysis of the causes of SO_2 and NO_2 concentration reduction scenarios during COVID-19

The above analysis results show that the COVID-19 epidemic scenario had a significant impact on the changes in atmospheric NO_2 and SO_2 pollution concentration in the BTH region. However, it is still necessary to analyze the emission reduction causes of gaseous pollutants in this complex scenario so as to determine the main contributor of gaseous pollutants in the region, namely, the focus of pollution control. As for source analyses of atmospheric pollutants, the research methods mainly focus on component analysis (Garbariene et al. 2020) and model analysis (Bai et al. 2021). In addition, through the induction and analysis of social development data in the research area (e.g., relevant data of economy, road traffic transportation, and industrial production) and comparative analysis of the changes in the pollutant mass concentration, the causes of pollutant emission reduction can also be explored.

Analysis of the change of output of major above-scale industrial products

The output of major products of industries above a certain scale in a region can be used to reflect the situation of local industrial production. In this study, the production status of industrial industries that generate high air pollution above the scale in the BTH region was selected and counted (note: data for Tianjin and Hebei are missing in some months), including the steel industry (Tang et al. 2020), the cement industry (Hua et al. 2016), and the aluminum industry (Liu and Wang 2014). In addition, statistics were also analyzed on the output above the scale of the automobile industry in the BTH region. Although SO_2 and NO_2 pollution emissions in automobile manufacturing are not considered serious, statistics were also analyzed on pollution in the upstream industry, which is considered quite serious.

As can be seen from Fig. 8, although affected by the epidemic, output above a certain scale of major products of various industries was reduced; however, the production status was not stopped. Overall, industrial production in the BTH region decreased significantly during the epidemic period and gradually recovered, which was consistent with the changes in NO_2 and SO_2 pollution in the BTH region during the epidemic period, and industrial production contributed significantly to air pollution (Sun et al. 2019). It can be seen that through the production reduction and control of some polluting industries in industrial production, the concentrations of NO_2 and SO_2 pollution in the region can be effectively reduced.

Analysis of the growth rate of industrial added value above scale

As can be seen from the previous section, the changes in industrial production in the BTH region during the COVID-19 epidemic were similar to the changes in NO_2 and SO_2, which is consistent with the argument in existing studies that industrial emissions are the main sources of NO_2 and SO_2 pollution in the BTH region (Qi et al. 2017). In order to better understand the impact of industrial sources on NO_2 and SO_2 pollution in the BTH region, the contribution of each source of pollution can be further analyzed from the perspective of industry. Existing research shows that the industrial sources of SO_2 and NO_x emissions in the BTH region are most concentrated in four industries, including the ferrous metal smelting and calendar processing industry, electricity thermal production and supply industry, non-metallic mineral products industry, chemical raw materials, and chemical products manufacturing industry (Zhang et al. 2017). The four industries of NO_2 and SO_2 emissions accounted for approximately 90% of all industrial emissions in the BTH region. The spatial distribution of pollution emission concentrations of the four major industries is shown in Table 3. The key pollution emission concentration area of an industry is the region where industrial pollution emission is dominant in the region.

As can be seen from Fig. 9, before and after the COVID-19 epidemic, the year-on-year growth rate of industrial added value of electricity thermal production and supply industry in Beijing, Tianjin, and Hebei Province fluctuated slightly around 0%, indicating that the industry's contribution to the change in industrial source pollution emissions in the BTH region during the COVID-19 epidemic was not significant. The year-on-year growth rates of industrial added value of ferrous metal smelting and the calendar processing industry in Hebei province were positive and were significantly higher over the same period in 2019, which was inconsistent with the change in pollution during this period. This indicated that the ferrous metal smelting and rolling processing industry did not contribute significantly to the change in industrial source pollution emissions in the BTH region during the COVID-19 epidemic.

During this period, the year-on-year growth rates of industrial added value of chemical raw materials and chemical products manufacturing industries in Tianjin and Hebei Province and the non-metallic mineral products industry in Hebei Province all showed negative growth and gradually increased with the reduction of the control degree during the epidemic. This is consistent

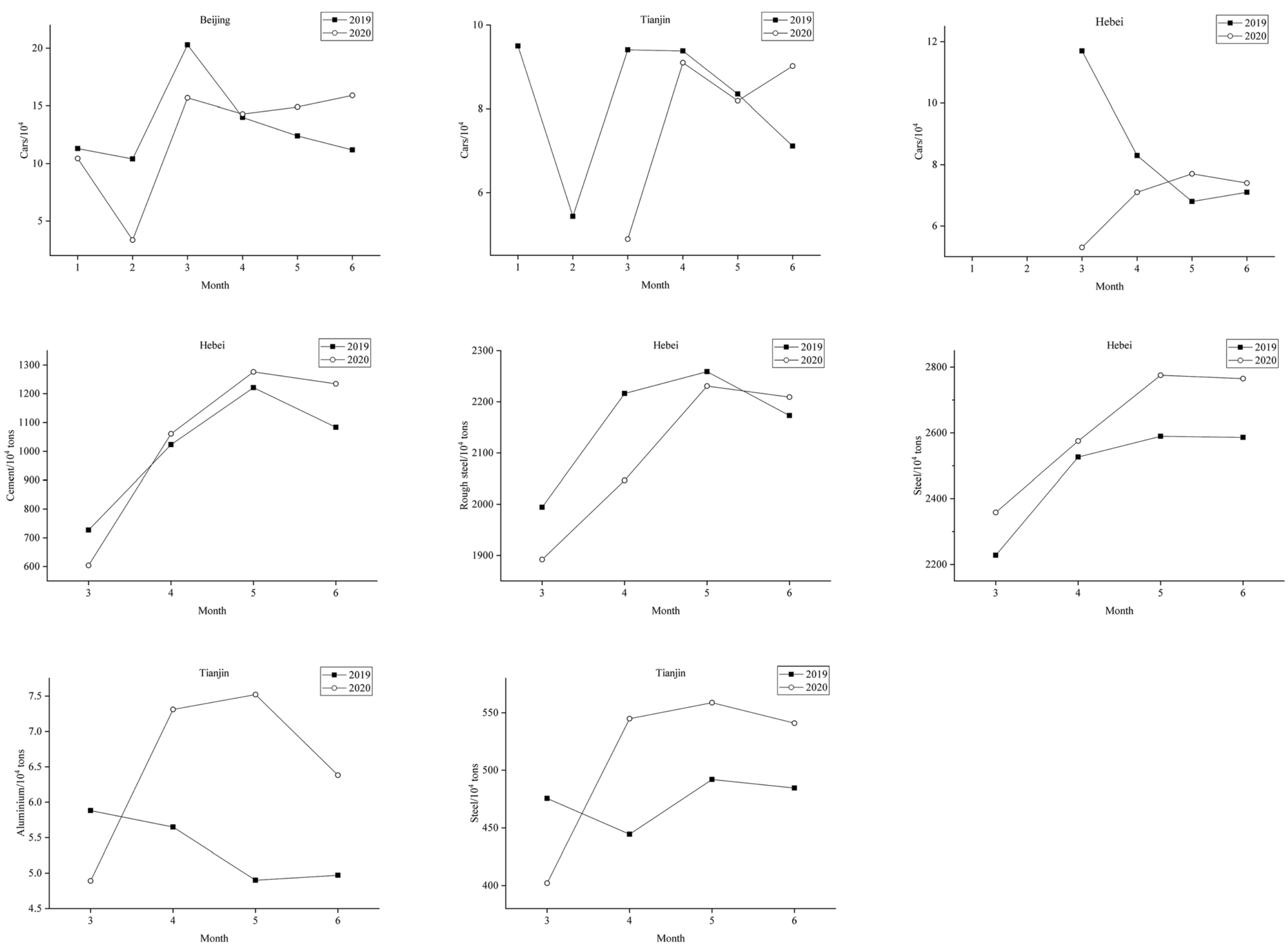

Fig. 8 Changes in above-scale industrial output in the Beijing-Tianjin-Hebei (BTH) region during COVID-19 and the same period in 2019

with the change trend of SO_2 and NO_2 pollution in the BTH region during the same period, indicating that the manufacturing of chemical raw materials and chemical products and the non-metallic mineral products industry made a significant contribution to the change in industrial source pollution emissions in the BTH region during the COVID-19 epidemic.

Analysis of road traffic changes

As can be seen from the previous section, the control caused by COVID-19 may have influenced NO_2 pollution in the BTH region by influencing transport, which is consistent with existing studies that argue that road traffic emissions are an important contributor (i.e., accounting for approximately 30%) to NO_2 pollution in the region (Qi et al. 2017). In order to better understand the impact of road transport on NO_2 pollution in the BTH region, further analysis can be made from the statistical data.

Business road transport and business road freight, as important indexes in the statistics of local departments, can be used to reflect changes in local road traffic. As can be seen from Fig. 10, the business road transport and business road freight of Beijing, Tianjin, and Hebei in 2020 during the outbreak of the epidemic were generally reduced compared to the same period in 2019, and the degree of difference varied among different regions. In February and March, when the epidemic was most severe and the emergency response level

Table 3 Distribution of NO_2 and SO_2 pollution emission regions in four industries in the Beijing-Tianjin-Hebei (BTH) region

Industry	Key pollution emission concentration area
Ferrous metal smelting and calendar processing industry	Hebei
Electricity thermal production and supply industry	Beijing; Tianjin; Hebei
Non-metallic mineral products industry	Hebei
Manufacturing of chemical raw materials and chemicals	Tianjin; Hebei

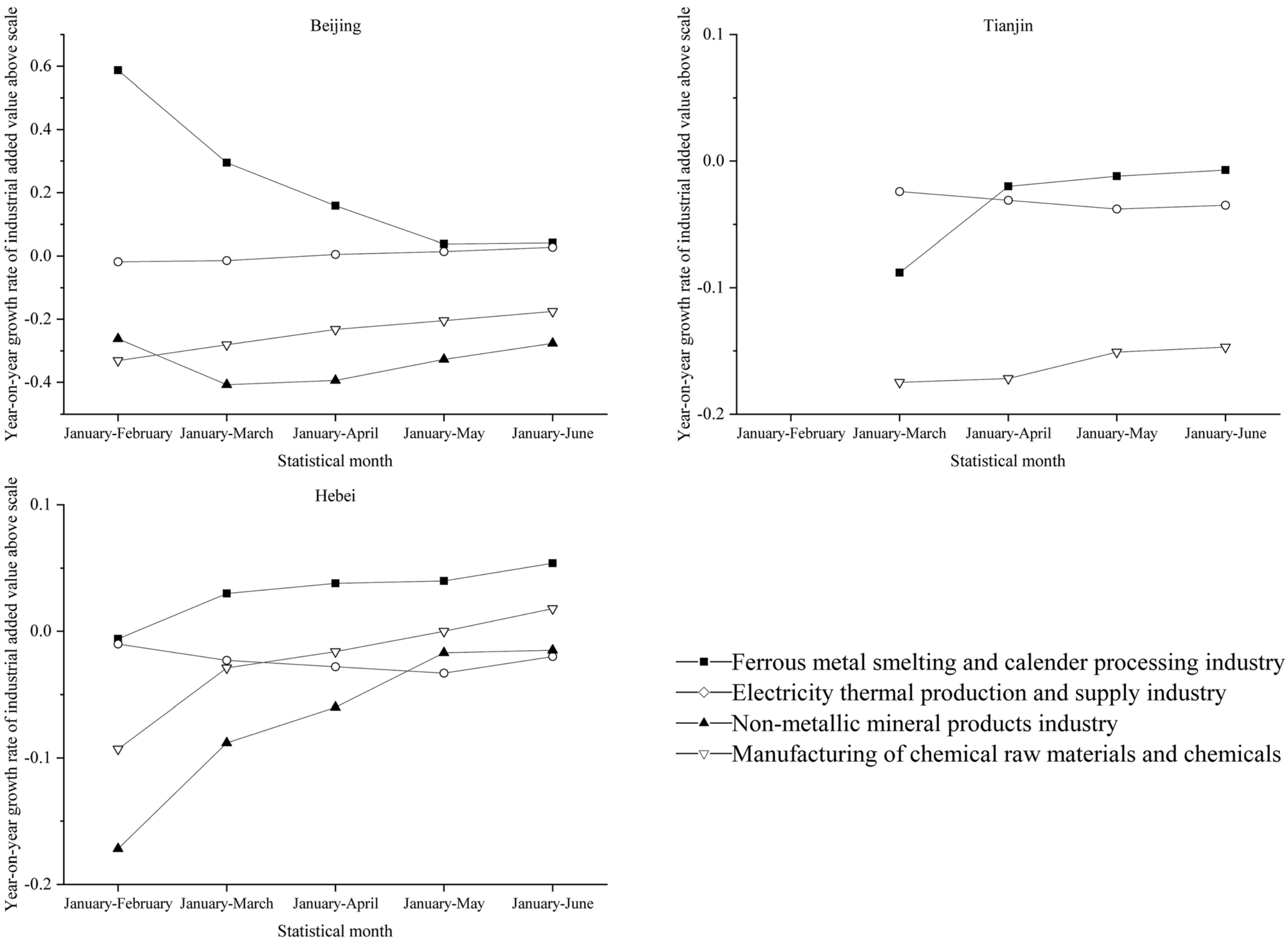

Fig. 9 Year-on-year growth rate of industrial added value above scale in the Beijing-Tianjin-Hebei (BTH) region during COVID-19

in the BTH region was at level 1, the road traffic volume in the BTH region dropped to its lowest point and began to gradually increase after March. Perhaps more notable is that the business road freight of Beijing increased to a higher level than that of the same period of 2019 after March 2020, which may be related to the fact that Beijing (as an important hub in the northern region) had assumed more functions as the transportation center of freight transportation. Overall, the road traffic volume in the BTH region showed an obvious change of first decreasing and then increasing during the COVID-19 epidemic. This is consistent with the variation trend of the NO_2 mass concentration in the BTH region, indicating that road traffic emissions remained an important source of NO_2 emissions in the region during this period. Hence, it can be seen that NO_2 emission reduction can be effectively achieved by controlling road traffic transportation.

Conclusion

This study analyzed the characteristics of NO_2 and SO_2 changes at different stages under the COVID-19 emission reduction scenario in the BTH region to provide an effective reference for the selection of air pollution control measures and the formulation of air pollution control policies. A “multi-angle” analysis method was adopted to analyze the causes of pollution changes. In addition to the intuitive analysis method based on the analysis of air NO_2 and SO_2 data changes in the BTH region, the causes of pollution changes were analyzed in combination with industrial production and transportation data. The conclusions are as follows:

First, influenced by the epidemic, the concentrations of NO_2 and SO_2 pollution in the BTH region decreased significantly during the epidemic period. The spatial distribution pattern of NO_2 pollution in the BTH region was consistently “high in the southeast and low in the northwest,” and SO_2 pollution in the BTH region was consistently higher the southern and eastern parts of Hebei.

Second, the initiation of emergency response level 1 had an obvious effect on reducing NO_2 and SO_2 pollution in the region, while the impacts of emergency response level 2 and below were limited. Compared with the single traffic control, the comprehensive control

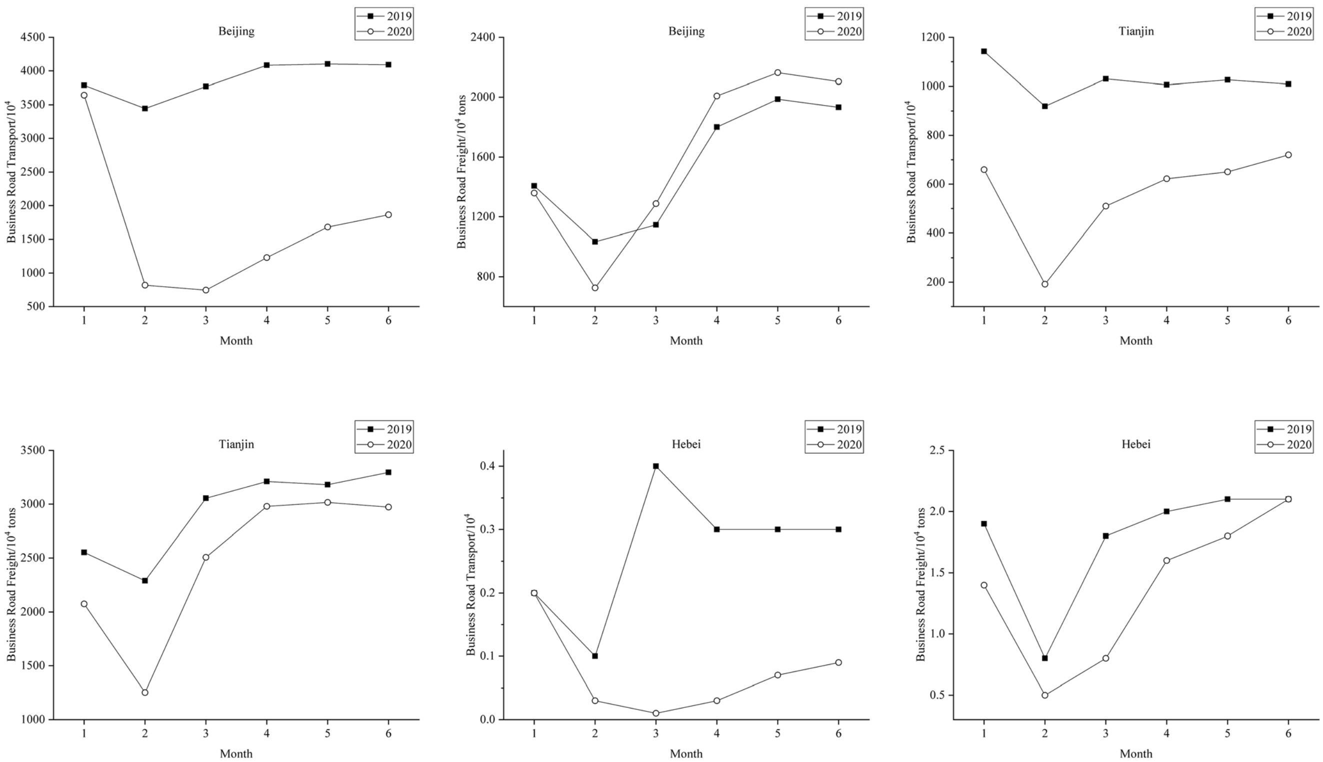

Fig. 10 Changes in transport volume in the Beijing-Tianjin-Hebei (BTH) region during COVID-19 and the same period in 2019

similar to emergency response had a better effect on reducing NO_2 pollution in the region. The control of major large cities in the region also had a certain effect on alleviating NO_2 and SO_2 pollution across the entire region. Moreover, for activities under short-term control, it is particularly important to guard against the "retaliatory growth" after controls are lifted.

Third, through the analysis of above-scale industrial production in the BTH region, it was found that industrial production initially obviously declined and then gradually recovered during the epidemic period. Evidently, by reducing and controlling some polluting industrial production industries, the degree of NO_2 and SO_2 pollution in the region can be effectively reduced. Changes in the NO_2 and SO_2 pollution emission industries in the BTH region during the epidemic period were analyzed in detail, which showed that the manufacturing industry of chemical raw materials and chemical products and the non-metallic mineral products industry made considerable contributions to the change of industrial source pollution emissions in the BTH region during the COVID-19 epidemic.

Finally, further analysis of the change of road traffic volume in the BTH region showed that the road traffic volume in the BTH region had an obvious change of first decreasing and then increasing during the epidemic period. This is consistent with the change trend of the NO_2 concentration in the BTH region, indicating that road traffic emissions remained an important source of NO_2 emissions in the BTH region during this period. It can be seen that effective NO_2 emission reduction can be achieved through control of road traffic and transportation.

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Data availability The atmospheric NO_2 and SO_2 data used in this study are available at http://106.37.208.233:20035/. Meteorological data are available at https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily. The tropospheric NO_2 column concentration data used in this paper are available at http://www.temis.nl. The output data of major industrial products above scale and the growth rate of industrial added value above scale in the BTH region are available at http://tjj.beijing.gov.cn/tjsj_31433/yjdsj_31440/gy_31782/2020/index.html, http://stats.tj.gov.cn/TJTJ434/SJCX629/, and http://tjj.hebei.gov.cn/hetj/tjsj/sjcx/101583911125077.html. Transportation data are available at http://tjj.beijing.gov.cn/tjsj_31433/yjdsj_31440/ysyd_31830/2020/index.html, http://jtys.tj.gov.cn/Page/InfoListPage_index.aspx?NCode=1705, and http://jtt.hebei.gov.cn/jtyst/zwgk/jcxxgk/jttj/zhtjfx/.

Declarations

Competing interest The authors declare no competing interests.

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