The Impact of the Control Measures during the COVID-19 Outbreak on Air Pollution in China

Supplementary Material

S1. Map with geographical indications used in the text

The concentrations of the trace gases and aerosols discussed in this paper vary strongly across China. To describe these, it cannot always be avoided to indicate locations. On the national scale of a large country such as China, this is most easily and straightforwardly done by using the names of the provinces. Because many readers may not be familiar with Chinese provinces, a map is provided in Figure S1. Reference is made in the text to the following regions:

- BTH: Beijing, Tianjin and Hebei.
- NCP: North China Plain, includes part of the provinces Henan, Hebei and Shandong, and the north of Anhui and Jiangsu.
- YRD: Yangtze River Delta, includes Shanghai, southern Jiangsu, eastern and southern Anhui, and eastern and northern Zhejiang.
- PRD: Pearl River Delta, includes part of Guangdong, Hong Kong, and Macau.
- SC: Sichuan and Chongqing.
- The Junggar Basin is located in the north of the Xinjiang.

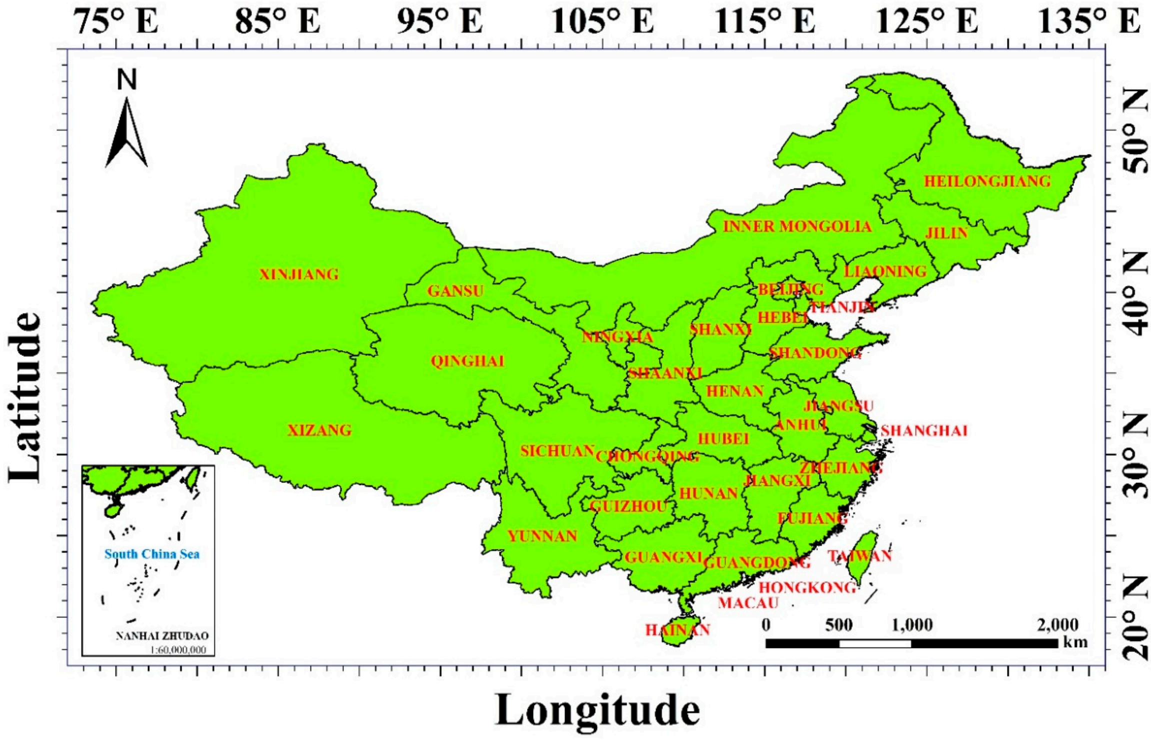


Figure S1. Map of China, including provinces, municipalities (Beijing Tianjin Shanghai, and Chongqing), autonomous regions (Ningxia, Guangxi, Xizang, Xinjiang, and Inner Mongolia), and special administrative regions (Hong Kong and Macau).

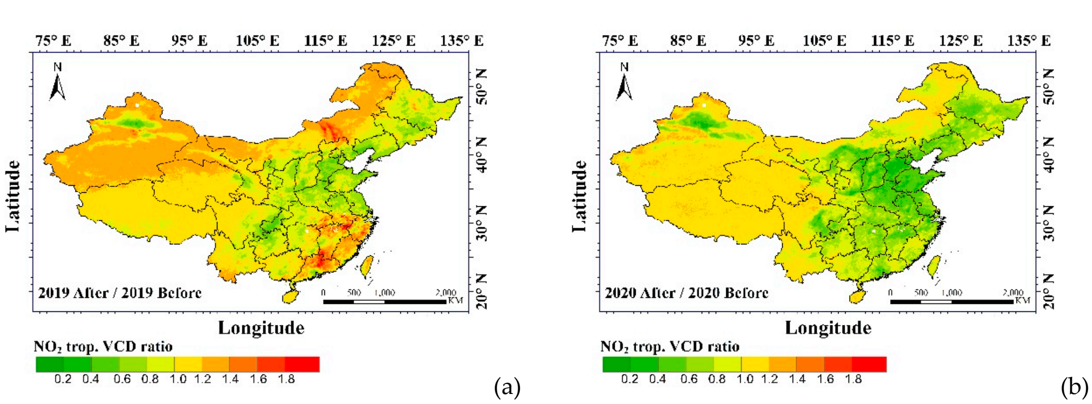
S2. NO_2 distribution and reduction estimates for different areas in China

S2.1 NO_2 reduction during the 2019 Spring Festival

To quantitatively show the reduction of the tropospheric NO_2 VCDs during the 2019 Spring Festival, the data presented in Figure 2a,b were used to produce a map showing the pixel-by-pixel ratio of the TNO2_ave (tropospheric NO_2 vertical column densities (VCDs) over China, averaged over 30 days) after the Spring Festival to that before (Figure S2a). The map in Figure S2a shows quantitatively that the largest TNO2_ave reductions, to about 50% of the concentration before the Spring Festival, occurred over areas with high population densities in east and central China, and Chongqing, and even 70–80% in the surrounding provinces, the south of China, and the Junggar basin. In some areas, a small increase by 10–20% is observed, for instance west of Shanghai (Jiangxi, Anhui, and Hubei) and in Guangxi. It is noted that apparent large reductions occur over Shaanxi, and apparent increases are observed over Fujian, Guizhou, Yunnan, and Guangdong; likely, these changes are artefacts due to the low concentrations for which a small difference leads to a large ratio (positive or negative). This also applies to the west of China and the Tibetan Plateau (TP), where NO_2 concentrations are small.

S2.2 Combined Spring Festival and lock-down effects

The ratio of the TNO2_ave column densities after the 2020 Spring Festival to those before (Figure S2b) shows a large reduction to 40–50% and in some regions even 70–80% of the concentration before the festival over the area where the TNO2_ave columns were high before the 2020 Spring Festival, such as the NCP, and extended areas in the mountains west of the NCP, in the north east, and in Sichuan/Chongqing. Additionally, a large reduction is observed over the Junggar basin in Xinjiang province. The reduction is somewhat larger in the north and west of China (Inner Mongolia and Xinjiang) than further south. This reduction pattern is also consistent with the distribution of China's railways (http://cnrail.geogv.org/enus/about); last access 7 April 2020). The area where the decline is obvious is also the area with a high density of trains, which, however, was reduced to less than 50% of the normal operation during the COVID-19 lockdown (http://xxgk.mot.gov.cn/jigou/zhghs/202003/t20200320_3348941.html, in Chinese; last access 7 April 2020), indicating the substantial reduction of human migration in that period. Figure S2d shows the ratio of the TNO2_ave after the Spring Festival in 2020 to that in 2019. Values larger than 1 were not observed anywhere. Comparison of Figures S2a and b shows the large differences between the combined Spring Festival and virus effects in 2020 and that of the Spring Festival alone in 2019, i.e., the substantial effect of the virus measures on the TNO2_ave column densities with a much stronger reduction over a much larger area.



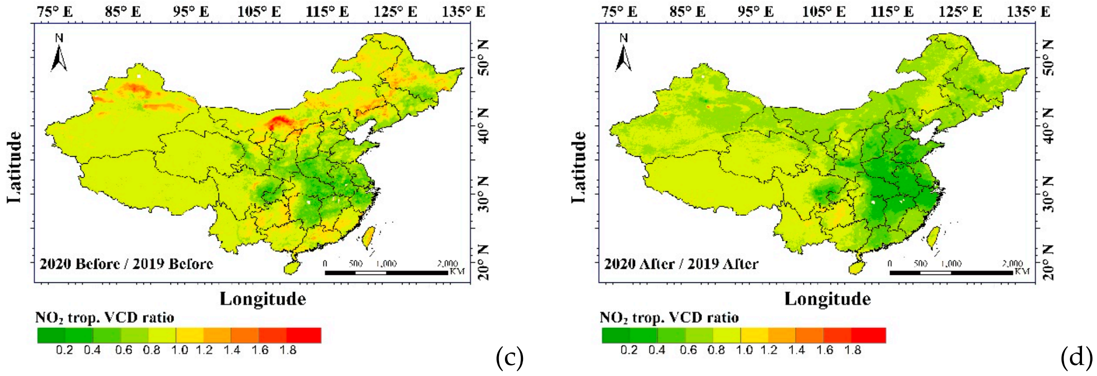


Figure S2. Ratio of NO_2 tropospheric VCDs. (**a**) 2019 Spring Festival after/before; (**b**) 2020 Spring Festival after/before; (**c**) 2020/2019 before the Spring Festival; (**d**) 2020/2019 after the Spring Festival.

S2.3 Regional distribution of the COVID-19 containment effects

The estimated effects of the COVID-19 containment measures, using Equation (2) in the main text, are presented in Figure 3. They show a substantial regional variation. Over those areas where the TNO2_ave was high before the crisis, mainly over the east of China, such as the NCP, and central China, the estimated reduction of the concentrations due to COVID-19 containment measures is on the order of 50–60%. The highest values of around 70% are observed in the area encompassing Shanghai, Anhui, and Jiangxi. Additionally, the TNO2_ave over the Junggar basin shows a strong Spring Festival effect, but the estimated effect of the virus containment measures was smaller than over east China. Small effects are observed in the north of China, of 10–30%, in Inner Mongolia and Xinjiang. Small areas with a high increase of TNO2_ave occur over areas with very low TNO2_ave where a small difference has a large effect on the results of our estimates, which therefore are not considered meaningful over such areas. Over large areas, such as the Tibetan Plateau, tropospheric NO_2 VCDs are very small (see Figure 2). Hence, a small deviation in the observations will likely cause a relatively large effect on the estimate provided by Equation (2). Figure 3 shows that the estimated effect over the Tibetan Plateau is less than ±10%. This is so small that the effect of the COVID-19 containment measures is considered to be within experimental uncertainty.

S2.4. SO_2 and CO

The principal sources of SO_2 are volcanic and anthropogenic emissions from burning sulfur-contaminated fossil fuels and the refinement of sulfide ores. The NCP has the world's most severe SO_2 pollution, but a decrease in the SO_2 VCDs is observed in the OMI data since 2007 [2]. SO_2 peaked in 2007, with a secondary peak in 2011. A substantial reduction of about 50% was observed in the period 2012–2015, due to the economic slowdown and government efforts to restrain emissions from power plants and industrial sectors [44].

Figure S3 shows the 30-day averages of the TROPOMI-retrieved SO_2 VCDs for 2019 and 2020 before and after the Spring Festival. The data in Figure S3 show that in addition to the high concentrations over the NCP, a hotspot is observed over the Junggar Basin in Xinjiang province similar to that for NO_2. SO_2 is also observed over the north of China and the southeast and central China but with much lower VCDs. The maps for 2019 before and after the Spring Festival show similar features as for NO_2, i.e., lower VCDs after the festival. Comparison of the SO_2 maps for 2019 and 2020, before the Spring Festival, shows that the concentrations were higher in 2020, in particular in the north of China, whereas after the Spring Festival they were overall substantially lower.

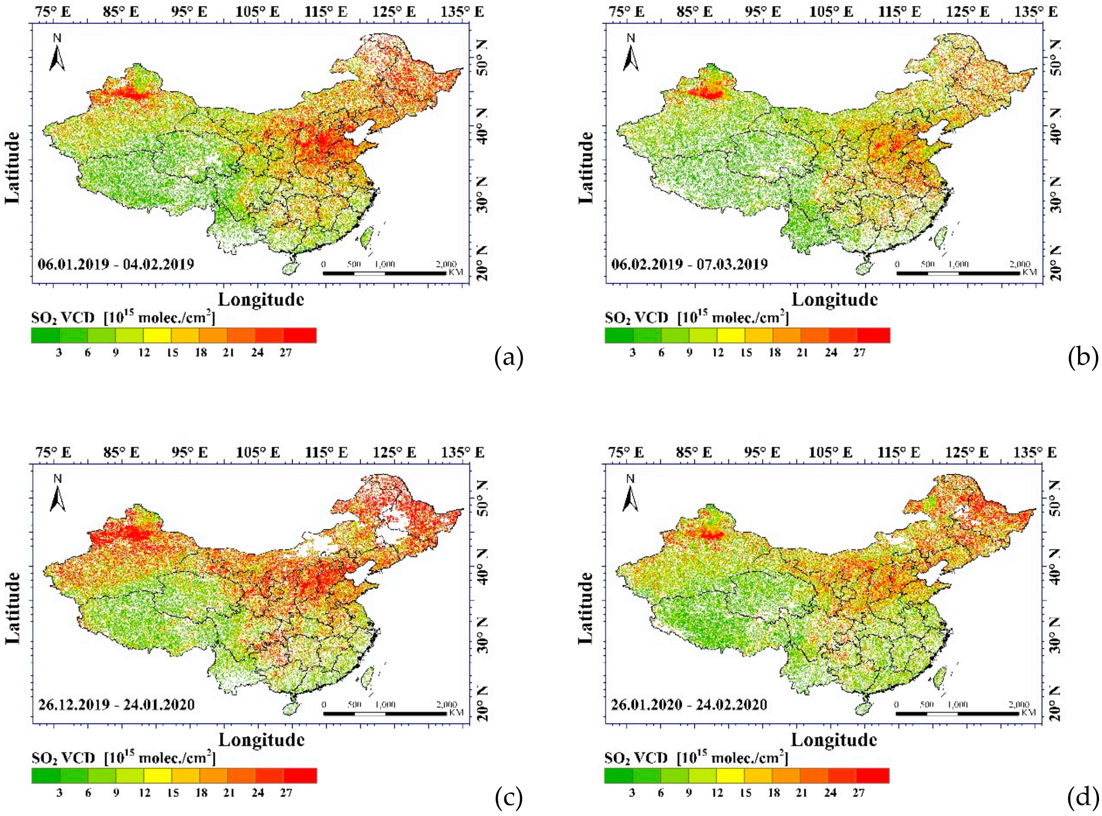


Figure S3. SO_2 vertical column density averaged over 30 days: (**a**) before the 2109 Spring Festival ; (**b**) after the 2019 Spring Festival ; (**c**) before the 2020 Spring Festival ; (**d**) after the 2020 Spring Festival The monthly averages were obtained as described in the text (Section 3.2). No smoothing was applied, and the results are somewhat spotty.

Carbon monoxide, CO, is mainly formed from incomplete combustion of fossil fuels and biofuels and open burning of biomass [45]. The TROPOMI-derived CO CVD maps, averaged over 30 days before and after the Spring Festivals in 2019 and 2020, presented in Figure S4, show the spatial distribution of CO VCDs over China. CO concentrations are very low over the Tibetan Plateau. The highest VCDs are observed over the industrialized areas in east China, in particular over BTH and Shandong, and somewhat lower over the coastal provinces from Heilongjiang in the north to Shanghai, stretching to the west to the HU Line, including the provinces Henan, Hubei, Anhui, Chongqing, Sichuan, Shanxi, and Shaanxi. Lower concentrations are observed over the coastal provinces south of Shanghai, over Yunnan, and in the north and west over Inner Mongolia and Xinjiang. The elevated concentrations in the north and west are probably due to heating-related emissions in the wintertime.

As discussed in the text, CO has an atmospheric lifetime of about 1–2 months [46] and thus CO concentrations are not very sensitive to short-term changes in anthropogenic emissions. To illustrate this point, Figure S4e was added to show that the CO VCD distribution over China in the second month after the 2020 Spring Festival is different from that in the month before. A substantial reduction is observed over China north of the Yangtze River, while actually further south and over Sichuan, the CO VCDs increase. This difference is quantitatively illustrated with the difference map in Figure S4f, showing the CO VCDs in month2 minus those in month1 after the 2020 Spring Festival. The difference map shows a substantial reduction in month2, with respect to month1, with up to 8×10^{17} molec.·cm^{-2} in parts of eastern and northwestern China, and an increase with up to about 8×10^{17} molec.·cm^{-2} in southern China.

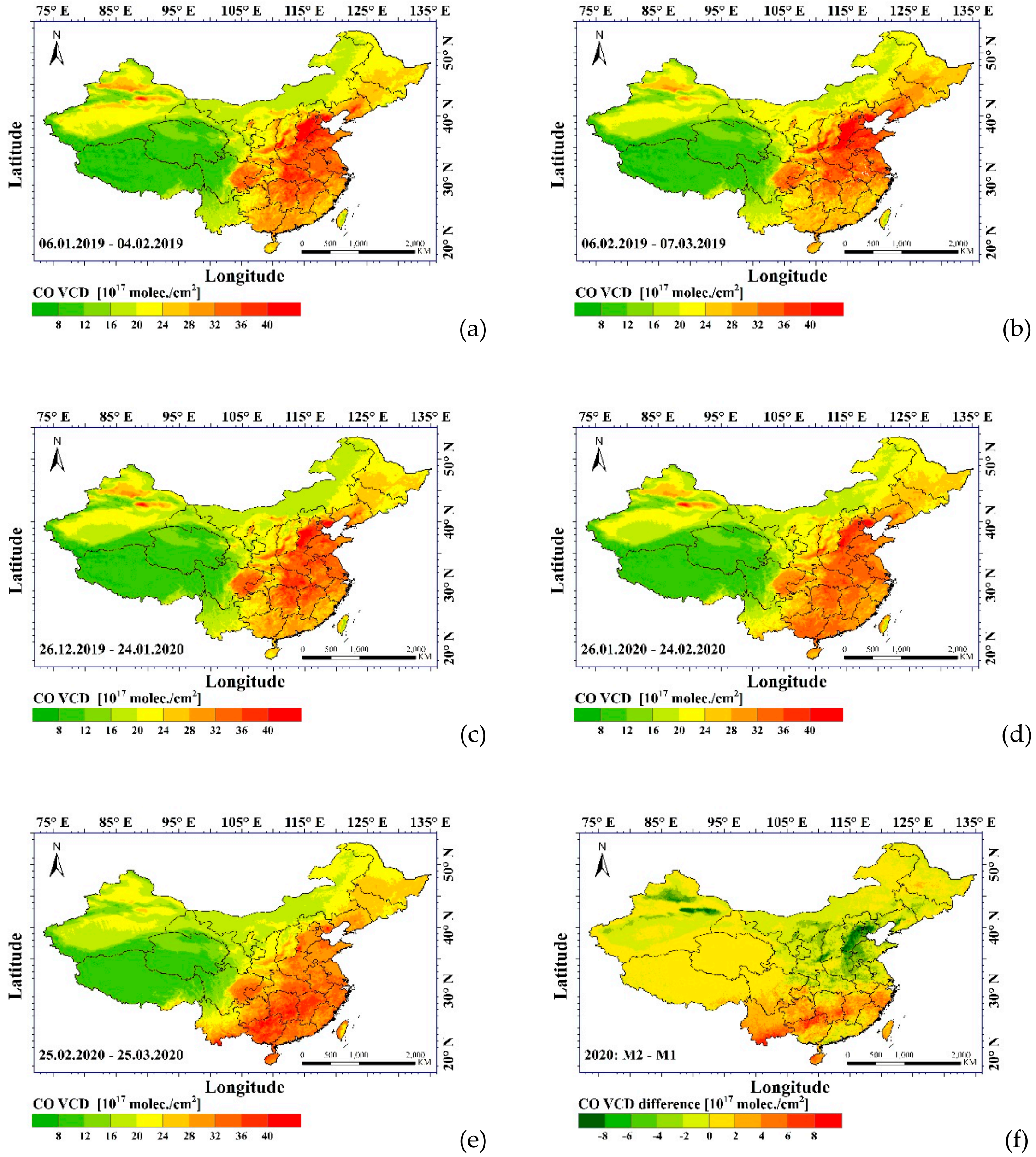


Figure S4. Same as Figure S3, but for CO; (**e**) second month after the 2020 Spring Festival; (**f**) CO VCD difference map, showing the CO VCDs in month2 minus those in month 1 after the 2020 Spring Festival.

S3. Comparison of ground-based concentrations in 26 cities

The ratios of the averaged concentrations of NO_2 and O_3 after the Spring Festival to those before the Spring Festival for four years in 26 provincial capital cities (Figure 1) are presented in Figure 8. Those for the other species included in this study (SO_2, $PM_{2.5}$, PM_{10}, and CO) are presented in Figure S5. Effects of the COVID-19 measures on the concentrations after the Spring Festival are discussed in the main text. Here, some additional information is presented as regards the variability of these ratios in different cities and different years. This variability may have different causes and, together with other complicating factors, render it hard to separate the effect of COVID-19 measures from those of the Spring Festival.

An example is the occurrence of meteorological conditions resulting in enhanced pollution levels and/or the formation of haze [30,54,55]. These conditions may have caused the notably high NO_2

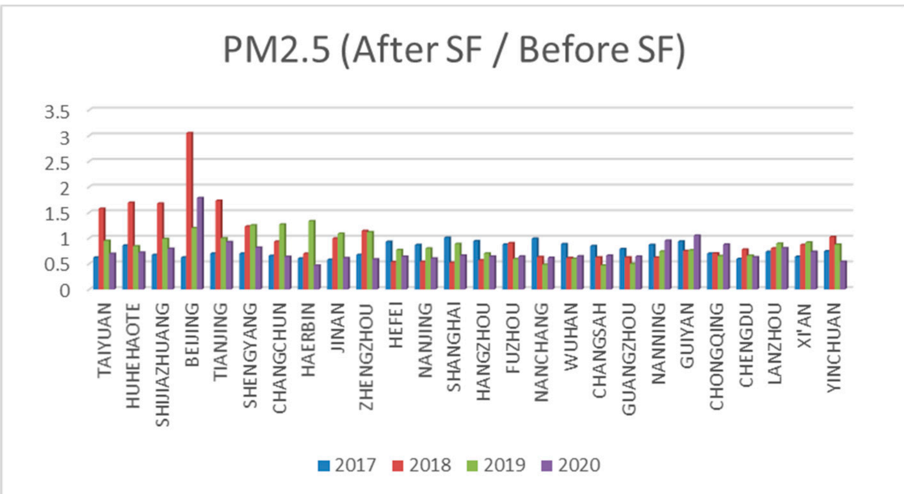
ratios observed in many cities in 2018, especially in the north, where the pollution after the Spring Festival was higher than before the Spring Festival.

The gradual decrease in Wuhan during the first three years (Figure 5) reflects that the decreasing NO_2 concentrations were accompanied by an even stronger decrease in the period after the Spring Festival. In view of the overall decrease of NO_2 concentrations over China observed from satellite data [2,44], a decrease of the surface concentrations would also be expected. This is confirmed by the ground-based measurements in the 26 cities included in the current study, where overall the pre-Spring Festival concentrations decreased from 2017 to 2020, with some exceptions when high concentrations occurred in certain years. Likewise, the post Spring Festival concentrations overall decreased and were lower than those before the Spring Festival, again with some exceptions when the ratios shown in Figure 7 actually increased. The pollutant concentrations are much influenced by local emissions and meteorological conditions, while also the Spring Festival period discussed here is during wintertime when the meteorological conditions may be conducive to haze formation, i.e., accumulation of pollutants [52,60]. The occurrence of such situations may be determined by local or large-scale meteorological conditions [56,57,61] and topography (such as in the Sichuan basin [58–59] or the Guanzhong basin [48]). The NO_2 data in Figure 8 clearly show the strong differences from year to year in different cities, but some regional dependence is visible as well. In particular, high ratios are observed in the BTH area in 2018, whereas in the north east, the ratios were highest in 2019.

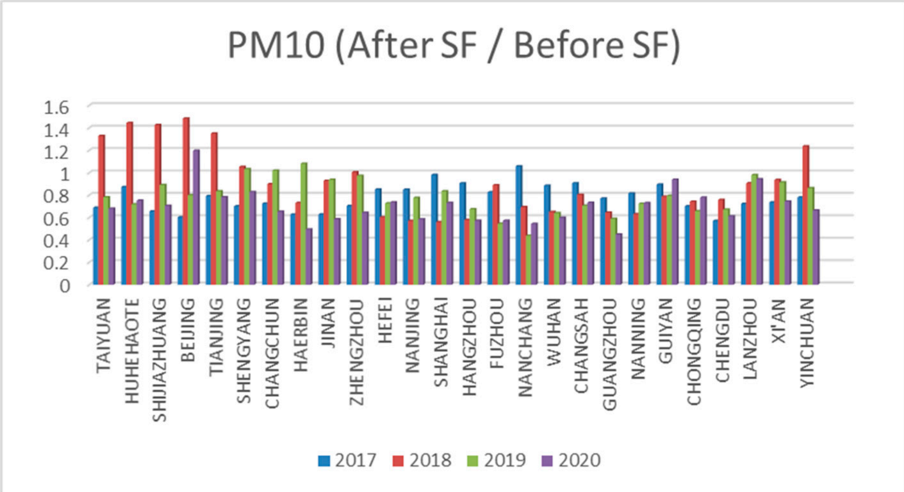
The high ratios in 2018 in northern cities are also observed in all other species, and especially in $PM_{2.5}$ and PM_{10}, CO and to a lesser extent in SO_2. These observations support the suggestion that the period after the Spring Festival in 2018 included an episode with high pollution in the north of China [54,55]. The $PM_{2.5}$ ratio in Beijing reached the highest value (3) in 2018, which is also the highest ratio of $PM_{2.5}$ after/before observed during the current study. Similarly, in 2019, there was an episode that affected the pollutants in the north east.

For SO_2, there is no clear tendency in the period 2017–2020: In some cities (e.g., Guangzhou and Jinan), the ratios gradually decreased; in other cities (e.g., Harbin and Lanzhou), the concentrations increased somewhat, with a slight decrease in Harbin in 2020 and in Lanzhou in 2019. In most cities, the ratios varied somewhat from year to year.

As mentioned in Section 4.2.1, the CO concentrations in Wuhan increase somewhat, as confirmed by both ground-based and satellite observations. In other cities, a small decrease in the ratio was observed, i.e., a decrease in the concentration after the Spring Festival as compared to the pre-Spring Festival period.



(a)



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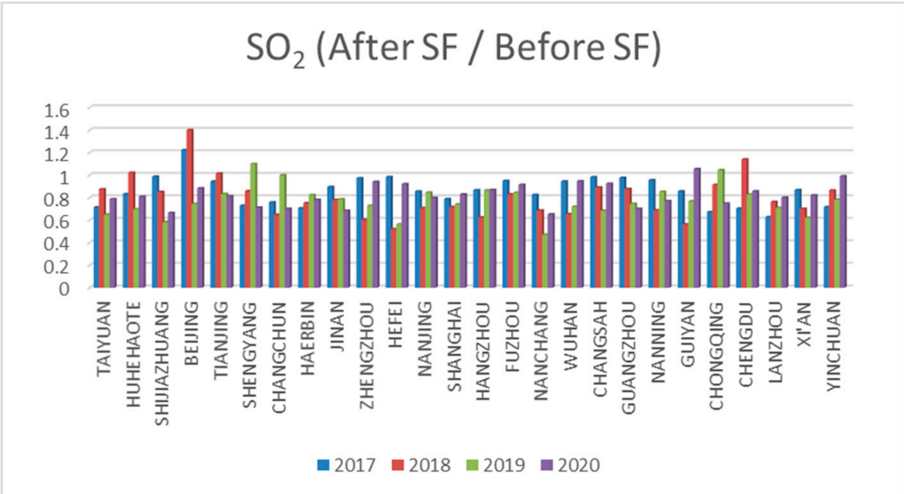

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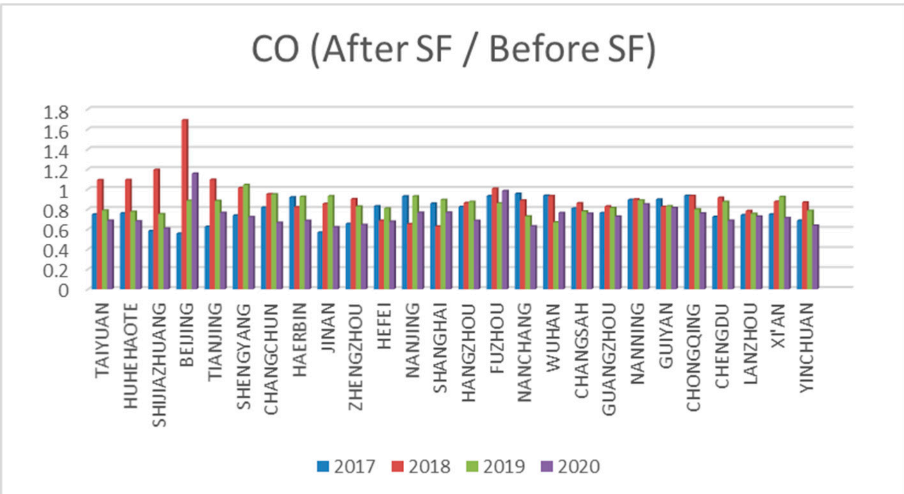

(d)

Figure S5. Ratio of the averaged concentrations of $PM_{2.5}$ (**a**) , PM_{10} (**b**), SO_2 (**c**), and CO (**d**) after the Spring Festival to those before the Spring Festival, for each of 26 provincial capital cities for the years 2017–2020. The concentrations were averaged over a period of 30 days before and after Spring Festival. Note the different scales on the vertical axes.