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Research article

Comparison of air pollutants and their health effects in two developed regions in China during the COVID-19 pandemic

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A B S T R A C T

Air pollution attributed to substantial anthropogenic emissions and significant secondary formation processes have been reported frequently in China, especially in Beijing-Tianjin-Hebei (BTH) and Yangtze River Delta (YRD). In order to investigate the aerosol evolution processes before, in, and after the novel coronavirus (COVID-19) lockdown period of 2020, ambient monitoring data of six air pollutants were analyzed from Jan 1 to Apr 11 in both 2020 and 2019. Our results showed that the six ambient pollutants concentrations were much lower during the COVID-19 lockdown due to a great reduction of anthropogenic emissions. BTH suffered from air pollution more seriously in comparison of YRD, suggesting the differences in the industrial structures of these two regions. The significant difference between the normalized ratios of CO and NO2 during COVID-19 lockdown, along with the increasing PM2.5, indicated the oxidation of NO2 to form nitrate and the dominant contribution of secondary processes on PM2.5. In addition, the most health risk factor was PM2.5 and health-risk based air quality index (HAQI) values during the COVID-19 pandemic in YRD in 2020 were all lower than those in 2019. Our findings suggest that the reduction of anthropogenic emissions is essential to mitigate PM2.5 pollution, while O3 control may be more complicated.

1. Introduction

Air pollution in China have attracted attentions due to its frequent regional and local haze events (Li et al., 2017a; Nie et al., 2018; Scott et al., 2018; Shen et al., 2020; Wang et al., 2016, 2019; Xu et al., 2019). The annual averaged PM10, PM2.5, CO and SO2 levels have remarkably decreased due to the efforts of emission reduction and energy optimization (Ma et al., 2016; Maji and Sarkar, 2020; Sun et al., 2018). However, other pollutants including NO2 and O3 are still complicated (Ma et al., 2019; Shen et al., 2020). For example, ~50.7% of the O3 monitoring stations showed a significant positive trend of ≥2 μg m−3 year−1. On the other side, only 20.9% of NO2 monitoring stations were associated with a negative trend of ≥−2 μg m−3 year−1 (Maji and Sarkar, 2020). In addition, previous studies have illustrated that particulate matters (PM) and gaseous pollutants (SO2, NO2, O3 and CO) can lead to heart disease, lung cancer, respiratory infections, and even premature deaths (Gu et al., 2002; He et al., 2009; Kan et al., 2012). Studies on health effects of air pollution on a large spatial scale in China are relatively limited, especially in some disease pandemic event (Shen et al., 2020). Furthermore, air pollution related health risks with some

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At the end of 2019, an epidemic of respiratory disease caused by a novel coronavirus (named as “COVID-19”) started to spread (Huang et al., 2020; Tian et al., 2020; Wang et al., 2020). As is well known, the disease has become a global pandemic with more than 30 million confirmed cases by September 20, 2020, with over 90,000 cases reported in China (https://coronavirus.jhu.edu/map.html). China, the first country facing with this unprecedented challenge, the central and local governments imposed strong restrictions on the movement/activities of people (“lockdown”) from Jan 24 to Feb 10, 2020, to contain the COVID-19 outbreak. Subsequently, the nationwide lockdown provides an experimental opportunity to investigate how the variations of air pollution response to the large reduction of the anthropogenic emissions. Additionally, as the remarkable regional differences of anthropogenic emission sources in the Beijing-Tianjin-Hebei region (BTH) and the Yangtze River Delta region (YRD), it makes the comparison of the atmospheric aerosol evolution processes before, in, and after the lockdown period of COVID-19 in these two regions possible. Previous studies illustrated that coal combustion and traffic-related emissions are the dominant sources in BTH (Li et al., 2017a; Tian et al., 2018; Wang et al., 2019; Xu et al., 2019). Moreover, it has been illustrated that aqueous-phase reactions play an important role in the formation of sulfate, nitrate, and some secondary organic aerosol (SOA) in BTH (Duan et al., 2020; Xu et al., 2017). However, industrial-related coal-combustion PM was reported in some certain areas in YRD (Wang et al., 2018; Wu et al., 2018; Yang et al., 2020). Furthermore, aqueous-phase driven secondary aerosols appear to be very important in enhancing PM$_2.5$ (particles with an aerodynamic diameter < 1 µm) pollution while organic aerosols (OA) pollution in YRD is due to photochemical processes (Wu et al., 2018). Similar emission-control events have been conducted in China for many times, e.g., the 2008 Beijing Olympic Games (Huang et al., 2010), the 2014 Asia-Pacific Economic Cooperation (APEC) summit (Sun et al., 2016), and the 2016 Hangzhou G20 summit (Li et al., 2018). However, emission-control events mentioned before were all small regional control (Huang et al., 2010; Sun et al., 2016). Thus, the COVID-19 lockdown provides an opportunity to examine how different types of emission sources, how meteorological conditions affect the formation and evolution of air pollution, and what implications have for the effects of nationwide lockdown on the future air quality and human health if China improves the energy structure in the future.

Herein, to investigate the atmospheric aerosol evolution processes before, in, and after the lockdown of COVID-19 in two typical regions (BTH and YRD), the variations of six criteria air pollutants (PM$_{2.5}$, O$_3$, NO$_2$, SO$_2$, CO, and PM$_{10}$) from Jan 1 to Apr 11 in 2020 were compared to the same period in 2019. In addition, the health-risked based air quality index (HAQI) from these six pollutants was also estimated proposed by Hu et al. (2015). The result of this study will provide an experimental opportunity to investigate the air pollution response to the large reduction of the anthropogenic emissions.

2. Methods

2.1. Study areas and data sources

Hourly averaged concentrations of six criteria air pollutants (PM$_{2.5}$, O$_3$, NO$_2$, SO$_2$, CO, and PM$_{10}$) from January 1 to April 11 in 2019 and 2020 from 1479 national monitoring sites in 367 cities of China (Figure S1, data from Taiwan, Hongkong, and Macau are not included) were downloaded from website of China Ministry of Ecology and Environment (http://datacenter.mee.gov.cn). The 8-h moving averaged concentrations of O$_3$ were used in this study. Thus, enough data follow the statistical significance and have great confidence that the results of the data might not be caused by chance.

In order to better elucidate the responses of concentrations of six air pollutants to the dramatic changes in human activities during COVID-19 lockdown, we classified the study period into ten stages (Table S1), which covered the period before (Pre-COVID-19, Stages I and II), during (COVID-19 lockdown, Stages III and IV) and after (Recovery period, Stages V-X) the lockdown. This work focuses on the comparison of characteristics of air pollutants in two developed regions, Beijing-Tianjin-Hebei (BTH) and Yangtze River Delta (YRD). There are great differences in the industrial categories between BTH and YRD (Wan et al., 2020). For example, secondary industry (e.g., steel-producing) is leading economy in BTH, while tertiary-industry (e.g., electronic products) is dominant in YRD (Wan et al., 2020).

Meteorological data, including ambient temperature, relative humidity (RH), wind speed (WS), wind direction (WD) and atmospheric pressure, were collected from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5 (ERA5) dataset (Hoffmann et al., 2019). It is the ECMWF’s latest reanalysis product and will replace the widely used ERA-Interim. ERA5 provides hourly estimates of a large number of atmospheric, land, and oceanic climate variables, with a spatial resolution of 0.25° × 0.25° and resolve the atmosphere using 137 levels from the surface up to a height of 80 km (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). In this study, the near-surface (950 hpa) data was used with a constant time point of 06:00 (UTC, 14:00 local time).

2.2. Estimation of health effects

In order to evaluate the health effects of varying air quality, we calculated the excess risk (ER) of all six pollutants (ER$_{\text{Total}}$) as well as the health-risked based air quality index (HAQI) (Hu et al., 2015; Shen et al., 2020). ER of each pollutant is summed up to calculate the ER$_{\text{Total}}$. After calculation of the ER$_{\text{Total}}$, the equivalent concentration (C*) of a pollutant by assuming its ER equals to the ER$_{\text{Total}}$ can be estimated, and the HAQI can be calculated in the same manner as AQI, by using C* of the six pollutants (Hu et al., 2015). Technical details can be found in Hu et al. (2015). The HAQI is proven to be a better index to reflect the combined health effects from all six commonly monitored pollutants than AQI (Shen et al., 2017, 2020). More details can be found in Text S1.

2.3. Data normalisation

As air pollutants are values of different orders of magnitude, the correlations between each air pollutant could not be discussed at the same level as equivalent parameters. Only after non-dimensional data process can different physical variables be of significance to make comparisons. Therefore, a Z-score data normalization method has been applied to discuss in relationships between each air pollutant in this study. The method can be described in the following equation:

$$X_{\text{normalized}} = \frac{X - X_{\text{mean}}}{SD}$$  \hspace{1cm} (1)

where $X$ is the measured value, $X_{\text{normalized}}$ is the processed normalized value, while $X_{\text{mean}}$ and SD are the mean values and standard deviation of sample dataset of X during Stage I, respectively.

3. Results and discussion

3.1. Overview of air quality in BTH and YRD during COVID-19 pandemic

In this study, remarkably spatial distributions of the six pollutants levels in most of China were presented in the first four stages of the pandemic (from 1 January to 9 February 2020) (Fig. 1). In Stage I, as the whole country was still running normally, high NO$_2$ levels were found over most parts of northern and northeastern, and some parts of southern China, especially in BTH (on average 30 ppb) and YRD (21 ppb). O$_3$ presented the lowest average values of 10 ppb and 12 ppb in other social problem, such as population, industry structure, pandemic, is still not yet studied.

Journal of Environmental Management 287 (2021) 112296
2
BTH and YRD, respectively. However, much higher values for PM$_{2.5}$, SO$_2$, CO, and PM$_{10}$ were found in northern and northeastern China. In Stage II, a large number of people were on travel for the Chinese Spring Festival. NO$_2$ had a great decrease in the southeastern part but no obvious change in the northeastern part. However, O$_3$ increased more greatly in the southern part than that in the northern part. Subsequently, the distributions of PM$_{2.5}$, SO$_2$, CO, and PM$_{10}$ in northern China consisted with the distribution pattern in Stage I. Stage III was the Chinese Spring Festival week, and most people were forced to stay at home because of the COVID-19 lockdown. As we can see from Fig. 1, NO$_2$ and CO were reduced about 70% and 30% in most regions of China. However, SO$_2$ showed no obvious variation in most of China. As O$_3$ concentration increased during Stage III owing to significant NO$_2$ reduction, we can infer O$_3$ produced by VOCs through complex photochemical reactions of volatile organic compounds (VOCs) and nitric oxide (NOx), which depends heavily on temperature and solar radiation (Kwok et al., 2015). Moreover, higher SO$_2$ levels in northern part which might be contributed by coal combustion and biomass burning for heat-supply. PM$_{2.5}$ was still at a very high level in the northern part, especially in BTH, which could reach as high as 120 μg m$^{-3}$ on average, whereas PM$_{10}$ was lower than that in Stage II. Some recent studies reveal that this was due to that secondary PM formation offsets the reduction of primary emission, which is further attributed to the enhancement of atmospheric oxidation capacity (Chang et al., 2020; Huang et al., 2020; Tian et al., 2020). Stage IV was still in the COVID-19 strict lockdown period. The mass concentrations of PM$_{2.5}$ and PM$_{10}$, together with NO$_2$, SO$_2$, CO, were much lower than those in other three stages, which might be attributed by primary emissions. O$_3$ concentration showed significant increase during Stage IV owing to NO$_2$ reduction, which is consistent with the first three stages. Hence, all the results related above can initially infer that the concentrations of the six pollutants during Stage IV were much lower than those in Stage I-III due to the great reduction of anthropogenic emissions.

In order to investigate the atmospheric aerosol evolution processes in
the two developed regions (BTH and YRD) during the COVID-19 pandemic, the differences in the six major pollutants during the same period in 2019 and 2020, have been compared in this study (Fig. 2). Briefly, in BTH, the entire period-average mass concentration of PM$_{2.5}$ in 2020 was 88% of that in 2019, whereas O$_3$ increased 7%. NO$_2$, SO$_2$, CO, and PM$_{10}$ were 81%, 67%, 89%, and 77% in 2020 of those in 2019, respectively. The implication is that anthropogenic emissions were largely reduced in BTH in the first season in 2020 when compared to those in 2019. For the cases, the PM$_{2.5}$ concentrations increased gradually in the first three stages in 2020 and then dramatically decreased to 50% of Stage III from Stage IV to VII. As the heating supply ended on March 15 in the northern part of China, PM$_{2.5}$ dropped to 20% of that in Stage III from Stage VIII to X. In the meantime, CO also showed a decrease from Stage VIII to X. PM$_{2.5}$ in Stage III (Spring Festival week) in 2020 was even higher than that in Stage III of 2019, while the PM$_{2.5}$ levels were similar in 2019 and 2020 for both Stage I and II. In Stage III, the differences of CO in 2019 and 2020, suggests there might be a different PM$_{2.5}$ formation pathway during the Spring Festival of 2020. In comparison to the gradually increasing O$_3$ in 2019, O$_3$ in Stage III dramatically increased to two-fold of that in Stage II of 2020, indicating photochemical processes may act as a contributor to PM$_{2.5}$ formation in Stage III. As expected, O$_3$ was keeping at a high level in the other stages in BTH, and NO$_2$, SO$_2$, CO, and PM$_{10}$ were at lower concentrations in 2020 when compared to those in 2019.

However, in YRD, the entire period-average mass concentration of PM$_{2.5}$ was much lower than that in BTH in both 2019 (54 μg m$^{-3}$ in YRD and 71 μg m$^{-3}$ in BTH, respectively) and 2020 (39 μg m$^{-3}$ in YRD and 63 μg m$^{-3}$ in BTH, respectively). Besides, the concentrations of SO$_2$, CO, and PM$_{10}$ were also significantly lower than those in BTH in both 2019 (SO$_2$, CO, and PM$_{10}$ were 47%, 74%, and 67% of that in BTH, respectively) and 2020 (SO$_2$, CO, and PM$_{10}$ were 56%, 70%, and 60% of that in BTH, respectively), whereas NO$_2$ levels were similar between BTH and YRD (88% and 80% of that in BTH in 2019 and 2020, respectively). Regarding the differences in the industry-structure of these two regions, BTH was more polluted from winter to early spring, and more SO$_2$ and CO were released to the atmosphere.

3.2. Implications of the variations of PM$_{2.5}$, O$_3$, NO$_2$, and CO for the economic activities during the COVID-19 pandemic

Fig. 3 displays the temporal variations of normalized ratios of PM$_{2.5}$, O$_3$, NO$_2$, and CO by their mean values from pre-COVID-19, in BTH and YRD, respectively. The normalized ratios of primary concentrations, e. g., NO$_2$ and CO, present better correlation ($r^2$ of 0.47, Figure S2) in BTH than that in YRD ($r^2$ of 0.14, Figure S2), which suggests that there are great differences in emission sources between BTH and YRD. The significant difference between the normalized ratios of CO and NO$_2$ during COVID-19 lockdown (Stage III–IV) in both BTH and YRD, along with the increasing PM$_{2.5}$, which can be initially inferred indicated the dominant contribution of secondary processes on PM$_{2.5}$ during those stages. The normalized NO$_2$ and CO were kept less than 1 during the whole recovery period from Stage V to X. Since NO$_2$ and CO are two primary emissions directly related to anthropogenic activities, illustrating that the economic activities/anthropogenic emissions in BTH were still not fully recovered during this period. In comparison, the normalized CO and NO$_2$ in YRD were close to those in Stage I, suggesting that the recovery of economic activities in YRD was better than that in BTH.

Fig. 4 showed different relationships between each air pollutant. CO, originated from primary sources (Khalil and Rasmussen, 1988), can help to distinguish the primary and secondary sources of PM$_{2.5}$. Therefore,
the variation of normalized PM$_{2.5}$ with normalized CO is displayed in Fig. 4a. In BTH, the normalized PM$_{2.5}$ in heavy-polluted periods (Stage I–III) increased from 1 to 1.6, however, there is no significant change in the normalized CO, which indicates that partial PM$_{2.5}$ was likely attributed to the secondary processes in Stage II and Stage III (Spring Festival week). During the less-polluted periods (Stage IV to Stage X), the normalized PM$_{2.5}$ and normalized CO was basically on the 1:1 line in BTH, suggesting the PM$_{2.5}$ pollution was mainly from primary emissions. In comparison, in YRD, the normalized PM$_{2.5}$ shows a poor correlation with normalized CO, indicating different sources, including primary emissions and secondary formation. However, the normalized PM$_{2.5}$, as a function of O$_3$, shows a remarkable difference between the heavy-polluted periods and less-polluted periods for both BTH and YRD.

Figure S3 illustrates the maps of mean values of temperature (T), relative humidity (RH), wind speed (WS), and wind direction (WD) at 950 Pa in China from the EPA5 reanalysis data. Stage III in BTH was under a cold (average T of $-0.8^\circ$C), high moisture (average RH of 63%), stable (average WS of 1.5 m s$^{-1}$ with regional cycling air masses) meteorological condition. Subsequently, a huge amount of primary emissions was accumulated in BTH in Stage III. In addition, the Stage III (Spring Festival week) in BTH was of particular interest. In Stage III, most factories were shut down or set at a lowest operating efficiency. In addition, the vehicle emissions have also been reduced to the lowest

![Figure 3](https://example.com/figure3.png)

**Fig. 3.** Temporal variations of normalized ratios of PM$_{2.5}$, O$_3$, NO$_2$, and CO by their mean values of pre-, during- and after-lockdown in (a) BTH and (b) YRD.

![Figure 4](https://example.com/figure4.png)

**Fig. 4.** The relationships between (a) normalized PM$_{2.5}$ and normalized CO, (b) normalized PM$_{2.5}$ and normalized O$_3$, (c) normalized PM$_{2.5}$ and normalized NO$_2$, and (d) normalized O$_3$ and normalized NO$_2$ in BTH and YRD.

The increase of O$_3$ could be driven by decreasing PM$_{2.5}$ concentrations due to HO$_2$ and NO$_x$ radicals scavenged by fine particles (Li et al., 2019). However, when compared with PM$_{2.5}$, the origins of and factors influencing O$_3$ are more complex.

The relationship of the normalized PM$_{2.5}$ and the normalized NO$_2$ was shown an opposite result (Fig. 4c). Negative relationships between NO$_2$ and O$_3$ can be found in Fig. 4d. Furthermore, the normalized O$_3$ displayed a negative correlation with the normalized NO$_2$, especially in BTH (Fig. 4d). The implication is that more primary emissions may produce more O$_3$ through photochemical reactions with NO$_2$ during the heavy-polluted periods, while high O$_3$ concentrations in the less-polluted periods may attribute to higher intensive of more VOCs emissions.
because of lockdown. However, the averaged mass concentration of PM2.5 (120 μg m$^{-3}$) was even higher than those in Stage I and II, which was the highest during the entire period in 2020. Hence, it aroused a nationwide concern of people.

Moreover, photochemical processing may play a significant role in the increase of PM$_{2.5}$ pollution as displayed in Figure S4. CO and SO$_2$ in Stage III were comparable to those in Stage I and Stage II, however, NO$_2$ varied greatly and showed obvious negative correlations with PM$_{2.5}$ and O$_3$, respectively. The implication is that NO$_2$ was oxidized to nitrate in PM$_{2.5}$, especially organic nitrates, such as RO$_2$NO$_2$ (PAN) and RONO$_2$ (methyl nitrate). Actually, the reduction of NOx emission could lead to an increase of organic nitrate due to the increase of O$_3$ and consequently a major availability of OH radical that can oxidize VOCs (Huang et al., 2021). However, there is no evidence to support the observation of organic nitrate in gaseous and particulate phase in this study.

3.3. Health effect

In this study, the health risks from these six pollutants were also estimated. Here we used the threshold value of ambient air quality standards of China (CAAQS) Garde II. Figure S5 presents averaged excess risks (ERs) of individual pollutants and the total ERs in the entire study duration in 2019 and 2020. Overall, the total ER decreased slightly, from 3.04% in 2019 to 2.92% during the COVID-19 epidemic in 2020, which is due to the national lockdown strategy and emission reduction in each industrial section. The main health risk factors were PM$_{2.5}$, PM$_{10}$, NO$_2$, of which PM$_{2.5}$ contributed the most, accounting for 53% in 2019 and 54% in 2020, followed by PM$_{10}$ with the proportion of 45% in 2019 and 44% in 2020, and finally NO$_2$, accounting for 2% in 2019 and 1% in 2020. In addition, the ERs of other pollutants (SO$_2$, O$_3$, and CO) can be ignored. The averaged HAQI values from January 1 to April 11 in both 2019 and 2020 in most of China are shown in Fig. 5. Overall, it was found that the averaged HAQI values in 2020 was 75.9, a decrease of 14.4% over the same period in 2019 (88.7). Relative higher averaged HAQI values (>100) in both 2019 and 2020 were observed in northern China, especially in BTH, indicating higher health risks in these regions. Apparently higher HAQI values (>100) can be found in BTH during the same period in both 2019 and 2020. However, almost all people in YRD lived in healthy air with the HAQI values less than 100.

Obvious declines of the HAQI values in 2020 in BTH and YRD have been observed with decreases of 24.5% and 18.1%, respectively. Our results might be explained by the dramatic increase of PM in Stage III as discussed above. Besides, Shen et al. (2020) also found that HAQI values were responsible for other socioeconomic factors, such as total population, population density and built-up area, secondary industry. Interestingly, in YRD, the HAQI values decreased with the decreasing of PM concentrations but increasing of O$_3$, indicating the relatively negligible O$_3$ contributions to HAQI. Actually, the health effect of O$_3$ could not be negligible in reality due to their contribution to respiratory tract disease and cardiovascular disease. This is because the lower β values of O$_3$ in the HAQI estimation method. Therefore, the parameters of HAQI estimation should be adjusted in the future work.

4. Conclusion

In this study, we analyzed ambient monitoring data of six air pollutants including PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, CO from January 1 to April 11 in both 2020 and 2019 to investigate the aerosol evolution processes before, in, and after the lockdown period of COVID-19 pandemic. The six ambient pollutants concentrations were found to be much lower during the COVID-19 lockdown because of the declines of anthropogenic emissions. Regarding the differences in industrial structures of BTH and YRD, BTH was more polluted with more SO$_2$ and CO release. The significant difference between the normalized ratios of CO and NO$_2$ during COVID-19 lockdown, along with the increasing PM$_{2.5}$, indicated the dominant contribution of secondary processes on PM$_{2.5}$. NO$_2$ showed obvious negative correlations with PM$_{2.5}$ and O$_3$, suggesting a large number of NO$_2$ was oxidized to nitrate in PM$_{2.5}$. In addition, the national total ER decreased slightly during the COVID-19 pandemic, which is due to the national lockdown strategy and emission reduction in each industrial section. The most health risk factor was PM$_{2.5}$ followed by PM$_{10}$ and NO$_2$, while other pollutants (SO$_2$, O$_3$, and CO) can be ignored. Obvious declines of the averaged HAQI values in BTH and YRD have been observed with decreases of 24.5% and 18.1%, respectively. Our results will provide experimental opportunity to investigate the air pollution response to the large reduction of the anthropogenic emissions.

Credit author contribution statement

Junfeng Wang, planed and designed the research, conducted the statistical analysis, contributed to writing the manuscript. Yali Lei, planned and designed the research, conducted the statistical analysis, were responsible for reviewing and editing the manuscript. Yi Chen, were responsible for reviewing and editing the manuscript. Yangzhou Wu, conducted the statistical analysis. Xintei Ge, supervised the study. Fuwen Shen, conducted the statistical analysis. Jie Zhang, conducted the statistical analysis. Jianhuai Ye, were responsible
for reviewing and editing the manuscript. Dongyang Nie, were responsible for reviewing and editing the manuscript. Xiuyong Zhao, were responsible for reviewing and editing the manuscript. MinDong Chen, supervised the study. All authors read and approved the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Chang, Y., Huang, R.-J., Ge, X., Huang, X., Hu, J., Duan, Y., Zou, Z., Liu, X., Lehmann, M. F., 2020. Puzzling haze events in China during the coronavirus (COVID-19) shutdown. Geophys. Res. Lett. 47, e2020GL086553.
Duan, J., Huang, R.-J., Li, Y., Chen, Q., Zheng, Y., Chen, Y., Lin, C., Ni, H., Wang, M., Ovadnevaite, J., 2020. Summertime and wintertime atmospheric processes of secondary aerosol in Beijing. Atmos. Chem. Phys. 20, 32703–32727.
Gu, D., Reynolds, K., Wu, X., Chen, J., Duan, X., Münchner, P., Huang, G., Reynolds, R.F., Su, S., Whelpot, P.K., He, J., 2002. Prevalence, awareness, treatment, and control of hypertension in China. Hypertension 40, 920–927.
He, J., Gu, D., Chen, J., Wu, X., Kelly, T.N., Huang, J.-F., Chen, J.-C., Chen, C.-S., Bazzano, L.A., Reynolds, K., Whelpot, P.K., Klag, M.J., 2009. Premature death attributable to blood pressure in China: a prospective cohort study. Lancet 374, 1765–1772.
Hofmann, L., Günther, G., Li, D., Stein, O., Wright, J.S., 2019. From ERA-Interim to ERA5: the considerable impact of ECMWF’s next-generation reanalysis on Lagrangian transport simulations. Atmos. Chem. Phys. 19, 3097–3124.
Hu, J., Ying, Q., Wang, Q., Zhang, H., 2015. Characterizing multi-pollutant air pollution in China: comparison of three air quality indices. Environ. Int. 84, 17–25.
Huang, W., Yang, Y., Wang, Y., Gao, W., Wang, Y., 2021. Exploring the inorganic and organic nitrate aerosol formation regimes at a suburban site on the North China Plain. Sci. Total Environ. 768, 144538.
Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., Tang, R., Wang, J., Ren, C., Nie, W., 2020. Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. National Science Review.
Huang, X.F., He, L.-Y., Hu, M., Canagaratna, M., Sun, Y., Zhang, Q., Zhu, T., Xue, L., Zeng, L.-W., Liu, X.-G., 2010. High-time resolved chemical characterization of atmospheric submicron particles during 2008 Beijing olympic games using an aerodynamic high-resolution aerosol mass spectrometer. Atmos. Chem. Phys. 10, 8093–8112.
Kan, H., Chen, R., Tong, S., 2012. Ambient air pollution, climate change, and population health in China. Environ. Int. 42, 10–19.
Khalil, M.A.K., Rasmussen, R.A., 1988. Carbon monoxide in the Earth’s atmosphere: indications of a global increase. Nature 332, 242–245.
Kwok, R.H.F., Baker, K.R., Napelenok, S.L., Tonnesen, G.S., 2015. Photoc hemical grid model implementation and application of VOC, NOx, and O3 source apportionment. Geosci. Model Dev. Discuss. (GMD) 7, 99–114.
Li, K., Jacob, D.J., Liao, H., Zhu, J., Zhai, S., 2019. A two-pollutant strategy for improving ozone and particulate air quality in China. Nat. Geosci. 12.
Li, W., Yu, L., Lin, Y., Xiong, L., Lin, Y., Yao, Y., Gao, H., Zhang, D., Chen, J., Wang, W., Harrison, R.M., Zhang, X., Shao, L., Fu, P., Nenes, A., Shi, Z., 2017a. Air pollution-aerosol interactions produce more bioavailable iron for ocean ecosystems. Science Advances 3, e1601749.
Li, Y.-J., Sun, Y., Zhang, Q., Li, X.-L., Mou, Z., Chan, C.K., 2017b. Real-time chemical characterization of atmospheric particulate matter in China: a review. Atmos. Environ. 158, 270–304.
Ma, X., Gong, W., Zhu, Z., 2016. The study of long-term air pollution characteristic in Wuhan, China. 2016. IEEE International Geoscience and Remote Sensing Symposium (IGARSS) 4119–4122.
Ma, X., Jia, H., Sha, T., An, J., Tian, R., 2019. Spatial and seasonal characteristics of particulate matter and gaseous pollution in China: implications for control policy. Environ. Pollut. 248, 421–428.
Maij, K.J., Sarkar, C., 2020. Spatio-temporal variations and trends of major air pollutants in China during 2015–2018. Environ. Sci. Pollut. Control. Ser. 27, 33792–33808.
Nie, D., Wu, Y., Chen, M., Liu, H., Zhang, K., Ge, F., Yuan, Y., Ge, X., 2018. Bioaccessibility and health risk of trace elements in fine particulate matter in different simulated body fluids. Atmosphere. Environ. 186, 1–8.
Scott, C., Arnold, S., Monks, S., Amini, A., Pazosenn, P., Spracklen, D., 2018. Substantial large-scale feedbacks between natural aerosols and climate. Nat. Geosci. 11, 44–48.
Shen, F., Ge, X., Hu, J., Nie, D., Tian, L., Chen, M., 2017. Air pollution characteristics and health risks in Henan Province, China. Environ. Res. 156, 625–634.
Shen, F., Zhang, L., Jiang, L., Tang, M., Gai, X., Chen, M., Ge, X., 2020. Temporal variations of six ambient air pollution (CO, O3, NO2) in Henan province, China. Environ. Sci. Pollut. Control. Ser. 27, 33792–33808.
Tian, H., Lin, L., Li, Y., Wu, C.-H., Chen, B., Kraemer, M.U., Li, B., Cai, J., Xu, B., Yang, Q., 2020. An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. Science 368, 638–642.
Tian, J., Ni, H., Han, Y., Shen, Z., Wang, Q., Long, X., Zhang, Y., Cao, J., 2018. Primary PM2.5 and gas emissions from residential coal combustion: assessing semi-coke briquette for emission reduction in the Beijing-Tianjin-Hebei region, China. Atmos. Environ. 191, 378–386.
Wan, Z., Wang, P., Wang, Q., Wang, Q., Wang, T., Wei, G., 2020. China Statistical Yearbook 2019. National bureau of statistics of China.
Wang, G., Zhang, R., Gomez, M.E., Yang, L., Zamora, M.L., Hu, M., Lin, Y., Peng, J., Guo, S., Meng, J., 2016. Persistent sulfate formation from London Fog to Chinese haze. Proc. Natl. Acad. Sci. Unit. States Am. 113, 13630–13635.
Wang, J., Wu, Y., Ge, X., Shen, G., Ge, S., 2018. Characteristics and sources of ambient refractory black carbon aerosols: insights from soot particle mass spectrometer. Atmos. Environ. 185, 147–152.
Wang, T., Xue, L., Brimblecombe, P., Lam, Y.F., Li, L., Zhang, L., 2017. Oxone pollution in China: a review of concentrations, meteorological influences, chemical precursors, and effects. Sci. Total Environ. 575, 1582–1596.
Wang, Y., Wang, Q., Ye, J., Yan, M., Qin, Q., Prevot, A.S., Cao, J., 2019. A review of aerosol chemical composition and sources in representative regions of China during wintertime. Atmosphere 10, 277.
Wang, Y., Wen, Y., Wang, Y., Zhang, S., Zhang, K.M., Zhang, H., Xing, J., Wu, Y., Hao, J., 2020. Four-month changes in air quality during and after the COVID-19 lockdown in six megacities in China. Environ. Sci. Technol. Lett. 7, 802–808.
Wu, Y., Ge, X., Wang, J., Shen, Y., Ye, Z., Ge, S., Wu, Y., Yu, H., Chen, M., 2018. Responses of secondary aerosols to relative humidity and photochemical activities in an industrialized environment during late winter. Atmos. Environ. 193, 66–78.
Xu, W., Han, T., Du, W., Wang, Q., Chen, C., Zhao, J., Zhang, Y., Li, J., Fu, P., Wang, W., 2017. Effects of aqueous-phase and photochemical processing on secondary organic aerosol formation and evolution in Beijing, China. Environ. Sci. Technol. 51, 762–770.
Xu, W., Sun, Y., Wang, Q., Zhao, J., Wang, J., Ge, X., Xie, C., Zhou, W., Du, W., Li, J., 2019. Changes in aerosol chemistry from 2014 to 2016 in winter in Beijing: insights from high-resolution aerosol mass spectrometry. J. Geophys. Res.: Atmosphere 124, 1142–1147.
Yang, H., Wang, J., Chen, M., Nie, J., Shen, F., Lei, Y., Ge, P., Gu, T., Gai, X., Huang, X., 2020. Chemical characteristics, sources and evolution processes of fine particles in Lin’an, Yangtze River Delta, China. Chemosphere 126851.