

How Did Air Pollution Change during the COVID-19 Outbreak in China?

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In early December 2019, an outbreak of the novel coronavirus pneumonia (COVID-19) occurred in Wuhan, Hubei Province, China, and spread fast throughout China. As of 15 June 2020, there have been about 84,000 confirmed cases over China. The Chinese government launched a national emergency response upon the detection of the COVID-19 in Wuhan. To curb the spread of the epidemic, the outbound channels of Wuhan have also been closed since 23 January 2020 (Li et al. 2020; China Internet Information Center 2020). On 26 January, the second day of the Chinese Lunar New Year, all motor vehicles were banned in urban central Wuhan, except for special vehicles to supply epidemic prevention (Hubei Government 2020). In terms of the national prevention and control measures, the government encouraged people to stay at home; discouraged mass gatherings; extended the Lunar New Year holiday; closed all cross-province bus services; and closed schools, government offices, and factories (Chen et al. 2020).

The nationwide antiviral battle in China brought great changes to personal daily life and society operation, and caused a huge challenge to some sensitive sectors, including transportation, tourism, retail, and entertainment, which led to GDP decreasing by 6.8% in the first quarter of 2020 (National Bureau of Statistics 2020). But on the other hand, many regions in China have been suffering from severe air pollution in recent years. A drastic drop of air pollutant emissions occurring with the national lockdown improved the human living environments greatly (Patel 2020). The nationwide lockdown can be considered as an ideal and unique field experiment for the prevention and control of current severe air pollution. It is still unclear how the air quality changes during the lockdown period and what we should learn about air pollution mitigation from this nationwide ideal experiment.

Air quality variations during COVID-19 epidemic

Given the effect of city vehicles, air quality within two months after 26 January (i.e., “AF1 period”: 26 January 2020–25 February 2020; “AF2 period”: 26 February 2020–27 March 2020) are compared with air quality within one month before 23 January (i.e., “BF”: 23 December 2019–22 January 2020). The corresponding historical average air quality data of BF, AF1, and AF2 (i.e., His_BF: 23 December–22 January during 2013–18; His_AF1: 26 January–25 February during 2014–19; His_AF2: 26 February–27 March during 2014–19) are included to show the relative variation of air quality during the nationwide lockdown. The response of air quality to the epidemic is evaluated at the provincial scale, because the detailed lockdown measures have regional differences according to the severity of the local epidemic.

According to the corresponding historical averages of air quality during each month of BF, AF1, and AF2 period (in Fig. A1), air quality has obvious monthly variations in most parts of China (e.g., $PM_{2.5}$ concentration in the Hist_BF period is higher than that of the Hist_AF1 and Hist_AF2 periods). To avoid the effect of air quality monthly variations, the air pollutant concentrations in BF, AF1, and AF2 period are normalized relative to their historical averages. It can be found that, except for O_3 , the concentration of other air pollutants from the BF to AF2 periods are lower than their historical average (cf. Fig. A1), with the normalized concentrations lower than 100%, indicating the achievements of recent air pollution mitigation in China. As shown in Fig. 1, the normalized air pollutant concentrations are generally lowest in the AF1 period, and then rebound partially in the AF2 period. As far as the national average

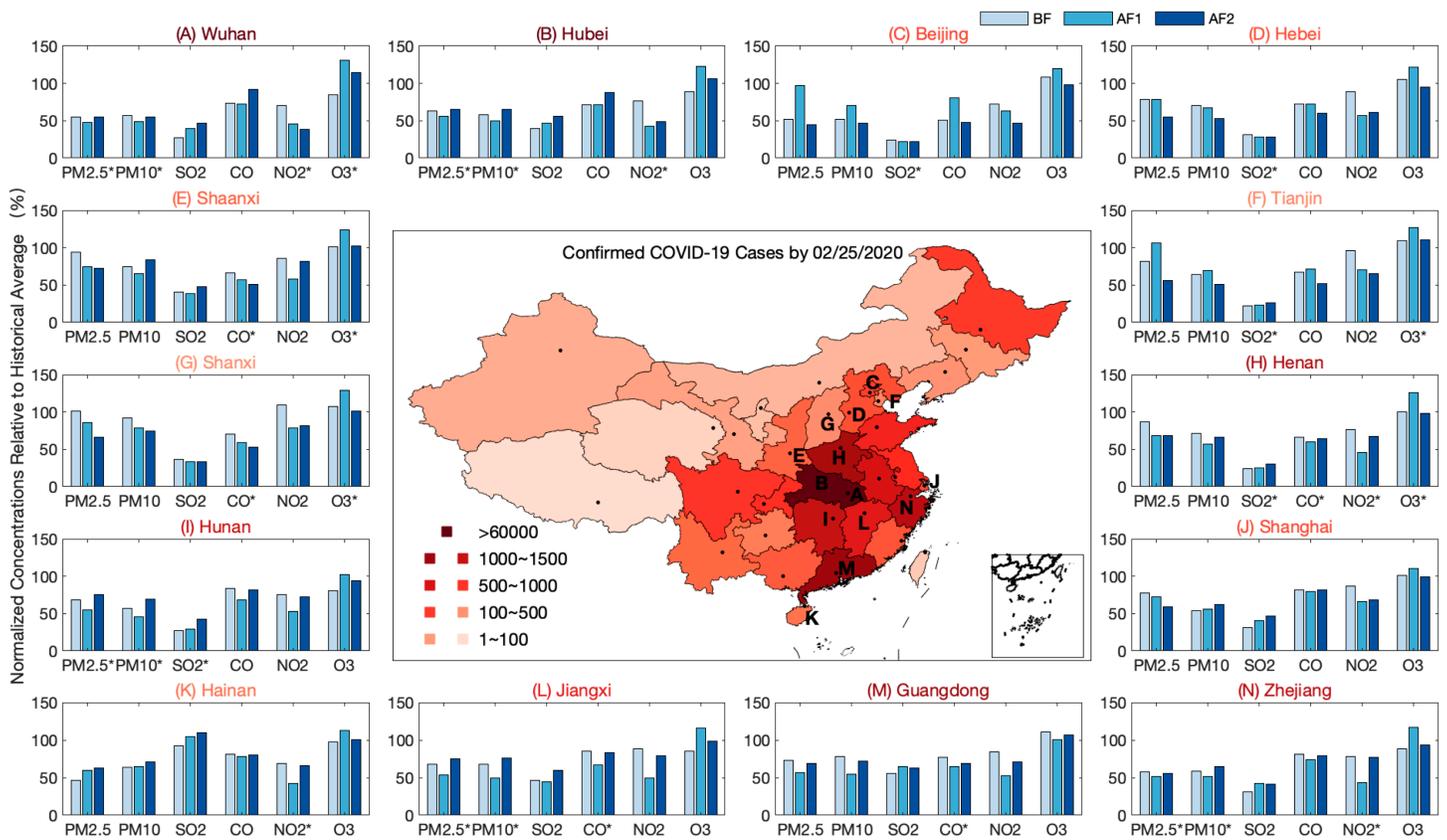


Fig. 1. (center) Distribution of the confirmed COVID-19 cases by 25 Feb 2020 and (a)–(n) normalized air pollutant concentration in the BF, AF1, and AF2 periods. Provinces with the lowest five normalized air pollutant concentration (highest for O_3) during the AF1 period are listed here. An asterisk (*) in the label of x axis indicates the five selected provinces for the specific species. Air quality variation over the megacity Shanghai is also shown. Concentrations of Hubei Province are the average of 12 cities excluding Wuhan. Subplot titles are colored according to the confirmed-cases magnitude. Normalized air pollution concentrations relative to the historical average are calculated as $(BF/His_BF) \times 100$, $(AF1/His_AF1) \times 100$, and $(AF2/His_AF2) \times 100$; i.e., a normalized concentration lower than 100% indicates the concentration during the specific period is lower than its historical average, and the relative variation compared with historical average is 100% minus the normalized value. The air quality dataset can be obtained from the website of the Ministry of Ecology and Environment of China (<http://106.37.208.233:20035>).

is concerned, $PM_{2.5}$, PM_{10} , SO_2 , CO , NO_2 , and O_3 concentrations show remarkable variations compared with those of historical averages, with -27%, -36%, -52%, -27%, -40%, and 15% changes during the first month of the lockdown period, and -32%, -30%, -48%, -38%, -29%, and 2% changes during the second month of the lockdown period. The Chinese government rolled out the most ambitious and aggressive disease containment effort in the AF1 period. Some unnecessarily tough measures restricting economic activities were stopped with the decrease in daily confirmed new COVID-19 cases in the AF2 period (Tian et al. 2020), which may cancel out the effect of the lockdown on air quality.

In general, it shows more notable variations in air quality during the AF1 period than that of the AF2 period. Thus, we will go through some detailed air quality variation in the AF1 period here. Provinces with the lowest five normalized air pollutant concentration (highest for O_3) during the AF1 period are listed in Fig. 1. Most of the exhibited provinces are the hardest hit by COVID-19 with more than 500 confirmed cases, which proves the effects of disease prevention and control measures on air quality in China. With the strictest antivirus measures during the pandemic, $PM_{2.5}$, PM_{10} , and NO_2 concentrations decreased significantly—by approximately 52%, 51%, and 54% along with 30% increase in O_3 —when comparing AF1 with its historical period in Wuhan. In addition to Wuhan, the provinces of Zhejiang, Jiangxi, Hunan, and Hubei are in the top five list of AF1 $PM_{2.5}$ concentration decrease, with 49%, 47%,

and 45% decreases compared with the historical average, the descent scopes of which are greater than those of the BF period. Provinces with remarkable reductions in $PM_{2.5}$ concentration also show significant decrease in PM_{10} concentration, by 49%–54%. Approximately 65% of provinces and areas in China show normalized $PM_{2.5}$ and PM_{10} concentrations lower than 80% and 70%, respectively, in the period of AF1; however, Beijing, Tianjin, and surrounding areas have relatively high normalized particulate pollution concentrations of about 100% for $PM_{2.5}$ and 70%–80% for PM_{10} . In terms of SO_2 , its major anthropogenic sources are thermal power plants, industry, and residential emission in China (Zheng et al. 2018). According to the low normalized concentration in the BF period, SO_2 concentration shows significant decrease throughout China in recent years, especially over northern China, indicating the importance of coal desulfurization and nationwide emission reduction. In the AF1 period, the decreasing extents of SO_2 concentrations over Beijing, Tianjin, and Henan Provinces are more significant than other regions. CO mainly originates from the direct emissions of industry, residential, and transportation. It shows lower CO concentrations in the AF1 period, with normalized concentrations lower than 100% over all the regions, but its decline rate is not as obvious as other air pollutants, with the most significant decrease of 40% over Shaanxi, Shanxi, and Henan Provinces.

As for NO_x , transportation, industry, and power plants are its major anthropogenic emission sources in China. Although lots of effort has been taken to improve air quality, the decreasing trend of nationwide NO_2 concentration is weak in recent years, with the national average normalized NO_2 concentration of 89% in the BF period, i.e., an 11% decrease compared with the historical average. In contrast, during the COVID-19 outbreak, there was a remarkable NO_2 decrease of more than 55% over some of the hardest hit areas, e.g., Hubei, Zhejiang, Henan, and Hainan Provinces. Comparing with His_AF1, NO_2 concentrations decreased by more than 30% during the AF1 period over approximately 78% of the country, and even the lowest decrease rate reached 18.5% over Qinghai Province. Considering O_3 , the concentration of which is driven by two major classes of directly emitted precursors, i.e., NO_x and volatile organic compounds (VOCs), except for the Guangxi Province, O_3 over the other provinces and areas increased significantly with the outbreak of coronavirus. The normalized O_3 concentrations range from 81% to 116% in the BF period and from 99% to 134% in the AF1 period. Wuhan, Tianjin, and the province of Shanxi show the most significant increase in O_3 concentration during the AF1 period, with a more than 30% increase compared with the historical average. The current O_3 production over most urban regions of China is considered to be VOC limited (Li et al. 2019). The opposite trend between O_3 and other air pollutants is inferred to be connected with the concurrent decrease of NO_2 . In addition, the obvious reduction of particulate pollutants leads to more solar radiation reaching to the surface, which benefits photochemistry and O_3 production.

Effect of meteorological elements

It has been recognized that local ambient air quality is driven by both air pollutants emission and meteorological conditions. How did the meteorological elements behave during the epidemic period? Two atmospheric dynamic indexes (i.e., 10-m wind speed and vertical wind shear between 500 and 850 hPa) and two thermodynamic indices [i.e., potential temperature difference between 850 and 1,000 hPa ($\Delta\theta$) and surface relative humidity (RH)] are used to evaluate the meteorological conditions during the AF1 period, which have been verified in our previous work (Zhang et al. 2014). Figure 2 shows the relative difference of the above four indices between the AF1 and His_AF1 periods. Generally, lower surface wind speed, lower vertical wind shear, higher $\Delta\theta$, and higher RH are more unfavorable for the diffusion of surface air pollutants. Extensive unfavorable conditions in surface wind speed and vertical wind occurred in the AF1 period compared with its historical average.

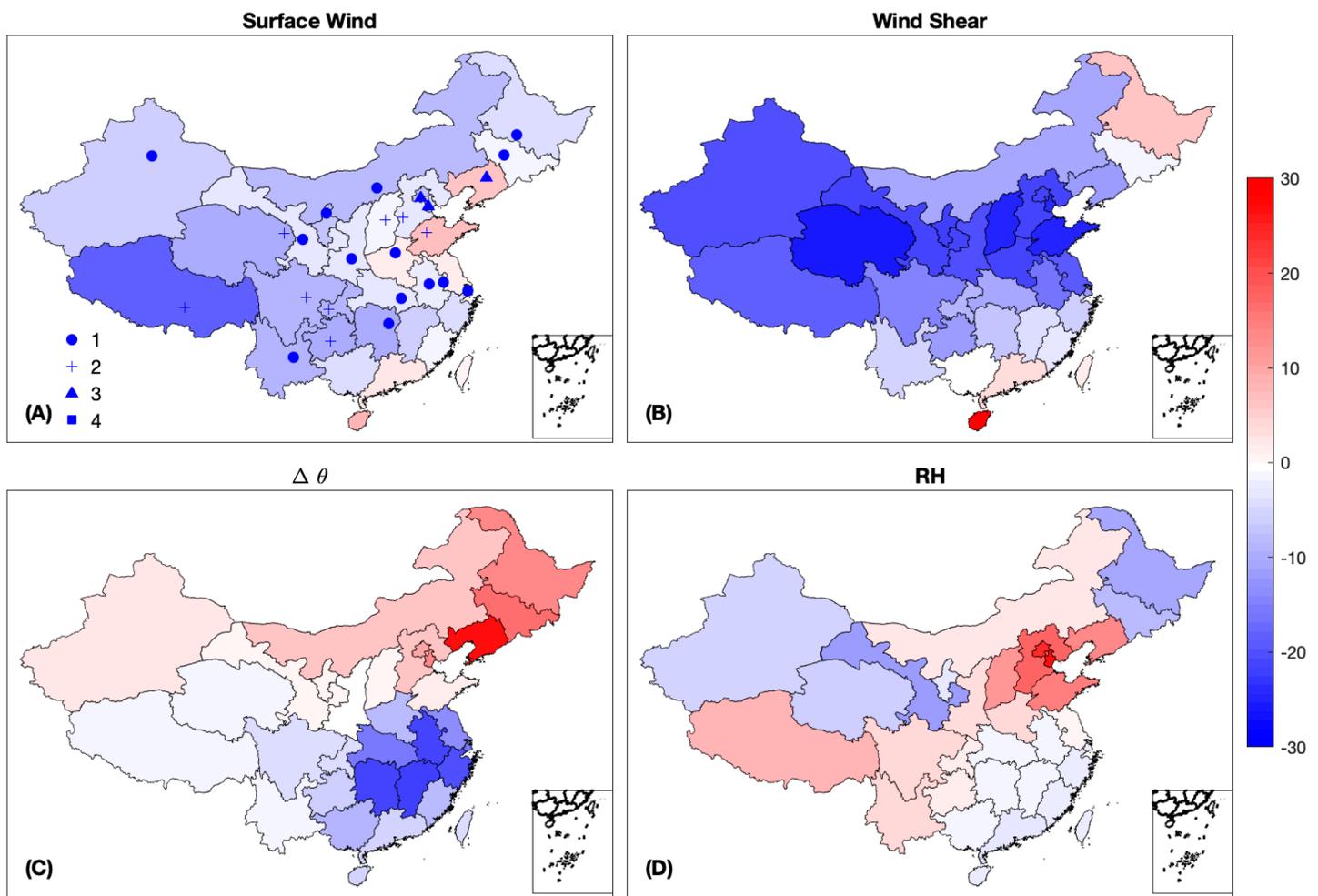


Fig. 2. Relative difference of (a) 10-m wind speed, (b) vertical wind shear, (c) vertical potential temperature ($\Delta\theta$), and (d) surface relative humidity (RH) between the AF1 and His_AF1 periods [i.e., values of $[(AF1 - His_AF1)/His_AF1] \times 100$]. Vertical wind shear is defined as $\sqrt{(u_{500} - u_{850})^2 + (v_{500} - v_{850})^2}$. $\Delta\theta$ is defined as $\theta_{850} - \theta_{1,000}$, where θ_{850} is the potential temperature at 850 hPa. Positive differences of wind speed and wind shear as well as negative differences of $\Delta\theta$ and RH indicate more favorable meteorological conditions for the diffusion of air pollutants. Taking the $\pm 10\%$ difference as a threshold of significance, (a) shows the number of significant unfavorable indices among the four indices. Meteorological variables are downloaded from ECMWF ERA5 with a $0.5^\circ \times 0.5^\circ$ resolution, which are averaged to provincial scale to evaluate the meteorological conditions.

It shows a north–south $\Delta\theta$ dipole pattern over mainland China, which indicates a favorable vertical diffusion situation for air pollutants in southern China. RH during the AF1 period is higher than that during the His_AF1 periods by at least 20% over Beijing and surrounding regions. When taking the $\pm 10\%$ difference as a threshold of significance, the number of significant unfavorable indexes shown in Fig. 2a indicates Beijing, Tianjin, and northeast Liaoning Province experienced three more significantly unfavorable indexes for air pollutants simultaneously in the AF1 period, followed by Hebei, Shanxi, Shandong, Sichuan, Qinghai, Guizhou, and Xizang Provinces, and Chongqing with two unfavorable indexes. Except for Beijing and Tianjin, most of the provinces and regions with a remarkable variation in air quality displayed in Fig. 1 did not show significant favorable or unfavorable meteorological diffusion conditions for air pollutants during the AF1 period, which indicates the variations in air pollutant concentrations can be attributed to the changes of anthropogenic activities during the lockdown. However, the unfavorable atmospheric horizontal and vertical diffusion conditions working with the relatively high humidity over Beijing and Tianjin regions benefit the accumulation of ambient air pollutants, hygroscopic

growth, and secondary formation of particles, which might negate the effects of emission reduction during the lockdown period.

Although China's air quality improved greatly due to the strict emission reduction measures in recent years, the government is still taking steps to win "the battle for blue sky." The variations in the nationwide air quality during COVID-19 should be referenceable in determining the goals of future emission reduction policies. With the nationwide reduction of anthropogenic activities, the pollution of particulate matter, SO₂, NO₂, and CO could be eased substantially, whereas the O₃ problem is obviously going to receive more attention. The nationwide increase in O₃ concentration along with reduction in NO₂ demonstrates that O₃ production in China will always be in a VOC-limited stage in the near future. The increase of particulate pollution in Beijing during the pandemic indicates air pollution episodes may still occur with the unfavorable background meteorology, even with the emission reduction efforts as during the COVID-19 period. It is worthy of serious consideration to keep the balance of improving particulate matter and O₃ pollution. In addition, as the domestic coronavirus epidemic is getting controlled, China is already working to bolster its economy and restore the normal social operations in a stepwise fashion. Blue skies and economic development are equally important after the work resumption taking place across China.

Acknowledgments. Daily mean air pollutant concentration observations were obtained from the website of the Ministry of Ecology and Environment of China (<http://106.37.208.233:20035>). The four-times-daily ERA5 dataset from December 2013 to March 2020 was downloaded from www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. This study was supported by the National Natural Science Foundation of China (41790470 and 41805117).

Appendix: Air Pollutant Concentrations during the COVID-19 Outbreak Versus the Historical Average

Figure A1 shows the air pollutant concentrations during BF, AF1, and AF2 as well as their historical average. The historical average over most of the listed provinces shows notable monthly variation from His_BF to His_AF2, with the concentrations of particulate pollutants, SO, CO, and NO₂ decreasing and the O₃ concentration increasing gradually.

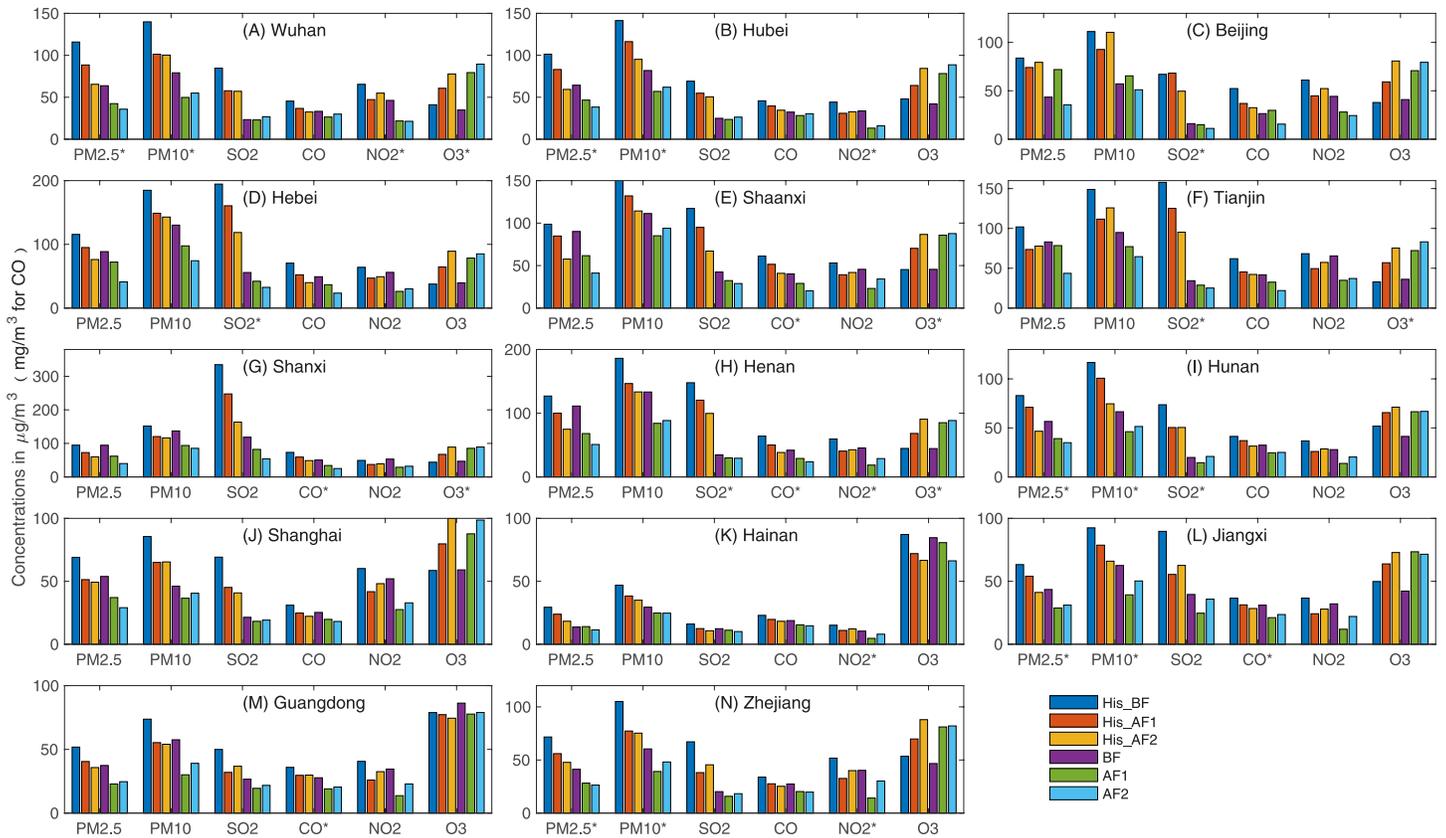


Fig. A1. Air pollutant concentration during the BF, AF1, and AF2 periods as well as their historical average. Provinces with the lowest five normalized air pollutant concentrations (highest for O₃) during the AF1 period are listed here (same as Fig. 1). An asterisk (*) in the label of the x axis indicates the five selected provinces for the specific species. To maintain the comparability of different species, SO₂ and CO concentrations are magnified 3 and 30 times, respectively.

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