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Key Points:

- Significant air pollutant changes during and after the lockdown implies that emission is still the primary driver of nationwide air pollution
- Ozone showed rapid growth of about 60% across the country during the lockdown
- Southeast Asia wildfires caused an abnormal increase in carbon monoxide (CO) and particulate matter (PM) in southwest China

Supporting Information:

Supporting Information may be found in the online version of this article.

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The Role of Primary Emission and Transboundary Transport in the Air Quality Changes During and After the COVID-19 Lockdown in China

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Abstract In late January 2020, China's rapid and strict control measures to curb the COVID-19 spread led to a sharp halt in socio-economic activity and a significant reduction in emissions. Using the ground-based observational data, the authors synergistically quantify the nation-wide variations of major air pollutant as well as meteorology during and after the lockdown. Their concentrations (except O₃) exhibited significant reduction during February and March 2020, by more than 24% during the lockdown compared with the earlier time period and by more than 17% compared with that in the same period in 2019. In contrast, ozone increased rapidly by about 60% across the country during the lockdown. Abnormal increases in carbon monoxide and particulate matter concentrations in southwest China are attributed to the severe wildfires in Southeast Asia. The concentration of air pollutants bounced back rapidly after the full-scale reopen in March 2020, indicating the decisive role of emissions in the pollution formation.

Plain Language Summary Previous studies have reported unexpected increases in air pollution over certain region during the first few weeks of the pandemic in China, due to strong modulation from meteorological variations and complex atmospheric chemistry. Here, we show that on the national scale, the major air pollutants (other than ozone [O₃]) still exhibited significant reduction between February and March 2020. The concentration of major pollutants fell by more than 24% during the lockdown period compared with that before the lockdown and by more than 17% compared with that in the same period in 2019. In contrast, ozone showed rapid growth of about 60% across the country during the lockdown, which underscores the importance of coordinated management of PM (particulate matter) and O₃. The concentration of air pollutants bounced back rapidly after March 2020. We also find increases in CO and PM concentrations in southwest China due to abnormal wildfires in Southeast Asia, revealing the nonnegligible influence of transboundary transport of pollutants in the regional scale.

1. Introduction

The sudden outbreak of COVID-19 has exerted severe socio-economic impacts on China (Le et al., 2020; Tian et al., 2020). Wuhan, a major transportation hub in central China, was the first city to be put under lockdown on January 23, 2020, in an effort to prevent the spread of the virus ahead of the Chinese Lunar New Year. Since then, other Chinese provinces and cities have implemented lockdown measures to prevent the spread of the virus. The duration of the lockdown varies slightly across China, but the restrictions on economic activity, industrial production, and transport during this period are unprecedented in terms of uniformity and consistency (Le et al., 2020; Sun et al., 2020).

In the past few decades, China's rapid economic development has been accompanied by serious air pollution, which has become a social and environmental concern (An et al., 2019; Li et al., 2017; Wang et al., 2020). In an effort to curb air pollution and protect public health, China has launched its strictest series of air pollution control measures since 2013, and the air quality has improved significantly (Wang et al., 2020; Zhang et al., 2020). By 2017, the annual average PM_{2.5} concentration has decreased from ~61.8 to 42.0 μg m⁻³ in 5 years (Zhang et al., 2019). Compared with 2014, the annual mean concentrations of CO, NO₂, SO₂, PM₁₀, and PM_{2.5} decreased by about 25, 20, 52, 20, and 28%, respectively in 2018 (Fan, et al., 2020). All those results

lend support to the notion that the reduction of anthropogenic emissions is likely the main reason for the improvement of air quality in China (Fan et al., 2020; Guo et al., 2020; Zhang, Zheng, et al., 2019). However, recent studies have shown that emission control did not prevent ozone from increasing its quantity (Li et al., 2019a, 2019b; Liu & Wang, 2020).

COVID-19 is still widely spreading worldwide, and many countries and regions have adopted control measures. The lockdown essentially serves an unintended experiment, which could effectively distinguish the difference in air quality between the lockdown period and the original emission scenario and facilitate researchers to analyze the changes in air quality caused by emission reduction during the special period. Studies of changes in air quality during outbreaks have been conducted in several countries (Venter et al., 2020), including the United States (Bashir et al., 2020), Spain (Tobías et al., 2020), Italy (Conticini et al., 2020), and China (Chang et al., 2020; Shi & Brasseur, 2020; Sun et al., 2020), with the focus mostly on NO₂ or SO₂. In China, previous studies have analyzed the air quality changes during the lockdown period (Fan, et al., 2020; Zhang et al., 2021; Zhao, et al., 2020), by focusing on typical regions in eastern China (Huang, Ding, et al., 2020; Miyazaki et al., 2019) or a single city (Lian et al., 2020). These studies have emphasized the increase in O₃ (Huang et al., 2020; Shi & Brasseur, 2020), the formation of secondary aerosols (Huang, Ding, et al., 2020), and the contribution of biomass burning (Metya et al., 2020) leading to a regional increase in air pollutants. As known, China is the country with the earliest outbreak and control of the epidemic (Tian et al., 2020), has gradually restarted economic activities. Therefore, it is necessary to comprehensively analyze the changes of near-surface air pollutants on the larger spatial and temporal scales.

In this study, we used the latest ground-based air pollutant data and reanalysis data, as well as backward trajectory simulation to quantitatively investigate the variation characteristics of six air pollutants throughout the COVID-19 outbreak, which indicated that the main cause of changes in air pollution in China is still emissions.

2. Data and Methods

2.1. Study Period Division

This study sets China's COVID-19 lockdown period is from January 26 to March 5, 2020 (referred to as period III), a total of 40 days. The setting was based on the fact that on January 26, 2020, epidemic prevention and control had been in place across the country, and pollutant concentrations had begun to plummet. On March, 2020, the State Council officially issued a circular on precisely and steadily promoting the resumption of work and production of enterprises (<http://www.gov.cn/index.htm>). As a comparison, we take the 40 days before the lockdown, namely from December 17, 2019 to January 25, 2020, as period II. At the same time, we take the corresponding COVID-19 lockdown period from January 26 to March 5, 2019 as period I. It should be noted that the concentrations of major air pollutants (except O₃) in China decreased year by year from 2014 to 2018 (Fan, Zhao, & Yang, 2020), since China has achieved significant improvement in air quality associated with the air pollution control. Therefore, we prefer not to take the average of air pollutants for previous years as a reference, as it will interfere with the emission reduction effect brought by the lockdown period in this study. Previous studies have described the pollution and meteorological characteristics of the Chinese New Year (CNY) from 2015 to 2019 (Gong et al., 2014; Le et al., 2020; X. Wang & Zhang, 2020), and we did not repeat those efforts in this study. Meanwhile, we acknowledge that the reduction in air pollutants could be partially attributed to the reduced anthropogenic emissions associated with CNY, while exact contribution amount is beyond the scope of current study.

2.2. Ground Station Observations

The distribution of monitoring stations from 367 cities used in this study is shown in Figure S1. Hourly air quality data of PM_{2.5}, PM₁₀, O₃, NO₂, CO, and SO₂ were obtained from the website of Ministry of Ecology and Environment of the People's Republic of China (<http://www.cnemc.cn/en/>). It should be noted that in this study, the O₃ metric we used is the maximum daily 8-h average ozone concentration (O₃MDA8). The measurement method of air quality variables follows the national standard GB 3095-2012 (http://english.mee.gov.cn/Resources/standards/Air_Environment/quality_standard1/201605/t20160511_337502.shtml). PM_{2.5} was measured by β-ray absorption method and micro-oscillation balance method. NO₂, SO₂, and O₃

were determined by chemiluminescence, ultraviolet fluorescence, and ultraviolet absorption methods, respectively. CO was determined by non-dispersive infrared absorption method and gas filter correlation infrared absorption method. All the original data in this study have passed strict quality control (Table S1). According to existing research (Le et al., 2020), it is known that monitoring stations are often set up to avoid tall buildings and other obstructions that may impede air flow.

2.3. Reanalysis Data

We used the ERA5 reanalysis data set of the fifth-generation European Center for Medium-Range Weather Forecasts (ECMWF). Variables include planetary boundary layer (PBL) height, precipitation, and wind at 10 m above the ground. The spatial resolution is $0.25^\circ \times 0.25^\circ$. The ERA5 reanalysis data ingests more data sources, uses an updated numerical weather prediction model and data assimilation system and is widely used (ECMWF, 2018; Rohrer et al., 2020). CO, PM_{2.5}, and PM₁₀ emissions from biomass burning are provided by the Global Fire Assimilation System (GFAS). GFAS uses fire radiative power observations from NASA's Terra MODIS and Aqua MODIS active fire products to estimate daily emissions with a horizontal resolution of 0.1° (Kaiser et al., 2012).

2.4. HYSPLIT Model and Simulations

The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model has been widely used in air pollution and air mass trajectory tracking research around the world (Chen & Luo, 2018; Jana et al., 2018). In this study, the NOAA HYSPLIT Model was used to help analyze the increase of pollution in southwest China. The meteorological data of mode operation is the GDAS $1^\circ \times 1^\circ$ product provided by the National Centers for Environmental Prediction (NCEP). Kunming, the capital of Yunnan Province, was selected as the simulation site. The height of the simulated backward trajectory was 500 m, and the 3-day (72 h) backward trajectory upon arrival at the sampling point was calculated. The HYSPLIT Model was run for the entire period III, with analog output made every 3 h, and analog results are finally clustered and summarized.

2.5. Normalized Difference Calculation

In this study, the calculation of the difference between meteorological variables and pollutant concentration was normalized. The specific formula is as follows:

$$\Delta III - I = 100 \times (III_{obs} - I_{obs}) / I_{obs} \quad (1)$$

$$\Delta III - II = 100 \times (III_{obs} - II_{obs}) / II_{obs} \quad (2)$$

where $\Delta III - I$ represents meteorological or pollutant concentration differences between periods III and I, $\Delta III - II$ represents meteorological or pollutant concentration differences between periods III and II, and I_{obs} , II_{obs} , and III_{obs} represent meteorological variables or pollutant concentrations in the first, second, and third periods, respectively.

3. Results and Discussion

3.1. The Nationwide Concentration of Pollutants Changed Dramatically

Based on the latest ground-based observation data at 367 Chinese cities (Figure S1), we found that the national mean concentrations of PM_{2.5}, PM₁₀, NO₂, SO₂, and CO decreased to different degrees after around January 25, 2020 (Figure 1). This period coincided with the 2020 Spring Festival holiday, when an emergency halt to economic activity, industry, and transport has sent China's air pollution plummeting (Le et al., 2020; Shi & Brasseur, 2020). This result is similar to the variation trend of pollutant concentration obtained by satellite in relevant studies (Chang et al., 2020; Le et al., 2020; Sun et al., 2020).

Figure 1a shows that after the lockdown was implemented, PM_{2.5} concentration decreased to below $60 \mu\text{g m}^{-3}$ and remained below this value thereafter. For NO₂, SO₂, and CO, there was a similar downward trend. The reduction of these pollutants was attributed to the reduction of industrial activities and transportation

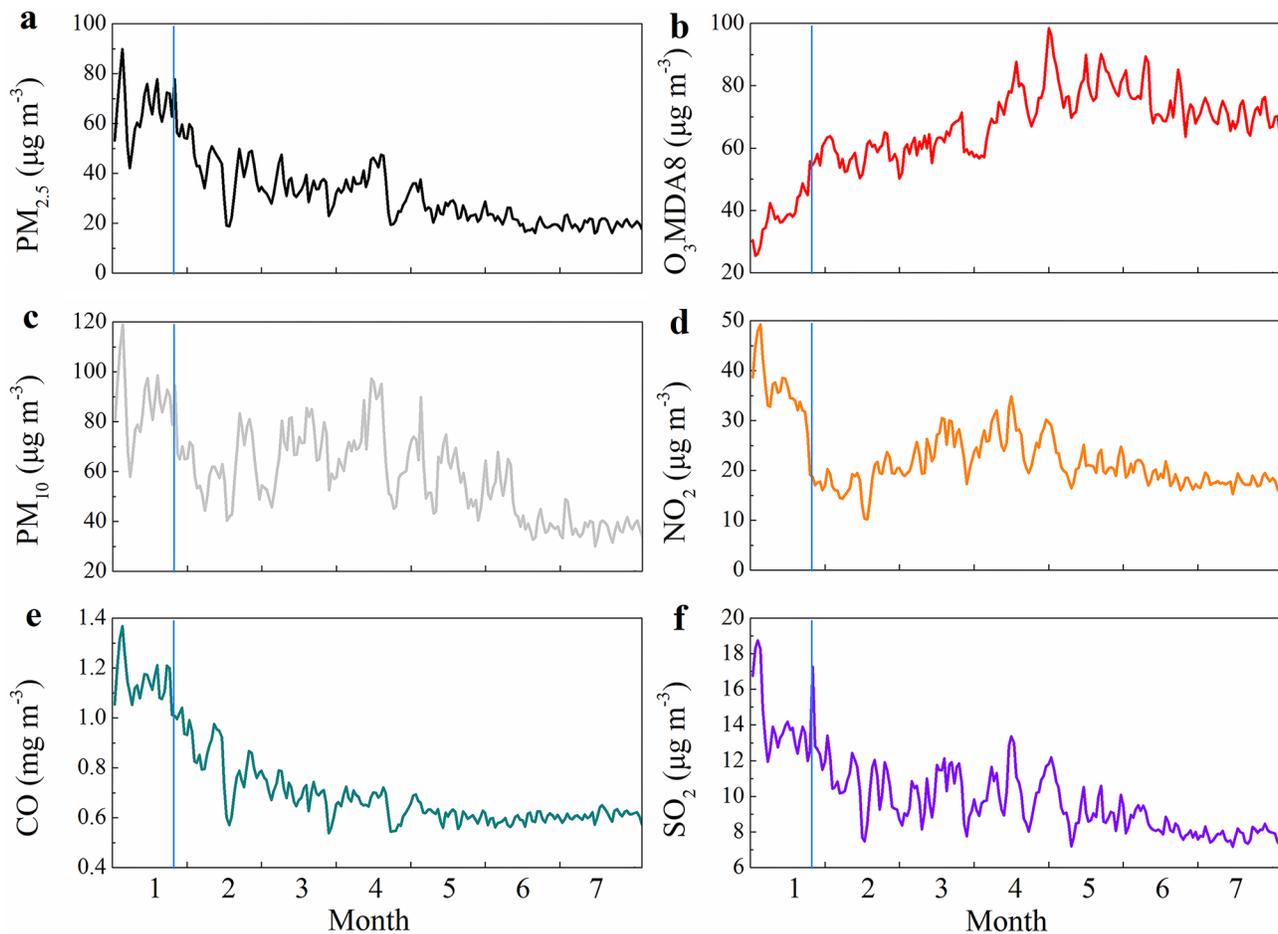


Figure 1. Evolution of the mean concentration of $\text{PM}_{2.5}$, $\text{O}_3\text{MDA8}$, PM_{10} , NO_2 , CO , and SO_2 in China from January 1, 2020 to July 31, 2020. All air pollutant data here are averaged over a whole nation. The blue vertical segment represents January 25, 2020, after which the pollutant concentration changes dramatically. It should be noted that the unit of CO is mg m^{-3} and other pollutants are $\mu\text{g m}^{-3}$. $\text{O}_3\text{MDA8}$ means the maximum daily 8-h average ozone concentration.

(An et al., 2019; Zheng et al., 2018). By comparing with the results of a previous study focusing on the period from 2014 to 2018 (Fan, Zhao, & Yang, 2020), we found that the concentration of the above pollutants in this year was significantly lower. After the rapid decrease in late January and early February, PM_{10} concentration showed obvious fluctuations in later time (Figure 1c), which was mainly due to the large-scale dust weather in northwest and northern China in spring (Fan, Zhao, & Yang, 2020; Huang, Wang, et al., 2014).

China has been working on air pollution control since 2013, and the concentration of air pollutants has been decreasing year by year (Fan, Zhao, & Yang, 2020; Zhang, Zheng, et al., 2019; Zhang, Wang, et al., 2020; Zhao, Wang, et al., 2019). Therefore, we need to clarify whether the lockdown measures will further improve air quality on the basis of existing governance. According to the comparison between the concentrations of pollutants in the spring of 2020 and 2019 in China (Figure S2a), $\text{PM}_{2.5}$, PM_{10} , NO_2 , SO_2 , and CO decreased by 6.8%, 8.7%, 4.5%, 3.9%, and 7.5%, respectively, while the maximum daily 8-h average ozone concentration ($\text{O}_3\text{MDA8}$) increased by 3.9%. Compared with the winter of 2019, $\text{PM}_{2.5}$, PM_{10} , NO_2 , SO_2 and CO had an even larger reduction (Figure S2b) during the lockdown period, with decreases of 6.9%, 18.1%, 8.5%, 14.6%, and 8%, respectively, while $\text{O}_3\text{MDA8}$ increased by 14%.

For a more detailed analysis, we defined three time periods which include lockdown period (period III) and two contrast periods, namely period I (i.e., the same time period as period III in 2019) and period II (i.e., before the period III). Figure 2 shows the variation of air pollutant concentration in period III compared to period II, and NO_2 and $\text{PM}_{2.5}$ declined by 50% and 32%, respectively. Compared with period I, the decreasing

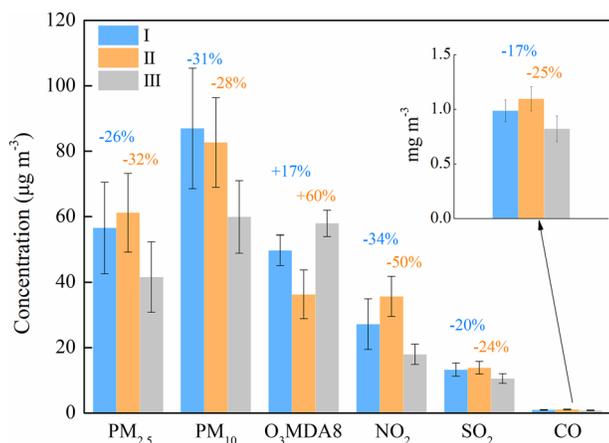


Figure 2. Comparison of the national air pollutant mean concentrations in the three periods. I represents period I (January 26, 2019 to March 5, 2019, blue), II represents period II (December 17, 2019 to January 25, 2020, orange), and III represents period III (January 26, 2020 to March 5, 2020, gray). The error bar represents the standard deviation, blue and orange numerical percentage represent the normalized result of the difference of period III compared to periods I and II (see the calculation method in the method section), + represents the increase, and – represents the decrease. O₃MDA8 represents the maximum daily 8-h average ozone concentration.

rate of various pollutants also exceeded 20% (Figure 2). Under the influence of physical and chemical processes and external environment, the concentration of atmospheric pollutants often has obvious diurnal variation (Li, Guo, et al., 2017; Zhang, Wang, et al., 2020). The diurnal variations of the average concentration of six pollutants in the country during the three periods are presented in Figure S3. It is found that the diurnal variation characteristics of atmospheric pollutant concentration in China during period III were basically the same as those in periods I and II. The overall decrease of air pollutant concentration in each hour further reflects the impacts from the emission reduction during the city lockdown (Le et al., 2020; Lelieveld et al., 2015).

3.2. Spatial Variations of Air Pollutant Concentrations During the Lockdown

We explored the spatial distribution of the near-surface air pollutant concentrations in China (Figure S4). Based on the comparative analysis of air pollutants among the three periods, it can be found that the North China Plain and the central and western Xinjiang are still heavily polluted regions, especially for the pollutants of CO (average concentration exceeds 1.6 mg m⁻³), NO₂ (average concentration exceeds 40 µg m⁻³), and PM in the North China Plain. This finding is consistent with the findings from a comprehensive study of air pollutants in China from 2014 to 2018 (Fan, Zhao, & Yang, 2020), where anthropogenic emissions and the proximity of dust sources contribute to relatively poor air quality in these two

regions (Huang, Wang, et al., 2014; Zhang, Gong, et al., 2003; Zhao, Yang, et al., 2020). We can also find that during the period II, the stations observing dense CO, NO₂, and PM_{2.5} pollutant concentration are much more than that during the other two periods, indicating that the pollution before the lockdown is significantly heavier. In addition, sites with dense CO, NO₂, and PM_{2.5} show low O₃MDA8.

We calculated the fractional difference of air pollutants between periods III and II, and between periods III and I, and analyzed the decrease amplitude in different areas (Figure 3). Relative to period I (Figure 3a), the reduction of air pollutants mainly occurred over the northern and central China, where the country's energy-consuming industries are concentrated. Relative to the period II (Figure 3b), NO₂ showed a significant decline across the country, which is highly consistent with the previous statistical results. NO₂ has never been reduced rapidly on a large scale in a short period of time, and this even exceeded more targeted regional control effects, such as “Olympic Blue” (Wang, Zhao, et al., 2010), “APEC Blue” (Huang, Zhang, & Lin, 2015), and “Parade Blue” (Xue et al., 2018). Correspondingly, the increase of O₃MDA8 in parts of northern and central China exceeded 150%, which has been far more than the annual increase in O₃ in China (Li, Jacob, Liao, Shen, et al., 2019; Fan, Zhao, & Yang, 2020).

3.3. The Ozone Concentration Rose Sharply

The rapid increase in O₃ in China during the lockdown has been observed on both a temporal and a spatial scale (Figures 2 and 3). O₃ is often the product of NO_x and VOCs photochemical reaction under the condition of enhanced light, and atmospheric oxidation provided by atmospheric free radicals generated by light is the core driving force of O₃ net production (Le et al., 2020; Li, Jacob, Liao, Shen, et al., 2019). Different from PM_{2.5}, the net production of O₃ is complex and nonlinear, so we specially compared the variation trend of NO₂ and O₃ with PM_{2.5} in the three periods, where PM_{2.5} induces the reduction of downwelling solar radiation to a certain extent (Figure S5).

During the daytime with sufficient solar irradiance (10:00–17:00 LST), ozone decreased significantly with the increase of NO₂ and PM_{2.5} concentration (Figures S5a, S5c, and S5e), but during the nighttime (18:00–24:00 LST), it still increased and accumulated and leveled off (Figures S5b, S5d, and S5f, S3). This indicates the importance and complexity of daytime photochemical reaction to ozone net production. Figures S5a

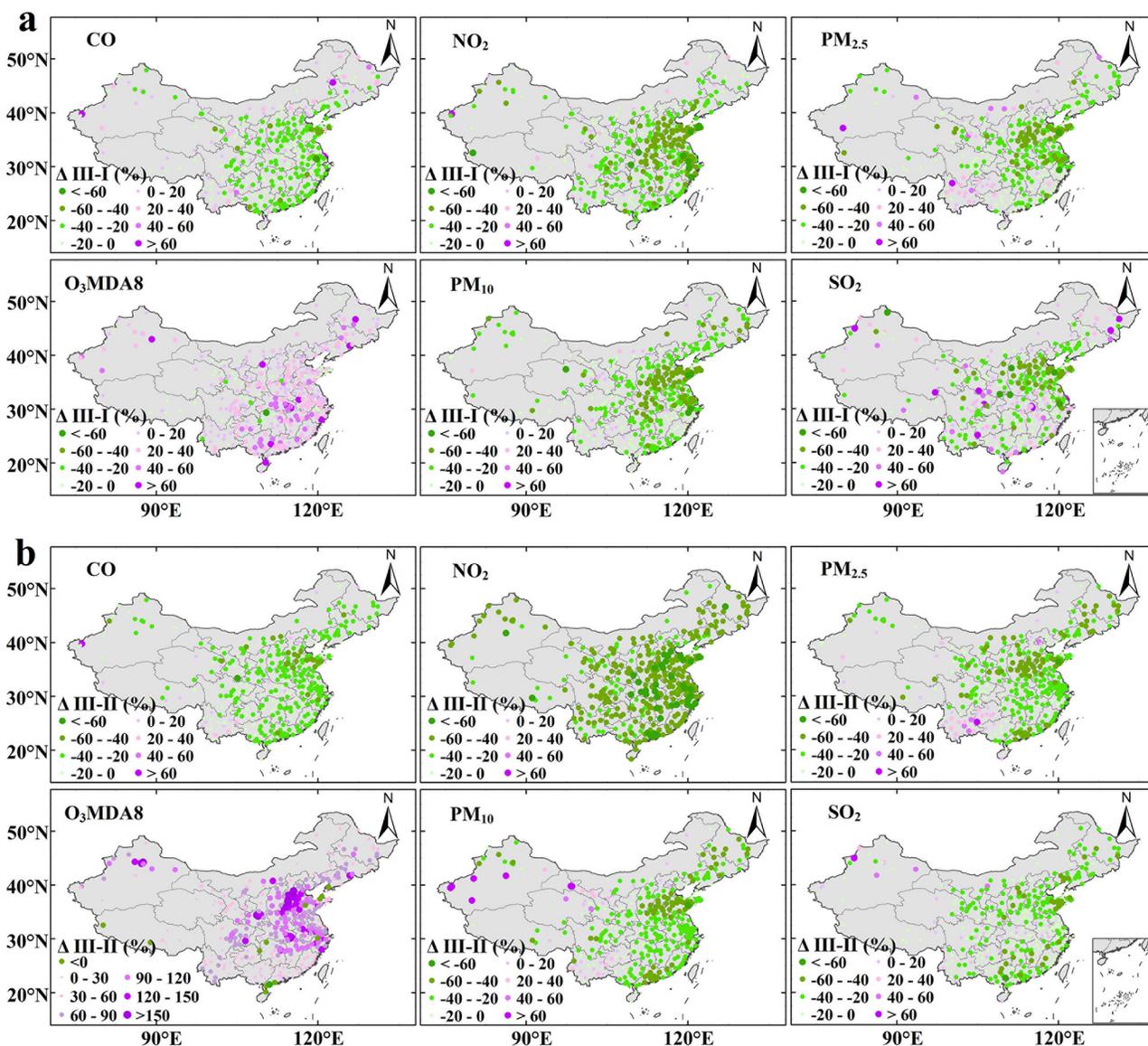


Figure 3. Spatial distribution of the difference result at all stations during lockdown in China compared with the periods I (a) and II (b), with the results having been normalized and displayed in a percentage form (see the calculation method in the method section). Purple indicates that the pollution concentration increases during the lockdown period, green indicates that the pollution concentration decreases during the lockdown period, and the circle size of the station indicates the extent of the concentration change.

and S5c show that in the two periods before the lockdown, as the NO_2 concentration increased, the O_3 concentration decreased significantly. The reason is that when NO_x emissions are large enough, the NO released into the atmosphere will convert most of the O_3 into NO_2 (Le et al., 2020; Li, Jacob, Liao, Shen, et al., 2019; Shi & Brasseur, 2020). It is found by comparing with daytime results that the O_3 and NO_2 intersection of periods I and II falls between the $\text{PM}_{2.5}$ concentrations of 100 and $150 \mu\text{g m}^{-3}$ (Figures S5a and S5c), but that of period III is significantly delayed to the $\text{PM}_{2.5}$ concentration of 200 – $250 \mu\text{g m}^{-3}$ (Figure S5e). This implies that the extremely low economic activity in China during the coronavirus lockdown significantly reduced NO_x emission, weakened the NO titration effect, and led to the rapid accumulation of O_3 (Le et al., 2020; Li, Jacob, Liao, Shen, et al., 2019). Especially when the solar radiation is weak, that is, when the $\text{PM}_{2.5}$ concentration is high, the O_3 concentration is also higher than the other two periods. Our results are consistent with previous studies in northern China (Le et al., 2020; Shi & Brasseur, 2020), suggesting that the change in ozone pollution in China is nationwide. Therefore, we suggest that in the face

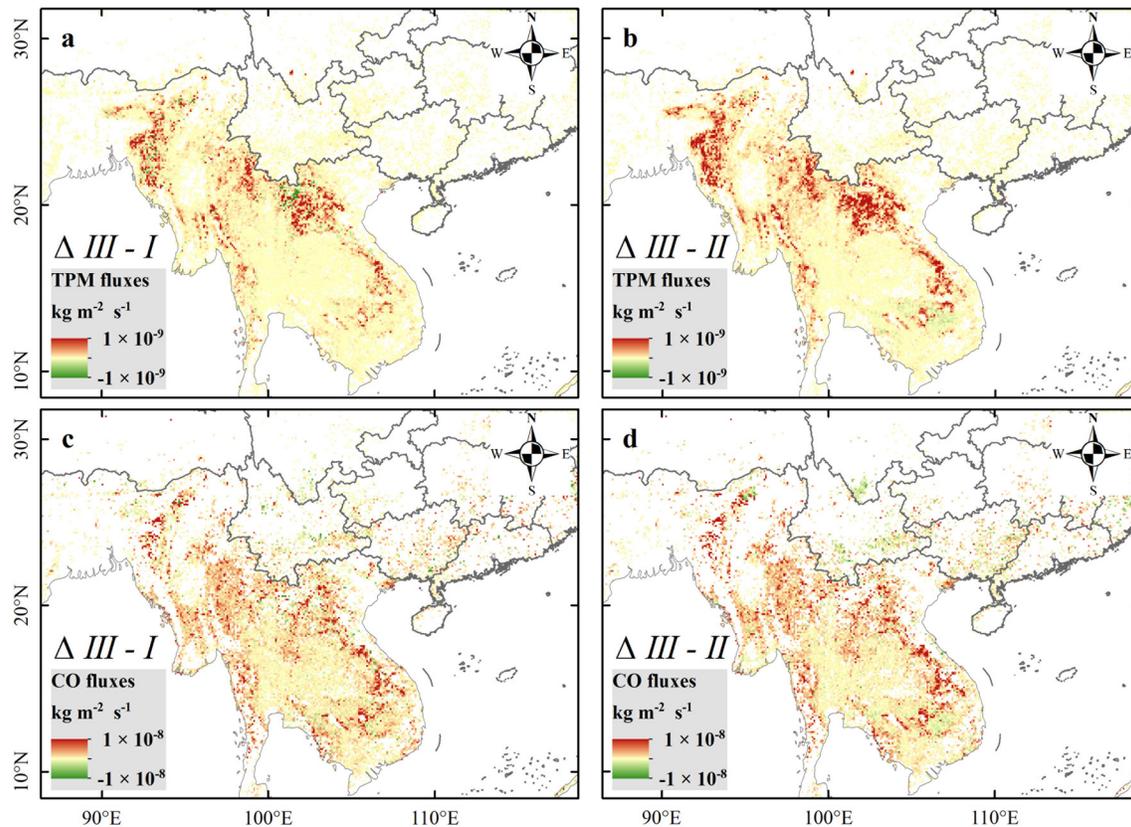


Figure 4. The difference result in flux from wildfires during lockdown (III, January 26, 2020 to March 5, 2020) compared with the periods I (January 26, 2019 to March 5, 2019) and II (December 17, 2019 to January 25, 2020). This result clearly shows that the TPM and CO fluxes produced by wildfires in the Indochina Peninsula during the lockdown were significantly higher than the other two periods.

of the current situation of compound pollution in China, attention should be paid to reducing both NO_x and VOCs emissions. A prerequisite for effective control of O₃ and PM_{2.5} is to actively reduce NO_x and VOCs emissions (Li, Jacob, Liao, Zhu, et al., 2019).

3.4. CO and PM Concentrations Increased Abnormally in Southwest China

Another important finding (Figure 3) is that CO and PM pollution concentrations in Yunnan and Guizhou provinces, China, are higher in period III than those in the other two comparative periods, showing an obvious phenomenon of increasing instead of decreasing trends. This contradicts the expected results of national emission reductions during the lockdown, and many previous studies did not capture these unusual changes in the region (Le et al., 2020; Wang & Zhang, 2020).

According to our analysis (Figure 4), during the lockdown period, the fluxes of CO, PM_{2.5}, and PM₁₀ generated by the wildfire in Indo-China Peninsula were much higher than that during the periods I and II. At the same time, there are weak local wildfire emissions in southwest China. Not only that, the air pollutants produced by wildfires in the Indochina Peninsula during the 2020 lockdown period are also strong when compared with the same period in the previous 5 years (Figures S6 and S7). The variability of air pollutants is closely related to the air cluster before reaching the sampling site, for which we performed backward trajectory simulation and trajectory clustering analysis (Figure S8). The results showed that about 51.39% and 32.22% of the air flows came from southwest and south Yunnan, respectively, which implies that transport from wildfire areas accounted for more than 83% of the total contribution. The findings help to explain the unusual increase in pollution, which is mainly caused by the regional transport in southwest China during the lockdown period. Metya et al. (2020) also found that 700 hPa CO over south-east China did not get

reduced by lockdown as the biomass burning in Indo-China peninsula remained high, which is consistent with our findings.

3.5. Limited Changes in Mean Weather Conditions During the Lockdown Period

Four major factors to determine air pollution include emission, atmospheric chemistry (An et al., 2019; Zhang, Wang, et al., 2020), transport, and meteorological conditions, among which emission was suggested as the main and internal cause (Butt et al., 2016; Fan, Zhao, & Yang, 2020; Guan et al., 2014; Wang, Wang, et al., 2014; Zhang, Zheng, et al., 2019). The reduction in emissions due to the impact of the lockdown is the main reason for the decrease in air pollutant concentrations across China. We have also seen an abnormal increase in air pollutant concentrations in southwest China mainly due to the transport of wildfire emissions from Southeast Asia. Here, we analyze the major meteorological elements that could cause large-scale pollutant changes. As shown in Figure S9, the PBL high value area in winter in China is located in the Qinghai-Tibet Plateau and the Yunnan-Guizhou Plateau, while the average value in other areas is below 800 m. The precipitation distribution is typical of more in the south and less in the north, and the near surface wind speed is the smallest in the east of China. In general, the PBL height, precipitation, and near-surface wind speed all show a completely consistent distribution pattern among the three study periods (Le et al., 2020).

We found after normalizing meteorological variables during the period III and other two periods (Figure S10) that, the PBL height during the lockdown in urban clusters in North, Central, and South China generally declined, resulting in stable boundary layers and stagnant air. During the period III, precipitation mainly concentrated in northeast China, but the influence on the air pollutant in northeast China was not obvious (Figure 3). According to the differences in the wind speed (Figure S10) and the results of wind direction (Figure S11), there was almost no change in the numerical value and wind direction pattern of China's near-surface wind fields. On the contrary, the wind speed in central and eastern China, where the pollution itself is heavy, was significantly weaker during the lockdown period (Le et al., 2020). Therefore, meteorological variables were not more conducive to the diffusion and removal of pollutants during the lockdown period. Obviously, meteorological conditions were not the main contributor to the sharp reduction of pollution (Le et al., 2020; X. Wang & Zhang, 2020).

3.6. Air Pollution Rebound with the National Reopen

We further analyzed the air pollution situation after the recovery of economic activities (Figure S12). The results showed that the concentration of air pollutants (except O₃) bounced back rapidly after March 2020, with PM_{2.5}, PM₁₀, NO₂, and SO₂ peaking in April (absolute value). In April–July 2020, the gap between air pollutant concentrations and the mean values in 2015–2019 is also significantly smaller than those in February–March.

Based on the difference between the monthly average concentrations of air pollutants in 2020 and 2015–2019, we further calculated the degree of pollution recovery from April–July 2020 (Figure S13). The results showed that the increases in NO₂ and SO₂ were the most significant during April–July 2020, reaching 19%–31% and 21%–26%, respectively. However, we noticed that the changes in PM_{2.5} and ozone were not dramatic, increasing by about 6.8% and decreasing by about 6.1%, respectively. In terms of time, PM_{2.5}, PM₁₀, and NO₂ all increased the most in April 2020, with an average increase of about 15% for all pollutants. This further confirms the significant role of emission reduction during the lockdown in determining air quality at a national scale.

4. Conclusion and Discussion

In summary, since the adoption of lockdown measures, the concentrations of PM_{2.5}, PM₁₀, NO₂, CO, and SO₂ in China have been reduced by more than 24%, while the concentration of O₃ has risen rapidly. The gradual return of air pollution to the pre-COVID level indicates that emission is still the primary driver of nationwide air pollution in China. Therefore, China should persist in reducing emissions and establish a composite pollution prevention and control system as soon as possible.

Although studies (An et al., 2019; Wang, Gao, et al., 2020; Zhang, Zheng, et al., 2019) have shown that in the past few years, the annual average concentration of PM_{2.5} in China has dropped significantly, along with decreased heavy air pollution incidents and increased number of clean days (Zhang, Wang, et al., 2020). However, our research confirms that the reduction of certain air pollutants alone is not sufficient to explain the efficiency of air pollution control, such as the rapid growth of ozone. The severe haze events caused by fine PM particles are largely driven by the formation of secondary aerosols (An et al., 2019; Chang et al., 2020). Similarly, due to the enhancement of O₃ in urban areas, it further increases the oxidation capacity of the atmosphere and promotes the formation of secondary aerosols (Le et al., 2020; Li, Jacob, Liao, Shen, et al., 2019). Thus, it becomes more essential to coordinate the controls of PM_{2.5} and O₃, and the top priority is the simultaneous treatment of NO_x and VOCs.

Our study also confirmed that large-scale transport may cause serious regional pollution incidents, which requires intensive collaborative governance and timely information sharing among regions. Moreover, although the meteorological conditions in this study are not the main factors in China's pollution change, it is difficult to alleviate air pollution under the conditions of stable boundary layers and weak wind speed (Wang, Dickinson, et al., 2018; Zhang, Zheng, et al., 2019). To this end, both the meteorology condition and emission inventory should be considered when we make the air pollution control plans.

Data Availability Statement

The air pollutant observation data and reanalysis data used in this article can be obtained from <https://zenodo.org/record/4074307>.

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