**Characteristics of air quality in different climatic zones of China during the COVID-19 lockdown**

Qihang Dai a, b, Tianyi Guan a, b, Honglei Wang a, c \*, Yue Tan a, Bin Zhu a

a Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science &Technology, Nanjing 210044, China

b Department of Earth and Environmental Sciences, The University of Manchester, Manchester, United Kingdom

c State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

\*Corresponding author. *E-mail address:* [hongleiwang@nuist.edu.cn](mailto:hongleiwang@nuist.edu.cn) (H. Wang)

**Abstract:** To understand the impacts of climate and socioeconomic factors on spatial differences in air pollutants variation during COVID-19 lockdown, this study divided 358 cities in China into eight climate zones. Spatial, temporal and diurnal variations of air pollutants from January 1st to April 18th 2020 are analyzed. Climate and socioeconomic led to distinctive regional differences in PM2.5, PM10, SO2 and CO, but their relationship with NO2 and O3 was complicated. PM2.5 decreased by 64.2%–59.0% in the temperate zones (except arid regions). In contrast, the reductions of PM2.5 in the south subtropical and plateau zones only reached 26.1%–17.0%. PM10 declined in most regions but increased by 48.9% and 21.7% instead in the arid temperate zone and the plateau zone. SO2 and CO reductions were around 20%–30% in the subtropical and plateau zones. In contrast, SO2 decreased by 41.1%–47.1% and CO decreased by 63.6%–47.4% in the temperate zones. NO2 dropped by 57.7%–49.1% in all regions but rebounded earlier and faster in regions with high GDP and vehicle populations. O3 surged by 79.2 %–115.5% in most regions except the south subtropical and plateau zones where the O3 merely rose by 24%. Despite the emission reduction in the lockdown, more severe pollution events occurred in the temperate zones or regions with high GDP and vehicle populations. The suppression of diurnal variations was most prominent in the coldest region.

**Keywords:** COVID-19; Climate zones; Socioeconomic; Regional differences; Air quality

**1. Introduction**

Till August 2020, the number of new COVID-19 cases worldwide still showed an increasing trend. Countries like China and South Korea that have adopted effective control measures had a substantial decrease in new cases (WHO, 2020). In January, the Chinese government adopted the emergency health response plan to inhibit the spread of COVID-19, including closing factories and restricting transportation, which has effectively controlled the epidemic (Tian et al., 2020; Wang, Chen, Zhu, Wang, & Zhang, 2020). Meanwhile, air quality was improved as a side effect. Studies have shown that the concentrations of major pollutants decreased significantly in the lockdown (Chu, Zhang, Liu, Ma, & He, 2020; Li et al., 2020; Lian et al., 2020). However, the lockdown measures did not reduce the concentration of some air pollutants. The ozone concentration continued to rise, and the SO2 concentration in some areas barely changed (Almond, Du, & Zhang, 2020; Li et al., 2020; Wang et al., 2020).

The lockdown measures for COVID-19 were conducted in the whole country and lasted for months. Although the air quality in some parts of China was once suddenly improved during APEC and Olympic Games due to short-term intervention (Chen, Jin, Kumar, & Shi, 2013; Cheng et al., 2016), the results of the long-term and large scale lockdown could be different. Many studies about the lockdown impacts on air pollutants have been conducted, mainly focusing on a particular region that shares similar climate and socioeconomic features or discussing general features of the whole country (Bao & Zhang, 2020; Chu et al., 2020; Li et al., 2020; Lian et al., 2020). However, China has a broad span of longitude and latitude with complex conditions in topography and geomorphology. Therefore, the regional climate and socioeconomic characteristics have significant impacts on air pollutants. For example, in the subtropical zones, high humidity conditions are conducive to converting NO2 and SO2 into secondary aerosols, and large amounts of precipitation are conducive to the removal of pollutants. Simultaneously, for arid regions in the mid-temperate zone, dry and windy weather will increase the concentration of suspended particulate matter (Miao et al., 2018). Although the lockdown brought about considerable emission reduction, conditions such as static wind and temperature inversion could still lead to a significant increase of PM2.5 (Sharma et al., 2020; Wang et al., 2020). In addition, the local economy and industrial structure would influence regional air pollutant concentration. Taking NO2 as an example, the NO2 concentration would be higher in areas with developed economies and massive transportation (Zhang, Zhang, Zhang, Li, & Qiu, 2007). In cold areas with heating demand in winter, SO2 emissions would be higher (Meng et al., 2018).

Furthermore, severe air pollution can cause respiratory infections and thus increase the risk of COVID-19 infection (Chauhan & Johnston, 2003; Hendryx & Luo, 2020). Zhang et al. (2020) have found that the high pollutant concentration in northern China offsets the suppression of the spread of COVID-19 by temperature rise. As a result, the study on the regional differences of air pollution variation in China has essential reference value for other countries still needing epidemic control.

This study analyzed the daily average variations, spatial differences and diurnal changes of six major pollutants (PM2.5, PM10, SO2, CO, NO2, O3) from January 1st to April 18th, 2020. Regional characteristics of air pollutant variations among eight climate zones were analyzed in conjunction with economic and meteorological data.

**2. Materials and methods**

**2.1.** **Study period and area**

The climate zoning scheme, which is the newest official and reliable scheme, was based on daily observation data of 609 stations from 1971 to 2000 (Zheng, Yin, & Li, 2010). Concerning this scheme and topographical features, we pick up eight general regions (Fig. 1, Table 1): North-East China (NEC), the cold temperate zone and the humid and semi-humid region of the mid-temperate zone, including 31 cities; inner Mongolia (MG), the semi-arid region of the mid-temperate zone, including 8 cities; North China Plain (NCP), the semi-humid regions of warm temperate zone, including 91 cities; North-Western (NW), the arid and semi-arid regions of the mid-temperate zone, including 30 cities; Yangtze River basin (YR), the humid north subtropical zone, including 60 cities; Central South (CS), the humid mid-subtropical zone, including 73 cities; Southern Coast (SC), the south subtropical zone, including 46 cities; Tibet Plateau (TP), the plateau climate zone, including 19 cities. Then the regional climate characteristics were validated by the NOAA meteorological data during the period from January 1st to April 18th.

The period from January 1st to April 18th 2020 was divided into four phases: Pre-lockdown (Prelock), Level 1, Level 2 and Level 3, based on the intensity of restriction measures in the public health emergency plan. According to the China State Council, all production activities and transportation were forcibly suspended during Level 1 (after January 24th) because of the dramatic growth of confirmed cases. In Level 2 (after February 26th), some necessary industries and transportation were allowed. Since Level 3 (after April 1st), the COVID-19 was well controlled, and most activities restarted, followed by the increase of emission. Although different cities did not adjust the restriction level simultaneously, their industry and transportation began to recover at a roughly similar time (Li et al., 2020; People’s Daily, 2020a, 2020b).

**2.2.** **Data source**

The air pollution data was downloaded from the National Urban Air Quality Real-time Release Platform of the Ministry of Environmental Protection of China (http://106.37.208.233:20035/). Using the data of 1,633 stations across the country, we averaged the data of stations in each prefecture city to obtain the city average. The data of cities in a climate zone was then averaged to obtain the regional average. A total of 367 cities were analyzed. Fig. 1 shows the distribution of monitoring stations.

Wind speeds have an important impact on the distribution of particulate matter (Chen & Ye, 2019; Zhu, Huang, Shi, Cai, & Song, 2011). The meteorological data comes from 406 Chinese surface stations in the National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Data (ISD) (ftp://ftp.ncdc.noaa.gov/pub/data/noaa/isd-lite/). Table 1 shows the average wind speed and precipitation of cities in each climate zone.

Moreover, air pollutants are tightly correlated with socioeconomic factors (Han, Zhou, Li, & Li, 2014; Wang, Zhou, Wang, Feng, & Hubacek, 2017; Zhao, Zhou, Han, & Locke, 2019). Concerning that Chinese cities have evident cluster characteristics along climatic zones and watersheds (Fang, Song, Zhang, & LI, 2005), obtaining regional socioeconomic data is essential for studying the regional differences in the variations of air pollution during the lockdown. Studies have shown that PM2.5 is significantly correlated with the gross domestic product (GDP) and vehicle population (Han et al., 2014; Wang et al., 2017; Zhao et al., 2019). Therefore, we chose GDP and vehicle population to evaluate the regional emission potential. Since the official 2019 statistical yearbook has not been published and vehicle population data were absent in some cities, we crawled GDP and private vehicle population from the 2019 Statistical bulletin of 367 cities in the China Statistical Information Network (http://www.tjcn.org/tjgbsy/nd/36163.html). Then the average value of every climate zone was calculated (Table 1, Fig. 2).

**3. Results and discussion**

**3.1. Temporal concentration variation (daily average) of air pollutants**

As is shown in Fig. 2, the fluctuation intensity (ranges between adjacent peak and valley) of PM2.5 in the temperate zones and north subtropical zone (NCP, YR, NEC, MG, and NW) dropped significantly. In Pre-lockdown, the fluctuations in these regions were higher than 90 μg/m3, which dropped to about 50 μg/m3 in Level 1, and less than 30 μg/m3 in Level 2. Nevertheless, there was no noticeable fluctuation in the mid and south subtropical zone and the plateau zone (SC, CS, and TP). There were several abnormally high values during the lockdown: the beginning of Level 1 in MG (215.4 μg/m3), the end of Level 2 in NW (lasting 3–4 days, higher than 100 μg/m3), the latter part of Level 3 in NEC (146.1 μg/m3). The abnormal value in MG might be a consequence of the calm wind condition (wind speeds remained less than 2m/s) in the first two weeks of Level 1 (Fig. S2). The high concentration in NW at the end of Level 2 was consistent with that of PM10. PM2.5 in NEC rapidly increased from 66.3 μg/m3 to 146.1 μg/m3 at the end of Level 3 due to work resumption, of which the growth was far more significant than that of NW where work resumption also existed. The wind speed in NW was 4 m/s–5 m/s around April 15th, while the wind speed in NEC dropped rapidly from 3.5 m/s to 2.5 m/s (Fig. S2). Unfavorable diffusion conditions exacerbated the Level 3 PM2.5 growth in NEC. This is consistent with the conclusion from Wang et al.(2020): despite the reduction of anthropogenic emission during the lockdown, severe air pollution events were not avoided when adverse weather conditions occurred.

PM10 concentration decreased to a certain extent, but the attenuation of fluctuation was not as significant as PM2.5. The average concentration in NEC, MG, and NCP dropped to less than 100 μg/m3 after the lockdown but frequently surged to 100–200 μg/m3. Meanwhile, the fluctuations in YR could still reach 70 μg/m3 in Level 2 and Level 3. PM10 concentration in NW became even higher during the lockdown, persisting at 150–360 μg/m3 for two months from Level 1 to Level 3. Due to the low precipitation and desert landforms in NW, coarse particles are easily suspended and transported to NEC, MG and NCP with the wind (Lu, Xu, Yang, & Zhao, 2017; Song et al., 2017; Zhu et al., 2011). Despite the massive emission reduction during the lockdown, PM10 concentration could still maintain high value in arid regions.

The SO2 concentration in NEC, NW, MG, NCP dropped from 20–40 μg/m3 to 10–20 μg/m3. In contrast, YR, CS, and SC maintained a low concentration of about 10 μg/m3 and weak fluctuations during the entire period. Like PM2.5 and PM10, the low wind speed (Fig. S2) in NEC, NW, MG, and NCP at the beginning of Level 1 led to SO2 surge: the peak (MG) reached 49.2 μg/m3.

The primary sources of CO are exhaust gases from motor vehicles and metal industries (Wang, Zhang, Hao, & He, 2005). CO in TP gradually decreased from the initial 0.95 mg/m3 to 0.50 mg/m3 at Level 3 as the temperature rose. Since TP had the lowest average GDP (28.41 billion yuan), which suggested inactive human activity, the CO reduction in TP might result from warmer and windier conditions in Spring. CO in NEC, NW, MG, and NCP all decreased by 1.0–1.5 mg/m3. In contrast, the decline in SC and CS was relatively small (within 0.5 mg/m3). CO in SC and CS maintained at about 0.7 mg/m3 through Level 1 to Level 3 owing to the excellent diffusion conditions in the mid and south subtropical zones. CO in NW and MG had peaks above 2 mg/m3 in Pre-lockdown. Nevertheless, the concentration dropped to 0.6–0.5 mg/m3 in Level 3, lower than that in SC and CS. It can be seen from Fig. S1 and Fig. S2 that at Level 3, the wind speeds in NW and MG were much higher than SC and CS. The diffusion conditions were primarily improved by rising temperature and wind speed (which were both relatively stable in SC and CS). Therefore, beneficial diffusion conditions kept CO in NW and MG low in Level 3, even though emission was supposed to be increased by work resumption.

NO2 decreased rapidly at the beginning of Level 1 owing to the active chemical nature of NO2 and the relationship with vehicles. The highest value (69.8 μg/m3) appeared in the early Pre-lockdown stage in NCP. Meanwhile, NCP was the most polluted area in the entire period, consistent with the highest vehicle population (1.185 million per city). Nevertheless, in Level 2 and Level 3, the abnormally high value appeared relatively more frequently in YR. Besides, NO2 was the major pollutant in SC. The high NO2 concentration in NCP, YR, and SC was mainly related to their large vehicle population (averagely around 1 million per city) (Table 1).

Variation trends of O3 were consistent across regions: keep rising due to increased duration and intensity of sunlight. The highest value (126.7μg/m3) appeared in NCP in Level 3. The concentration in NCP, YR and SC fluctuated more evident than other regions, resulting from the high local GDP and vehicle populations. NO2 and VOCs emissions from active production activities and traffic were the reasons for their large fluctuations (Zheng et al., 2009). Also, O3 was the major pollutant and exhibited the highest Prelock value in TP.

**3.2. The spatial distribution characteristics of air pollutants**

The percentages discussed below are calculated in this formula (Level Concentration refers to the average concentrations of a stage during the lockdown in a climate zone. Prelock Concentration refers to the average of Pre-lockdown.):

Overall, PM2.5 experienced a U-shaped curve (Fig. 3). Through the lockdown, the biggest concentration reductions in MG, NCP, and NEC reached 64.2%, 59.8% and 59.0% respectively (Fig. 4, Table S1). The reductions in YR and NW also reached 47.9% and 43.2%. But the reductions in CS, SC, TP only reached 26.1%, 17.0% and 32.3%. PM2.5 dropped more in NCP, NEC, MG and YR where SO2 and NO2 emissions were relatively high.

The decline of PM10 was not as prominent as that of PM2.5. In NEC, MG, and NCP, PM10 kept decreasing till Level 2 with reductions of 47.3% (NEC), 37.2% (NCP) and 40.3% (MG). Differently, PM10 in YR, SC, CS, and TP showed downward trends only in Level 1, with reductions of 33.7% (YR), 27.5% (SC), 21.3% (CS) and 8.7% (TP). However, PM10 in NW kept increasing despite the emission reduction, showing a growth of 48.9% at Level 3. Moreover, the concentration in TP increased by 21.7% in Level 3. The GDP of TP and NW was the lowest among all regions (28.4 and 119.1 billion yuan), indicating weak interference from human activity. The growth in NW and TP might be attributed to natural dust sources and adverse weather conditions (Zhu et al., 2011). For PM10, the intervention of natural factors partly offset the emission reduction.

SO2 experienced a downward trend in NEC, NW, MG, NCP and TP. The concentration of MG showed the largest decrease (48.1%) in Level 3, while that of TP dropped by only 21.7%. The reductions in NEC, NCP, and NW reached 46.9%, 42.2%, and 41.1%, respectively. In contrast, SO2 in YR, SC, and CS decreased merely by 7.5% (YR) – 23.2% (SC) and rose rapidly once the work resumption began after Level 1. In Level 3, SO2 in YR, CS and SC was respectively 20.9%, 13.4%, and 5.0% higher than Pre-lockdown due to enhanced emission.

CO generally decreased with time. Reductions in MG, NW, NCP, and NEC reached 63.6%, 61.5%, 52.6%, and 47.4% respectively. In contrast, CO in YR, CS, SC, and TP declined limitedly around 20%–30%. The private vehicle populations of SC and YR were 983,000 and 972,000, almost twice of NW and NEC, from which a large CO reduction was expected. However, the larger reductions occurred in NEC, NW, NCP and MG (Fig. 4). In SC, the wind speed, temperature and precipitation remained stable through time. CO began to rise soon after Level 1 due to the intensive resumption of work. On the contrary, CO kept decreasing in the temperate zones where temperature and wind speed increased significantly over time. Although more emission should have occurred after Level 2, improved diffusion condition kept CO concentration dropping in NW and MG (Fig. S1).

NO2 experienced a marked U-shaped curve in most regions. The reductions of NO2 reached 57.1% (MG), 54.6% (NEC), 53.2% (NCP), 53.2% (CS), 53.1% (YR), 50.0% (NW) and 49.1% (SC), 41.2% (TP) in Level 1 or Level 2. The lockdown greatly reduced traffic and industrial emissions, resulting in a significant drop in NO2. Furthermore, NO2 rebounded rapidly at Level 2 in regions with developed economics and high vehicle population, while the rebound started later (at Level 3) in regions like MG, NW, and NEC. Compared to other pollutants, NO2 was more sensitive to the changes in human activities in the lockdown.

O3 showed an upward trend over time in all regions. Warming temperature and increased sunlight may have caused the concentration to rise, but the increase was much larger than in previous years (Chu et al., 2020; Li et al., 2020). By Level 3, the rising percentages were 115.5% (NCP), 99.9% (CS), 99.0% (YR), 91.6% (MG), 86.2% (NEC), and 79.2% (NW). Since O3 is closely related to NO2, the plummet of NO2 concentration and inadequate control of VOCs contributed to enhanced O3 concentration during the lockdown. Besides, a significant reduction of PM2.5 led to less consumption of ozone precursors, leading to a more significant ozone increase (Ke et al., 2019). In contrast, the PM2.5 concentrations of SC and TP were not significantly affected by the lockdown. Although longer sunlight and higher temperature also occurred, O3 in the southern coast (SC) and Tibet Plateau (TP) experienced relatively little increases (23.2% in SC and 25.5% in TP).

**3.3. Diurnal variation of air pollutants**

The bimodal distributions of PM2.5 and PM10 were especially evident in NEC and TP (Fig. 5, Fig. S4). Once the lockdown started, the diurnal variation flattened out. The decrease in diurnal variability was most pronounced in NEC, where the diurnal range of PM2.5 dropped from 30.7 μg/m3 (Pre-lockdown) to 12.8 μg/m3 (Level 2), and that of PM10 dropped from 35.9 μg/m3 (Pre-lockdown) to 14.6 μg/m3 (Level 2). In Level 3, the diurnal range of NEC increased significantly to 52.3 μg/m3 (PM2.5) and 56.7 μg/m3 (PM10). However, NCP, which also had relatively high concentrations, maintained a low diurnal variation throughout the four stages. The diurnal ranges of NCP merely reached 11.5 μg/m3 (PM2.5) and 13.7 μg/m3 (PM10). The suppression of diurnal variation was evident in the cold temperate zone (NEC), mainly because of the work resumption and low temperature. However in TP, diurnal range was not inhibited in Level 1 and Level 2, and was even the lower in Level 3 due to improved dispersion condition (higher temperature) and inactive human activity (28.4 billion).

Diurnal variations in SO2 and CO were pronounced in NEC, NW, MG, TP (Fig. S5, Fig. S6). Although the mean concentration decreased in the lockdown, diurnal ranges did not change much among stages. Nevertheless, the pollutant concentration of NEC rose stronger than other regions in Level 3: SO2 increased from 6.74 μg/m3 (Level 2) to 9.9 μg/m3 (Level 3); CO increased from 0.21 mg/m3 (Level 2) to 0.39 mg/m3 (Level 3).

NO2 showed a double peak distribution. Since NO2 is easily photolyzed, the trough becomes more noticeable due to longer and stronger sunlight. The diurnal variation was evident in NEC, NW, and TP (Fig. S7). For instance, in NW, the diurnal range grew to 30.2 μg/m3 (Level 3) from 17.0 μg/m3 (Pre-lockdown). Diurnal ranges were strongly inhibited to 4-8 μg/m3 in the lockdown in regions with high vehicle populations (NCP, YR, SC).

In NEC, NCP, YR, SC, and CS, the diurnal range of O3 was significantly enhanced from 20-30 μg/m3 (Level 2) to 40-60 μg/m3 (Level 3) (Fig.S8) because human activity was more active and NO2 surged with the resumption of work in these regions. The diurnal variation in SC was 46.0 μg/m3 in Pre-lockdown and then was significantly suppressed to about 28.0 μg/m3 in Level 2. Although the mean concentration in SC did not vary much during the lockdown, the change in diurnal variation was noticeable.

**4. Conclusions**

During the lockdown, climate and socioeconomic led to distinctive regional differences in PM2.5, PM10, SO2 and CO, but their relationship with NO2 and O3 was complicated.The reductions of PM2.5 reached up to 64.2%–59.0% in MG, NCP, NEC with high emission potential and relatively low temperatures. The reductions only reached 26.1%–17.0% in the south subtropical and plateau climate zones (TP and SC) with less emission source and better dispersion conditions (high temperature or strong wind). PM10 increased by 48.9%–21.7% in the arid climate zones (NW and TP) that had little precipitation and influential natural dust source. SO2 and CO did not show marked decreases in the subtropical zones (YR, CS, SC) with relatively high temperatures and GDP. In contrast, the maximum decreases reached 46.9%–41.1% for SO2, and 63.6% for CO in the temperate zones (NEC, NCP, and NW) with considerable heating demand and seasonal change of temperatures and wind speeds. NO2 slumped by 57.7%–49.1% in all regions. Nevertheless, NO2 rebound began in Level 2 in NCP, YR and SC with high vehicle populations rather began in Level 3 in other regions. O3 surged by 79.2%–115.5% in most regions. The largest ratio growth of O3 was not in NEC where the temperature climbed most (Fig. S2), but in NCP that held the highest vehicle population. And the fluctuation was more evident in NCP, YR and SC with high GDP and vehicle populations. In SC and TP with less decline of PM2.5, O3 grew merely around 24%.

Severe pollution events under unfavorable weather conditions occurred more frequently in areas with greater emission potential (NCP and YR that held high GDP and intensive traffic) and the temperate climate zones with lower temperatures (MG, NW, and NEC). In comparison, SC, where GDP and private vehicle population were high as well, exhibited a slight change of pollutants owing to its conducive diffusion conditions (high temperature and wind speed) in the south subtropical zone. The diurnal range of pollutants generally decreased in the lockdown and rebounded in Level 3, most prominent in the coldest region (NEC).

**Acknowledgments**

This study was supported by the National Natural Science Foundation of China (41805096), the National Key Research and Development Program of China (2016YFA0602003), the China Postdoctoral Science Foundation (2018M640169) and the Natural Science Foundation of Jiangsu Province (BK20180801).

**References**

Almond, D., Du, X., & Zhang, S. (2020). *Ambiguous Pollution Response to COVID-19 in China* (No. w27086; p. w27086). Cambridge, MA: National Bureau of Economic Research. https://doi.org/10.3386/w27086

Bao, R., & Zhang, A. (2020). Does lockdown reduce air pollution? Evidence from 44 cities in northern China. *Science of The Total Environment*, *731*, 139052. https://doi.org/10.1016/j.scitotenv.2020.139052

Chauhan A. J., & Johnston S. L. (2003). Air pollution and infection in respiratory illness. *British Medical Bulletin*, *68*(1), 95–112. https://doi.org/10.1093/bmb/ldg022

Chen, X., & Ye, J. (2019). When the wind blows: Spatial spillover effects of urban air pollution in China. *Journal of Environmental Planning and Management*, *62*(8), 1359–1376. https://doi.org/10.1080/09640568.2018.1496071

Chen, Y., Jin, G. Z., Kumar, N., & Shi, G. (2013). The promise of Beijing: Evaluating the impact of the 2008 Olympic Games on air quality. *Journal of Environmental Economics and Management*, *66*(3), 424–443. https://doi.org/10.1016/j.jeem.2013.06.005

Cheng, N., Li, Y., Zhang, D., Chen, T., Li, L., Li, J., & Jiang, L. (2016). [Improvement of Air Quality During APEC in Beijing in 2014]. *Huan Jing Ke Xue= Huanjing Kexue*, *37*(1), 66–73.

Chu, B., Zhang, S., Liu, J., Ma, Q., & He, H. (2020). Significant concurrent decrease in PM2.5 and NO2 concentrations in China during COVID-19 epidemic. *Journal of Environmental Sciences*. https://doi.org/10.1016/j.jes.2020.06.031

Fang, C., Song, J., Zhang, Q., & LI, M. (2005). The formation, development and spatial heterogeneity patterns for the structures system of urban agglomerations in China. *ACTA GEOGRAPHICA SINICA-CHINESE EDITION-*, *60*(5), 827.

Han, L., Zhou, W., Li, W., & Li, L. (2014). Impact of urbanization level on urban air quality: A case of fine particles (PM2.5) in Chinese cities. *Environmental Pollution*, *194*, 163–170. https://doi.org/10.1016/j.envpol.2014.07.022

Hendryx, M., & Luo, J. (2020). COVID-19 prevalence and fatality rates in association with air pollution emission concentrations and emission sources. *Environmental Pollution*, *265*, 115126. https://doi.org/10.1016/j.envpol.2020.115126

Ke, L., Jacob, D., Liao, H., Shen, L., Zhang, Q., & Bates, K. (2019). Anthropogenic drivers of 2013-2017 trends in summer surface ozone in China. *Proceedings of the National Academy of Sciences*, *116*. https://doi.org/10.1073/pnas.1812168116

Li, L., Li, Q., Huang, L., Wang, Q., Zhu, A., Xu, J., … Chan, A. (2020). Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: An insight into the impact of human activity pattern changes on air pollution variation. *Science of The Total Environment*, *732*, 139282. https://doi.org/10.1016/j.scitotenv.2020.139282

Lian, X., Huang, J., Huang, R., Liu, C., Wang, L., & Zhang, T. (2020). Impact of city lockdown on the air quality of COVID-19-hit of Wuhan city. *Science of The Total Environment*, *742*, 140556. https://doi.org/10.1016/j.scitotenv.2020.140556

Lu, D., Xu, J., Yang, D., & Zhao, J. (2017). Spatio-temporal variation and influence factors of PM2.5 concentrations in China from 1998 to 2014. *Atmospheric Pollution Research*, *8*(6), 1151–1159. https://doi.org/10.1016/j.apr.2017.05.005

Meng, K., Xu, X., Cheng, X., Xu, X., Qu, X., Zhu, W., … Zhao, Y. (2018). Spatio-temporal variations in SO2 and NO2 emissions caused by heating over the Beijing-Tianjin-Hebei Region constrained by an adaptive nudging method with OMI data. *Science of The Total Environment*, *642*, 543–552. https://doi.org/10.1016/j.scitotenv.2018.06.021

Miao, Y., Liu, S., Guo, J., Yan, Y., Huang, S., Zhang, G., … Lou, M. (2018). Impacts of meteorological conditions on wintertime PM2.5 pollution in Taiyuan, North China. *Environmental Science and Pollution Research*, *25*(22), 21855–21866. https://doi.org/10.1007/s11356-018-2327-1

People’s Daily. (2020a). National Emergency Response Level Summary. Retrieved July 17, 2020, from National emergency response level summary: Five provinces are at level 2, 24, down to level 3 website: http://society.people.com.cn/n1/2020/0508/c1008-31701312.html

People’s Daily. (2020b). Schedule for resumption of work by province. Retrieved July 17, 2020, from https://weibo.com/ttarticle/p/show?id=2309404467436270256212

Sharma, S., Zhang, M., Anshika, Gao, J., Zhang, H., & Kota, S. H. (2020). Effect of restricted emissions during COVID-19 on air quality in India. *Science of The Total Environment*, *728*, 138878. https://doi.org/10.1016/j.scitotenv.2020.138878

Song, C., He, J., Wu, L., Jin, T., Chen, X., Li, R., … Mao, H. (2017). Health burden attributable to ambient PM2.5 in China. *Environmental Pollution*, *223*, 575–586. https://doi.org/10.1016/j.envpol.2017.01.060

Tian, H., Liu, Y., Li, Y., Wu, C.-H., Chen, B., Kraemer, M. U. G., … Dye, C. (2020). An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. *Science*, *368*(6491), 638–642. https://doi.org/10.1126/science.abb6105

Wang, L., Zhang, Q., Hao, J. M., & He, K. B. (2005). Anthropogenic CO emission inventory of Mainland China. *Acta Scientiae Circumstantiae*, *25*, 1580–1585.

Wang, P., Chen, K., Zhu, S., Wang, P., & Zhang, H. (2020). Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak. *Resources, Conservation and Recycling*, *158*, 104814. https://doi.org/10.1016/j.resconrec.2020.104814

Wang, S., Zhou, C., Wang, Z., Feng, K., & Hubacek, K. (2017). The characteristics and drivers of fine particulate matter (PM2.5) distribution in China. *Journal of Cleaner Production*, *142*, 1800–1809. https://doi.org/10.1016/j.jclepro.2016.11.104

Wang, Y., Yuan, Y., Wang, Q., Liu, C., Zhi, Q., & Cao, J. (2020). Changes in air quality related to the control of coronavirus in China: Implications for traffic and industrial emissions. *Science of The Total Environment*, *731*, 139133. https://doi.org/10.1016/j.scitotenv.2020.139133

WHO. (2020). WHO Coronavirus Disease (COVID-19) Dashboard. Retrieved August 3, 2020, from https://covid19.who.int

Zhang, X., Zhang, P., Zhang, Y., Li, X., & Qiu, H. (2007). The trend, seasonal cycle, and sources of tropospheric NO 2 over China during 1997–2006 based on satellite measurement. *Science in China Series D: Earth Sciences*, *50*(12), 1877–1884.

Zhang, Z., Xue, T., & Jin, X. (2020). Effects of meteorological conditions and air pollution on COVID-19 transmission: Evidence from 219 Chinese cities. *Science of The Total Environment*, *741*, 140244. https://doi.org/10.1016/j.scitotenv.2020.140244

Zhao, X., Zhou, W., Han, L., & Locke, D. (2019). Spatiotemporal variation in PM2.5 concentrations and their relationship with socioeconomic factors in China’s major cities. *Environment International*, *133*, 105145. https://doi.org/10.1016/j.envint.2019.105145

Zheng, Jingyun, Yin, Y., & Li, B. (2010). A New Scheme for Climate Regionalization in China. *Acta Geographica Sinica*, *65*(1). https://doi.org/10.11821/xb201001002

Zheng, Junyu, Shao, M., Che, W., Zhang, L., Zhong, L., Zhang, Y., & Streets, D. (2009). Speciated VOC Emission Inventory and Spatial Patterns of Ozone Formation Potential in the Pearl River Delta, China. *Environmental Science & Technology*, *43*(22), 8580–8586. https://doi.org/10.1021/es901688e

Zhu, L., Huang, X., Shi, H., Cai, X., & Song, Y. (2011). Transport pathways and potential sources of PM10 in Beijing. *Atmospheric Environment*, *45*(3), 594–604. https://doi.org/10.1016/j.atmosenv.2010.10.040