



Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.



Full length article

Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak

Pengfei Wang^{a,b}, Kaiyu Chen^b, Shengqiang Zhu^a, Peng Wang^c, Hongliang Zhang^{a,b,d,*}^a Department of Environmental Science and Engineering, Fudan University, Shanghai 200438, China^b Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA^c Department of Civil and Environmental Engineering, Hong Kong Polytechnic University, Hong Kong 99907, China^d Institute of Eco-Chongming (SIEC), Shanghai 200062, China

ARTICLE INFO

Keywords:

COVID-19

Severe air pollution

Emission reduction

Meteorology

China

ABSTRACT

Due to the pandemic of coronavirus disease 2019 in China, almost all avoidable activities in China are prohibited since Wuhan announced lockdown on January 23, 2020. With reduced activities, severe air pollution events still occurred in the North China Plain, causing discussions regarding why severe air pollution was not avoided. The Community Multi-scale Air Quality model was applied during January 01 to February 12, 2020 to study PM_{2.5} changes under emission reduction scenarios. The estimated emission reduction case (Case 3) better reproduced PM_{2.5}. Compared with the case without emission change (Case 1), Case 3 predicted that PM_{2.5} concentrations decreased by up to 20% with absolute decreases of 5.35, 6.37, 9.23, 10.25, 10.30, 12.14, 12.75, 14.41, 18.00 and 30.79 μg/m³ in Guangzhou, Shanghai, Beijing, Shijiazhuang, Tianjin, Jinan, Taiyuan, Xi'an, Zhengzhou, Wuhan, respectively. In high-pollution days with PM_{2.5} greater than 75 μg/m³, the reductions of PM_{2.5} in Case 3 were 7.78, 9.51, 11.38, 13.42, 13.64, 14.15, 14.42, 16.95 and 22.08 μg/m³ in Shanghai, Jinan, Shijiazhuang, Beijing, Taiyuan, Xi'an, Tianjin, Zhengzhou and Wuhan, respectively. The reductions in emissions of PM_{2.5} precursors were ~2 times of that in concentrations, indicating that meteorology was unfavorable during simulation episode. A further analysis shows that benefits of emission reductions were overwhelmed by adverse meteorology and severe air pollution events were not avoided. This study highlights that large emissions reduction in transportation and slight reduction in industrial would not help avoid severe air pollution in China, especially when meteorology is unfavorable. More efforts should be made to completely avoid severe air pollution.

1. Introduction

Along with the substantial development in the past decades, China is suffering severe air pollution, causing significant economic loss and health outcomes (Han et al., 2016a; Huang et al., 2012; Cheng et al., 2013; Chai et al., 2014; Zhao et al., 2013; Xu et al., 2015; Chen et al., 2016; Cao et al., 2011; Richter et al., 2005; Zhang et al., 2012b). With the expectation of controlling air pollution problem, the Chinese government released and implemented the Air Pollution Prevention and Control Action Plan (the "Action Plan") in September 2013 (China, 2019b). From the plan, the concentrations of fine particulate matter (PM_{2.5}) in Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD) and Pearl River Delta (PRD) area shall decrease by 25%, 20% and 15% by the end of 2017 compared with 2012, respectively. To fulfill this goal, tremendous effects have been made such as strengthen industrial and vehicle emission standards, closing small and polluting factories, and

upgrades on industrial boilers, and air quality has been largely improved (Zhang et al., 2019; Ma et al., 2019; China 2019a). The severe particulate pollution days were decreased from 122 and 33 in 2013 to 31 and 25 in 2017 within BTH and YRD areas (Li et al., 2019).

Meteorology plays significant roles in air pollution formation, transport, deposition and transformation and unfavorable meteorological condition could bring severe pollution days even the total emission is reduced (Shi et al., 2018; Xu et al., 2016; Li et al., 2017c; Cai et al., 2018; Gui et al., 2019; Wang et al., 2019b). In the pollution period of December 20–26, 2015 in BTH region, about 34% increasing of PM_{2.5} are believed due to adverse meteorological condition (Ma et al., 2020). Wu et al. (2019) found a high relative humidity (RH) enhanced aqueous-phase oxidation of SO₂ explosive growth was the main reason for the 7 days heavy PM_{2.5} pollution episode in North China Plain in December 2016. In the study of two haze episodes from January 6 to 16 in Chengdu Plain, Li et al. (2017a) indicated that the

* Corresponding author.

E-mail address: zhanghl@fudan.edu.cn (H. Zhang).<https://doi.org/10.1016/j.resconrec.2020.104814>

Received 26 February 2020; Received in revised form 5 March 2020; Accepted 5 March 2020

Available online 23 March 2020

0921-3449/ © 2020 Elsevier B.V. All rights reserved.

decreased Planetary boundary layer (PBL) height restrained the air pollutant dispersion and increased RH accelerated the transformation of secondary pollutants. Meteorological condition in winter are more unfavorable to pollutant dilution and dispersion than other three seasons (Yang et al., 2019). Compared with December 2015, the PM_{2.5} concentration increased by 36% in BTH region. Liu et al. (2017) attributed the increase to unfavorable meteorology of PBL, RH and wind.

Can severe air pollution events be avoided by controlling anthropogenic emissions? The answer is true. China has succeeded in various emission reduction campaigns such as during the 2014 Asia-Pacific Economic Cooperation (APEC) meeting and the 2015 China Victory Day Parade (Xu et al., 2017; Wang et al., 2017; Xue et al., 2018; Li et al., 2016). In order to reduce anthropogenic emission, factories, industrial plants, construction sites, and gas stations was temporarily closed in and around Beijing, vehicles were kept off the roads, and 6-days mandatory holidays were brought to state-owned enterprises, local government offices and educational institutions (Sun et al., 2016; Wang et al., 2016; Li et al., 2017d; Huang et al., 2015). "APEC Blue" and "Parade Blue" are referred to the good air quality during the time afterward. The daily PM_{2.5} concentrations in Beijing were 47.53 µg/m³ during "APEC blue" and 17.07 µg/m³ during "Parade blue" (Lin et al., 2017).

Coronavirus disease 2019 (COVID-19) is an infectious disease initially identified in Wuhan, China in December 2019. COVID-19 has led to 2700 deaths by February 25, 2020 worldwide (WHO, 2020). Due to the contagion of COVID-19, the unofficial transit going in and out of Wuhan was shut down on January 23, 2020 and in the whole Hubei Province a couple of days after. The 2020 Spring Festival holiday started on January 24, and was extended to after February 10 nationwide because of the disease. Most transportation was prohibited and almost all avoidable outdoor human activities stopped all around the country. However, severe air pollution episodes still occurred in the North China Plain (NCP). It is of great concern for people who are limited to use mobile vehicles on heavy pollution days why severe air pollution events were not avoided when no one was on road.

Thus, this study used the Community Multi-Scale Air Quality (CMAQ) model to assess emission and meteorology conditions for air pollution during the outbreak of COVID-19. Different emission cases were simulated to see why the severe air pollution was not avoided.

2. Methods

The CMAQ V5.0.1 model was applied to simulate air pollution in China with a horizontal resolution of 36 km × 36 km during January 1 to February 12, 2020 (Fig. 1). The model has been updated to better predict air pollutants in China and details can be found in Hu et al. (2016). The meteorological inputs were generated using WRF v3.7.1 with initial and boundary conditions from the National Center for Environmental Prediction (NCEP) FNL Operational Model Global Tropospheric Analyses dataset (Zhang et al., 2012a; NCEP, 2000). Multi-resolution Emission Inventory for China of 2016 (MEIC) (<http://www.meicmodel.org>) was used for the monthly anthropogenic emissions from China. Emissions from other countries were obtained from MIX Asian emission inventory (Li et al., 2017b). The Model of Emissions of Gases and Aerosols from Nature (MEGAN) v2.1 was used for generating biogenic emissions (Guenther et al., 2012). The emissions from biomass burning were based on the Fire Inventory from the National Center for Atmospheric Research (NCAR) (FINN) (Wiedinmyer et al., 2011).

In order to investigate the effect of reduced anthropogenic activities on air pollution, three simulation scenarios were performed and compared (Table 1). The base case scenario (Case 1) is using the original anthropogenic emission inventory of MEIC 2016 for the simulation period. Although the emissions keep changing since 2016, this does not affect the study much as emission inventories usually have larger uncertainties in comparison to changes in a few years (Zhao et al., 2011; Zheng et al., 2009; Fu et al., 2013; Chen et al., 2014). Compared with

the Case 1, Case 2 had a decrease of 40% and 20% in transportation and industry emission, respectively. Emission from residential was lifted by 10% and emissions from agriculture and power remain unchanged. In Case 3, transportation, industry and agriculture emission in Hubei province are decreased by 80% while residential and power emission is kept the same with the Case 1. For areas out of Hubei province, 80% of transportation emission and 20% of industry emission are cut while all the rest are kept still. Since there is no official emission inventory released, emission changes suggested by the Chinese Research Academy of Environmental Sciences are being used to set emission reduction scenarios (CRAES 2020). An interview of Professor Kebin He from Tsinghua University refers to the high-pollution in BTH regions in February 2020 by China Central Television (CCTV) was also considered (CCTV, 2020). Many people came back for the Spring Festival and were trapped due to COVID-19 epidemic, the residential emission from cooking and heating was assumed to increase in rural areas including Hebei, Henan and Shandong. The notices released from government were the basis for emission reduction in Hubei Province (Hubei, 2020f, 2020e, 2020d, 2020c, 2020b). The governme announced that from 10 am in January 23, 2020, buses, subways, ferries, and long-distance passenger transportation in Wuhan were temporarily suspended, and outbound of railway and air planes were closed (Hubei, P. s. G. o. 2020g). All the enterprises are remaining closed no earlier than February 13 except required for public service operation, epidemic prevention and control, and residential life needs (Hubei, P. s. G. o. 2020a). The agriculture production was highly affected because there was nowhere to buy seeds and fertilizer (Daily, 2020).

Hourly PM_{2.5} observations at monitoring sites nationwide were downloaded from the publishing website of the China National Environmental Monitoring Center (<http://www.mee.gov.cn/hjzl/dqhj/>). The data were validated, and sanity check was conducted as previous studies (Hu et al., 2015; Wang et al., 2014). Meteorological observations were obtained from National Climate Data Center (NCDC), including precipitation, WS and wind direction (WD) at 10 m, as well as air temperature (T2) and RH at 2 m above the ground level.

To better understand the role of emissions changes and meteorological conditions, a rough method is proposed with similar idea of a previous study (Wang et al., 2019b; Liu et al., 2017; WEI et al. 2017; Li et al., 2015). The changes due to emission changes are calculated by subtracting the concentrations in Case 3 from that in Case 1, while the changes due to meteorology are calculated using concentrations in high-pollution days minus concentrations in low-pollution days, assuming that meteorology is the reason for severe pollution as the emissions are not changing day by day. It should be note that this is a rough estimate without considering the feedbacks of aerosols on meteorology.

3. Results

3.1. Model validation

The performance of meteorology simulation by WRF for the simulation period is validated including T2, WS, and WD at 10 m and RH, as statistic results are shown in Table S1. The benchmarks are suggested by Emery et al. (2001). WRF has slightly underpredicted T2 with MB of -0.9. Both T2 and WD went beyond the GE benchmark by 40% to 50%. The GE of WS is within the benchmark, and high RMSE of 2.5 indicated oscillations among prediction results. WD prediction results were acceptable with MB of 8.5 while RH was slightly under-predicted. It should be declared that out of the benchmark does not mean failure of the prediction as the benchmark value is constructed on the MM5 simulations for the eastern United States with finer grid resolutions (12 km and 4 km). The WRF model predictions are normally reliable since the model performance statistics are like other WRF studies applied over China (Zhang et al., 2012a; Qiao et al., 2019; Hu et al., 2016).

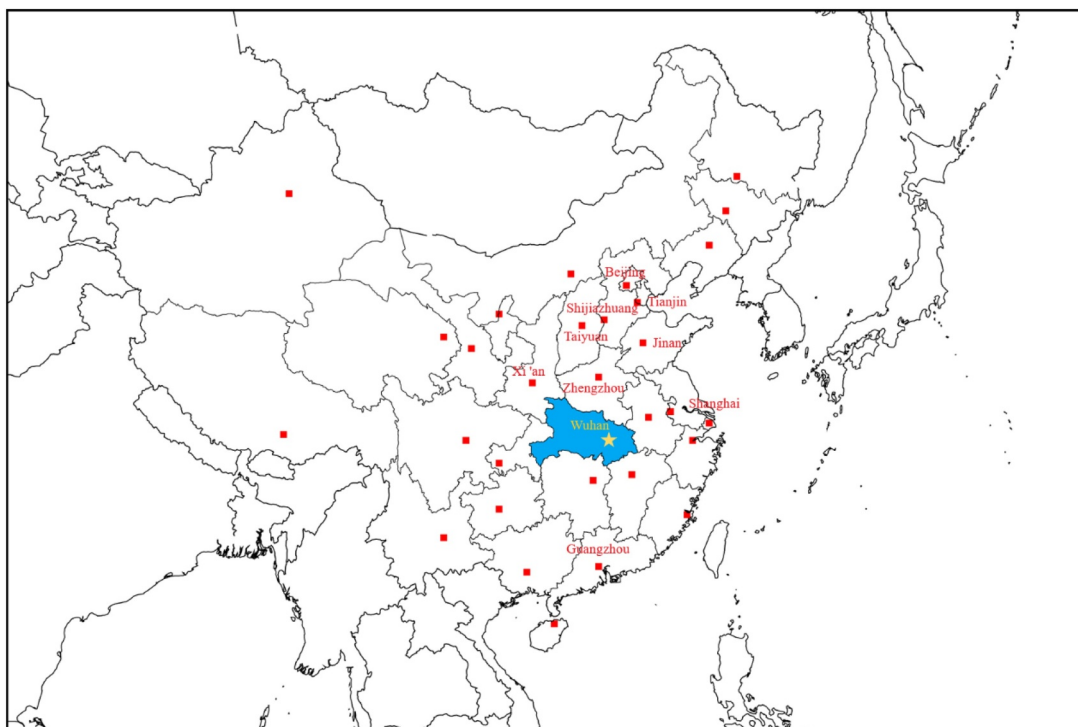


Fig. 1. Locations of domains and major cities (red point), Wuhan is marked as yellow star and Hubei province is in blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Tables S2 and S3 show the model performance statistics of $PM_{2.5}$ from the two emission reduction cases. Mean observations, mean predictions, mean fractional bias (MFB), mean fractional error (MFE), mean normalized bias (MNB) and mean normalized error (MNE) were calculated for each city from January 02 to February 12, 2020. $PM_{2.5}$ is well predicted in all cities in both cases except Wuhan in Case 2 with MFB exceeding the criteria suggested by EPA (EPA 2007). As activities in Hubei were much more strictly limited, Case 3 is a better estimation and is used in following discussion.

Fig. 2 shows the predicted and observed daily $PM_{2.5}$ and its components in 10 major cities based in Case 3. Compared with observation results, the model presented great performance. In Wuhan, the model captured the changes of $PM_{2.5}$ except for few overpredicted days. In all the other cities, the model successfully predicted peak and valley values not only in the most polluted cities like Xi'an, Zhengzhou but in relatively less polluted cities such as Shanghai and Guangzhou. The model also succeeded in reproducing the significant decrease of $PM_{2.5}$ that occurred from 29 January to 6 February in all cities.

3.2. Regional changes

The changes of predicted $PM_{2.5}$ and its major components between two emission reduction cases (Case 2 and Case 3) and Case 1 are shown in Fig. 3. The total $PM_{2.5}$ is decreasing mainly in south China in both cases (Case 2 and Case 3), while an increasing (up to $4 \mu g/m^3$) is observed in Northeast China in Case 2 as residential activities were

increased possible due to more people were staying at home. More significant $PM_{2.5}$ decrease (averaged 10–20%) is observed in Case 3 in Central China, while for Case 2 the averaged decreased rate is less than 10%. Among all the components, NO_3 shares the largest reduction since transportation is the key factor in both emission reduction cases. Except EC and POA, all the species were decreasing in Case 2. A 5% increase in EC is shown in Northeast and Southwest China (Fig. S3). POA increases by 10% on average in large areas of China with peak values in Northeast, Henan, Hebei and the Sichuan Basin as residential emissions were increased.

All the country experiences reduction of $PM_{2.5}$ by 10–20% due to the significant emission reductions in Case 3. Most significant decreases of $PM_{2.5}$ and its components (30–50%) of SO_4 , NO_3 , NH_4 , and SOA are observed in Hubei (Fig. S3). Based on the emission scenario, the falling of SO_4 concentration mostly results from the emission reduction of industry release. The decrease of NO_3 is likely due to the reduction of transportation and the drop of agriculture emission explains the NH_4 decrease. The amount of SOA was fell because of the lack of precursors due to the emissions reduction of all three. Overall, the emission reductions due to COVID-19 did result in reductions of $PM_{2.5}$ by 10–20% nationwide.

3.3. Changes in different cities

Fig. 4 shows the averaged predicted and observed $PM_{2.5}$ concentrations with components in 10 major cities of these three

Table 1
Configuration of simulation scenarios.

	Transportation	Industry	Residential	Agriculture	Power	
Case1	No change					
Case2	–40%	–20%	+10%	No change	No change	
Case3	–80%	–80%	No change	–80%	No change	Hubei
	–80%	–20%	No change	No change	No change	Other

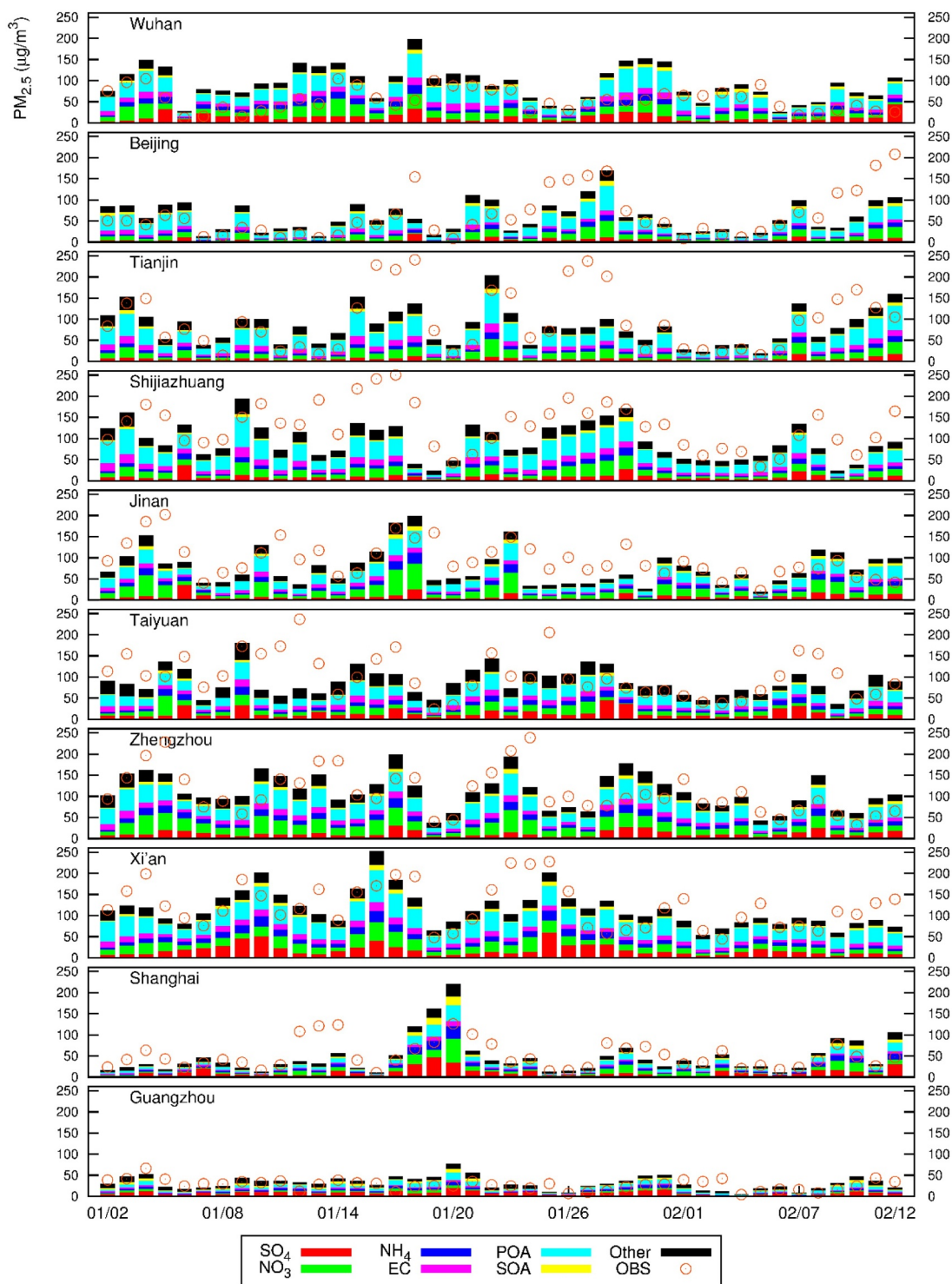


Fig. 2. Predicted daily PM_{2.5} and its components with observed daily PM_{2.5} in 10 major cities in Case 3. Units are µg/m³.

scenarios from January 21 to February 12, 2020. The positive effect of emission reduction on decreasing PM_{2.5} concentrations can be clearly observed. At least 5 µg/m³ (Guangzhou) decrease was found in each city while Wuhan had the largest decrease up to 30.79 µg/m³. Compared with the Case 1, the decreases of PM_{2.5} in Case 3 in Beijing, Tianjin, Shijiazhuang, Jinan, Taiyuan, Zhengzhou, Xi'an, and Shanghai were 9.23, 10.30, 10.25, 12.14, 12.75, 18.00, 14.41, and 6.37 µg/m³, respectively.

Fig. 5 shows the predicted and observed PM_{2.5} during the high-

pollution days and low-pollution days in these 10 cities (separated based on the standard of the second level of Chinese NAAQS, 75 µg/m³ of observation values). The PM_{2.5} reductions in high-pollution days in Case 3 were 13.42, 22.08, 14.42, 11.38, 7.78, 13.64, 16.95, 14.15, and 9.51 µg/m³ in Beijing, Wuhan, Tianjin, Shijiazhuang, Shanghai, Taiyuan, Zhengzhou, Xi'an, and Jinan. All the changes were larger than 10% compared with PM_{2.5} concentrations in Case 1 and the largest decrease of 19.04% was found in Wuhan. During low-pollution days, the reductions were 6.55, 32.63, 4.94, 7.07, 6.07, 11.60, 20.43, 14.81,

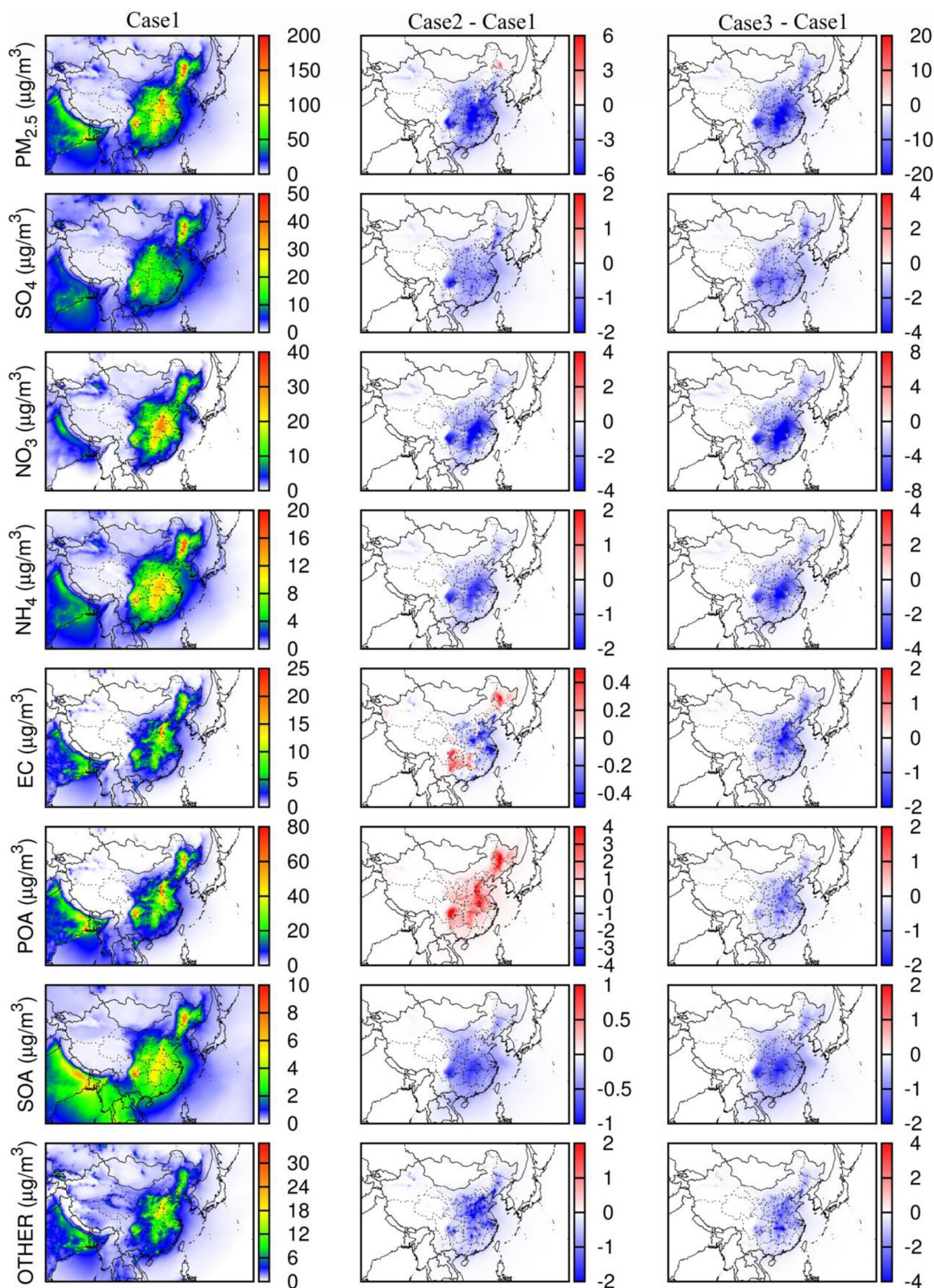


Fig. 3. Predicted PM_{2.5} and its major components and the changes between cases in unit of µg/m³ during January 20 to February 12, 2020. SO₄ is sulfate, NO₃ is a nitrate, NH₄ is ammonium, EC is elemental carbon, POA is primary organic aerosol, SOA is secondary organic aerosol and OTHER is the sum of inexplicit components.

and 14.57 µg/m³ in above cities with the same consequence, separately. With a 29.20% decrease in low-pollution days, Wuhan ranked first. Tianjin and Shijiazhuang had the decreases of 9.5% and 9.4%, separately. The reduction percentage in all other 6 cities were larger than

10%. Basically, secondary components of SOA, SO₄ and NO₃ contributed the most both in high and low-pollution days. This indicates that the role of chemistry and meteorological condition in secondary pollutants formation should not be neglected.

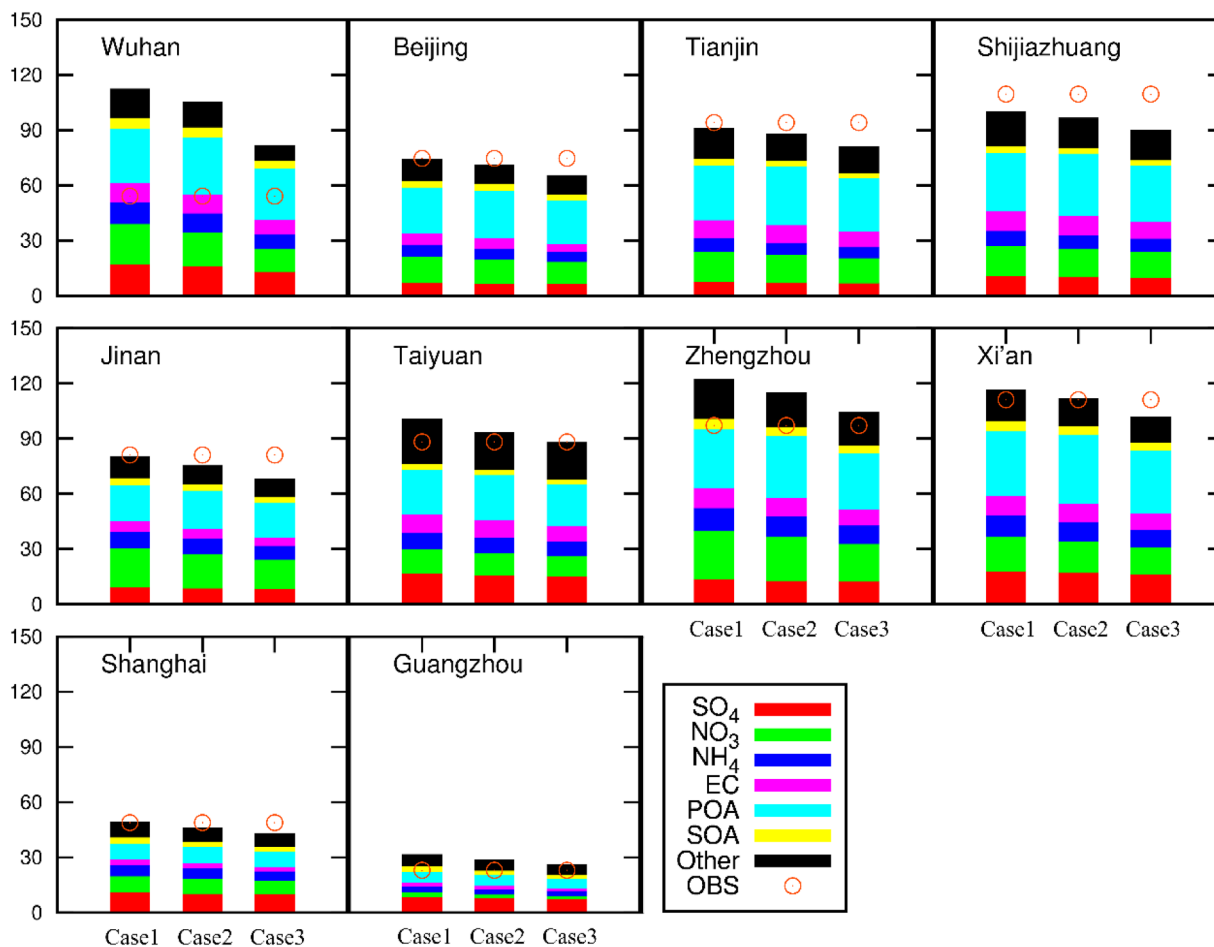


Fig. 4. Predicted daily $PM_{2.5}$ with components and observed $PM_{2.5}$ in 10 major cities of three scenarios during January 20 to February 12, 2020. Units are $\mu\text{g}/\text{m}^3$.

3.4. Comparison of changes in emission and concentrations

As we can see from above results that the concentrations of $PM_{2.5}$ did reduce within the emission reductions cases. But it is important to know how efficient it was. Fig. 6 shows decreasing ratios of predicted $PM_{2.5}$, EC, OC, SO_4 , NO_3 , and SOA concentrations by Case 3 and the emission rates of related precursors in Beijing, Wuhan, Guangzhou and Shanghai during the simulation period. All species decreased as the emissions were reduced in a monotonic but non-linear way. This is consistent with the nonlinearity of atmospheric processes as confirmed by previous studies (Cai et al., 2017; Zhao et al., 2017; Han et al., 2016b; Wang et al., 2011).

In Beijing, emissions of primary $PM_{2.5}$, EC and OC were decreased by 20%, 50% and 10%, while the concentrations of them were decreased by 10%, 25% and 5%. SO_2 , NO_x , and VOCs emissions were decreased by 20%, 50%, and 30% while concentrations of SO_4 , NO_3 , and SOA were decreased all by less than 20%. Similar cases are observed in other cities. For Wuhan and Guangzhou, the reductions in concentrations were about half of the decreases in emissions. While for Shanghai, the emission reduction ratios were only slightly higher than the concentration reduction ratios. Although nonlinear chemical processes are non-negligible in this situation, effects of meteorology should not be neglected.

3.5. Role of meteorology

Through the emission reduction process, the decreases in pollutant concentrations were observed. The ratios of $PM_{2.5}$ and precursors

reductions in emission are larger than the reductions in $PM_{2.5}$ and its components in four selected cities. This indicates that meteorological conditions were favorable for pollution formation. Fig. S4 showed the time series of meteorological parameters in Beijing and Guangzhou from January 21 to February 12, 2020. There was seldom wet deposition of PM in Guangzhou and Beijing due to the rare of rains during the simulation period. The low PBL increased atmospheric stability, the low wind speed made it worse for difficult dispersion of air pollutants (Wang et al., 2015; Liu et al., 2017). High RH and temperature usually accelerate secondary PM formation by speeding up chemical reactions (Li et al., 2018; Wang et al., 2019a; Rahman et al., 2019). Thus, it is very important to quantify the contribution of meteorological conditions when deciding controlling efficiency.

The contributions of emission reduction and meteorological conditions are estimated and shown in Fig. 7. Emission reductions led to the reductions of pollutants in all cities with the largest in Wuhan ($-22.08 \mu\text{g}/\text{m}^3$) and the lowest in Shanghai ($-7.78 \mu\text{g}/\text{m}^3$) and Jinan ($-9.51 \mu\text{g}/\text{m}^3$). All other cities experienced a $>10 \mu\text{g}/\text{m}^3$ contributions, with the exactly values of -13.42 , -14.42 , -11.38 , -13.64 , -16.95 , and $-15.15 \mu\text{g}/\text{m}^3$ in Beijing, Tianjin, Shijiazhuang, Taiyuan, Zhengzhou, and Xi'an, separately. In contrary, unfavorable meteorology resulted in increases of $PM_{2.5}$, with the largest value of $69.38 \mu\text{g}/\text{m}^3$ in Tianjin. For Wuhan and Jinan, unfavorable meteorology had less effect compared with emission changes. In Xi'an, the unfavorable meteorology brought $14.24 \mu\text{g}/\text{m}^3$ increase of $PM_{2.5}$, which almost fully counteracts the contribution of emission reductions. In all other cities, the increases caused by meteorological conditions timely overstepped the positive influences from emission reductions.

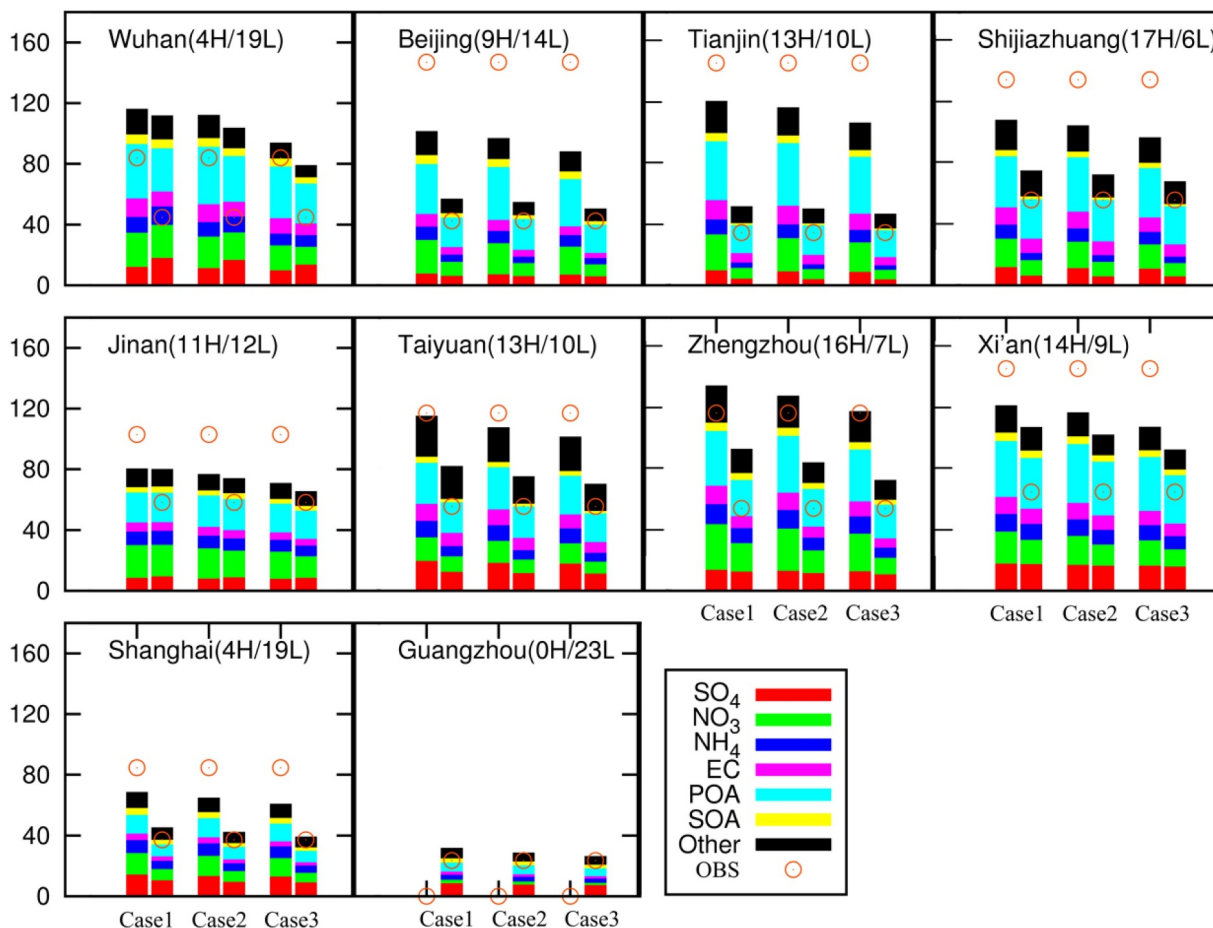


Fig. 5. Averaged predicted daily PM_{2.5} with components and observed PM_{2.5} in 10 major cities of three scenarios on high-pollution days (>75 μg/m³, left column) and low-pollution days (right column). The number of days in high (H) and low (L) pollution days are marked after the city names. Units are μg/m³.

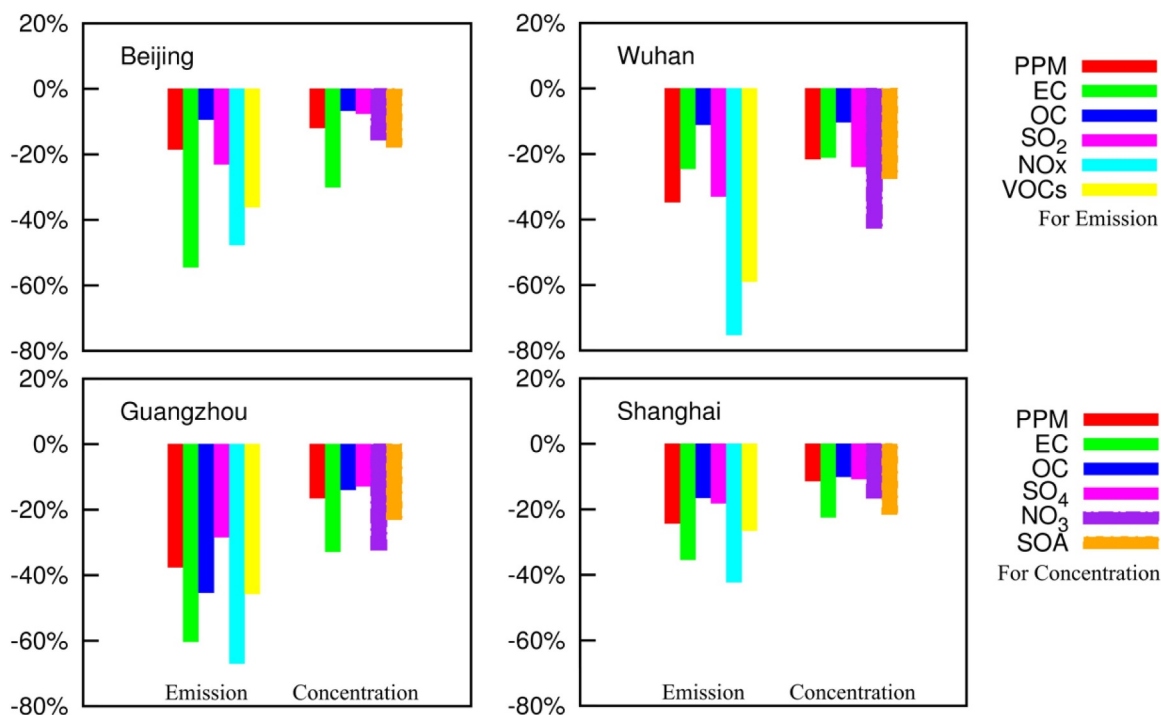


Fig. 6. Relative changes in concentrations of primary PM_{2.5} (PPM) and secondary components, and in emissions of related precursors in Case 3 to Case 1 in four cities.

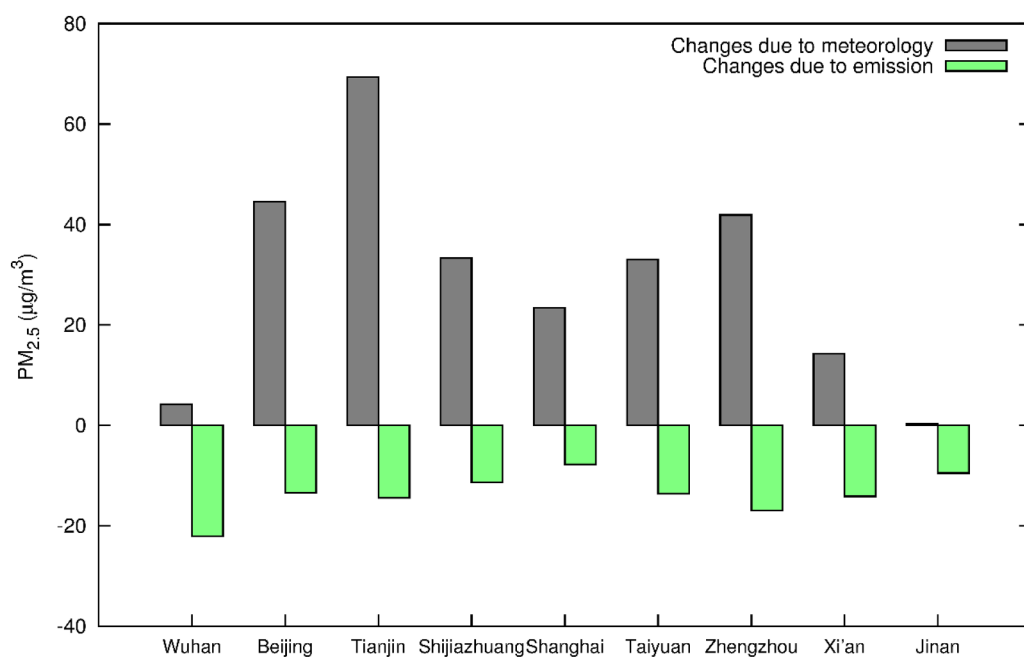


Fig. 7. Estimated contributions of meteorology and anthropogenic emissions changes to averaged $PM_{2.5}$ concentrations in selected cities during January 20 to February 12, 2020. Units are $\mu\text{g}/\text{m}^3$. Guangzhou is not included as it had no high-pollution days during the episode.

4. Conclusions

In this study, the influences of emission reductions due to reduced anthropogenic activities during the COVID-19 outbreak in China on air pollution were investigated. It is concluded that anthropogenic emission decreases, mainly on transportation and industry, contributed to the decreases of $PM_{2.5}$ concentrations. The decreases of $PM_{2.5}$ in Beijing, Shanghai, Guangzhou, and Wuhan were 9.23, 6.37, 5.35, and 30.79 $\mu\text{g}/\text{m}^3$, respectively. However, this is not enough to avoid severe air pollution events in most areas. The reduction ratios of $PM_{2.5}$ concentrations were smaller than the reduction ratios of precursor emissions, partially due to the unfavorable meteorological conditions. This study highlights the importance of understanding the role of chemistry and meteorology in designing emission control strategies.

Author statement

Pengfei Wang: Methodology, Simulation, Data collection, Visualization, Writing-Original draft preparation

Kaiyu Chen: Data collection, Post-processing, Visualization

Shengqiang Zhu: Data collection, Visualization

Peng Wang: Methodology, Writing-Reviewing and Editing

Hongliang Zhang: Conceptualization, Methodology, Writing-Reviewing and Editing.

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.

Acknowledgments

Portions of this research were conducted with high performance computing resources provided by Louisiana State University (<http://www.hpc.lsu.edu>).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2020.104814](https://doi.org/10.1016/j.resconrec.2020.104814).

References

- Cai, S., Wang, Y., Zhao, B., Wang, S., Chang, X., Hao, J., 2017. The impact of the "air pollution prevention and control action plan" on $PM_{2.5}$ concentrations in Jing-Jin-Ji region during 2012–2020. *Sci. Total Environ.* 580, 197–209.
- Cai, Z., Jiang, F., Chen, J., Jiang, Z., Wang, X., 2018. Weather condition dominates regional $PM_{2.5}$ Pollutions in the Eastern Coastal Provinces of China during Winter. *Aerosol Air Qual. Res.* 18 (4), 969–980.
- Cao, J., Yang, C., Li, J., Chen, R., Chen, B., Gu, D., Kan, H., 2011. Association between long-term exposure to outdoor air pollution and mortality in China: a cohort study. *J. Hazard. Mater.* 186 (2–3), 1594–1600.
- CCTV. 2020. [News 30 minutes] Experts interpretation: the recent heavy pollution in Beijing-Tianjin-Hebei and surrounding areas are due to emissions and low environmental capacity. <http://app.cctv.com/special/cbox/detail/index.html?guid=795fd7b3734d45a391d5707b0056165e&vsid=C10601&from=singlemessage&isappinstalled=0#0>.
- Chai, F., Gao, J., Chen, Z., Wang, S., Zhang, Y., Zhang, J., Zhang, H., Yun, Y., Ren, C., 2014. Spatial and temporal variation of particulate matter and gaseous pollutants in 26 cities in China. *J. Environ. Sci.* 26 (1), 75–82.
- Chen, L., Sun, Y., Wu, X., Zhang, Y., Zheng, C., Gao, X., Cen, K., 2014. Unit-based emission inventory and uncertainty assessment of coal-fired power plants. *Atmos. Environ.* 99, 527–535.
- Chen, X., Zhang, L.-w., Huang, J.-j., Song, F.-j., Zhang, L.-p., Qian, Z.-m., Trevathan, E., Mao, H.-j., Han, B., Vaughn, M., 2016. Long-term exposure to urban air pollution and lung cancer mortality: A 12-year cohort study in Northern China. *Sci. Total Environ.* 571, 855–861.
- Cheng, Z., Wang, S., Jiang, J., Fu, Q., Chen, C., Xu, B., Yu, J., Fu, X., Hao, J., 2013. Long-term trend of haze pollution and impact of particulate matter in the Yangtze River Delta, China. *Environ. Pollut.* 182, 101–110.
- China, M. o. E. a. E. o. t. P. s. R. o. 2019a. 2017 Report on the state of the ecology and environment in China. <http://english.mee.gov.cn/Resources/Reports/soe/SOEE2017/201808/P020180801597738742758.pdf>.
- China, S. C. o. t. P. s. R. o. 2019b. Notice of the general office of the state council on issuing the air pollution prevention and control action plan. http://www.gov.cn/zwqk/2013-09/12/content_2486773.htm.
- CRAES2020. [Expert's Interpretation] This is a tough battle and a protracted battle—Understanding the causes of pollution during the Spring Festival. <https://mp.weixin.qq.com/s/aXaEDuLL30XxWB1A1f6A>.
- Daily, E. 2020. Spring farming is busy at villages without epidemic. http://www.xinhuanet.com/local/2020-03/01/c_1125645258.htm.
- EPA, U., 2007. Guidance on the use of models and other analyses for demonstrating attainment of air quality goals for ozone, $PM_{2.5}$, and regional haze. US Environmental Protection Agency. Office Air Qual. Plan. Stand.
- Fu, X., Wang, S., Zhao, B., Xing, J., Cheng, Z., Liu, H., Hao, J., 2013. Emission inventory of primary pollutants and chemical speciation in 2010 for the Yangtze River Delta region, China. *Atmos. Environ.* 70, 39–50.
- Guenther, A.B., Jiang, X., Heald, C.L., Sakulyanontvittaya, T., Duhl, T., Emmons, L.K., Wang, X., 2012. The model of emissions of gases and aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions. *Geosci. Model Develop.* 5 (6), 1471–1492.
- Gui, K., Che, H., Wang, Y., Wang, H., Zhang, L., Zhao, H., Zheng, Y., Sun, T., Zhang, X., 2019. Satellite-derived $PM_{2.5}$ concentration trends over Eastern China from 1998 to

- 2016: Relationships to emissions and meteorological parameters. *Environ. Pollut.* 247, 1125–1133.
- Han, R., Wang, S., Shen, W., Wang, J., Wu, K., Ren, Z., Feng, M., 2016a. Spatial and temporal variation of haze in China from 1961 to 2012. *J. Environ. Sci.* 46, 134–146.
- Han, X., Zhang, M., Zhu, L., Skorokhod, A., 2016b. Assessment of the impact of emissions reductions on air quality over North China Plain. *Atmos. Pollut. Res.* 7 (2), 249–259.
- Hu, J., Chen, J., Ying, Q., Zhang, H., 2016. One-year simulation of ozone and particulate matter in China using WRF/CMAQ modeling system. *Atmos. Chem. Phys.* 16 (16), 10333–10350.
- Hu, J., Ying, Q., Wang, Y., Zhang, H., 2015. Characterizing multi-pollutant air pollution in China: Comparison of three air quality indices. *Environ. Int.* 84, 17–25.
- Huang, K., Zhang, X., Lin, Y., 2015. The "APEC Blue" phenomenon: Regional emission control effects observed from space. *Atmos. Res.* 164–165, 65–75.
- Huang, K., G. Zhuang, J. S. Fu, Q. Wang, T. Liu, R. Zhang, Y. Jiang, C. Deng, Q. Fu, and N. Hsu. 2012. Typical types and formation mechanisms of haze in an Eastern Asia megacity, Shanghai.
- Hubei, P. s. G. o.2020a. Notices of Wuhan coronavirus prevention and control headquarters. https://www.hubei.gov.cn/zhuanti/2020/gzxxgzbd/zxtb/202001/t20200129_2016284.shtml.
- Hubei, P. s. G. o.2020b. Notices of Wuhan coronavirus prevention and control headquarters (NO. 1). https://www.hubei.gov.cn/zhuanti/2020/gzxxgzbd/zxtb/202001/t20200123_2014402.shtml.
- Hubei, P. s. G. o.2020c. Notices of Wuhan coronavirus prevention and control headquarters (NO. 5). https://www.hubei.gov.cn/zhuanti/2020/gzxxgzbd/zxtb/202001/t20200124_2014608.shtml.
- Hubei, P. s. G. o.2020d. Notices of Wuhan coronavirus prevention and control headquarters (NO. 6). https://www.hubei.gov.cn/zhuanti/2020/gzxxgzbd/zxtb/202001/t20200124_2014657.shtml.
- Hubei, P. s. G. o.2020e. Notices of Wuhan coronavirus prevention and control headquarters (NO. 8). https://www.hubei.gov.cn/zhuanti/2020/gzxxgzbd/zxtb/202001/t20200124_2014820.shtml.
- Hubei, P. s. G. o.2020f. Notices of Wuhan coronavirus prevention and control headquarters (NO. 9). https://www.hubei.gov.cn/zhuanti/2020/gzxxgzbd/zxtb/202001/t20200125_2014946.shtml.
- Hubei, P. s. G. o.2020g. Notices of Wuhan Traffic Emergency Control. https://www.hubei.gov.cn/zhuanti/2020/gzxxgzbd/zxtb/202001/t20200123_2014524.shtml.
- Li, H., Zhang, Q., Duan, F., Zheng, B., He, K., 2016. The "Parade Blue": effects of short-term emission control on aerosol chemistry. *Faraday Discuss* 189, 317–335.
- Li, J., Liao, H., Hu, J., Li, N., 2019. Severe particulate pollution days in China during 2013–2018 and the associated typical weather patterns in Beijing-Tianjin-Hebei and the Yangtze River Delta regions. *Environ. Pollut.* 248, 74–81.
- Li, L., Tan, Q., Zhang, Y., Feng, M., Qu, Y., An, J., Liu, X., 2017a. Characteristics and source apportionment of PM_{2.5} during persistent extreme haze events in Chengdu, southwest China. *Environ. Pollut.* 230, 718–729.
- Li, M., Zhang, Q., Kurokawa, J.-i., Woo, J.-H., He, K., Lu, Z., Ohara, T., Song, Y., Streets, D.G., Carmichael, G.R., 2017b. MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP. *Atmos. Chem. Phys.* (Online) 17 (2).
- Li, W., Liu, X., Zhang, Y., Sun, K., Wu, Y., Xue, R., Zeng, L., Qu, Y., An, J., 2018. Characteristics and formation mechanism of regional haze episodes in the Pearl River Delta of China. *J. Environ. Sci.* 63, 236–249.
- Li, X., Ma, Y., Wang, Y., Liu, N., Hong, Y., 2017c. Temporal and spatial analyses of particulate matter (PM₁₀ and PM_{2.5}) and its relationship with meteorological parameters over an urban city in northeast China. *Atmos. Res.* 198, 185–193.
- Li, X., Qiao, Y., Zhu, J., Shi, L., Wang, Y., 2017d. The "APEC blue" endeavor: causal effects of air pollution regulation on air quality in China. *J. Cleaner Prod.* 168, 1381–1388.
- Li, X., Zhang, Q., Zhang, Y., Zheng, B., Wang, K., Chen, Y., Wallington, T.J., Han, W., Shen, W., Zhang, X., 2015. Source contributions of urban PM_{2.5} in the Beijing-Tianjin-Hebei region: Changes between 2006 and 2013 and relative impacts of emissions and meteorology. *Atmos. Environ.* 123, 229–239.
- Lin, H., Liu, T., Fang, F., Xiao, J., Zeng, W., Li, X., Guo, L., Tian, L., Schootman, M., Stamatakis, K.A., Qian, Z., Ma, W., 2017. Mortality benefits of vigorous air quality improvement interventions during the periods of APEC Blue and Parade Blue in Beijing, China. *Environ. Pollut.* 220 (Pt A), 222–227.
- Liu, T., Gong, S., He, J., Yu, M., Wang, Q., Li, H., Liu, W., Zhang, J., Li, L., Wang, X., 2017. Attributions of meteorological and emission factors to the 2015 winter severe haze pollution episodes in China's Jing-Jin-Ji area. *Atmos. Chem. Phys.* 17 (4), 2971–2980.
- Ma, S., Xiao, Z., Zhang, Y., Wang, L., Shao, M., 2020. Assessment of Meteorological Impact and Emergency Plan for a Heavy Haze Pollution Episode in a Core City of the North China Plain. *Aerosol Air Qual. Res.* 20 (1), 26–42.
- Ma, T., Duan, F., He, K., Qin, Y., Tong, D., Geng, G., Liu, X., Li, H., Yang, S., Ye, S., Xu, B., Zhang, Q., Ma, Y., 2019. Air pollution characteristics and their relationship with emissions and meteorology in the Yangtze River Delta region during 2014–2016. *J. Environ. Sci. (China)* 83, 8–20.
- NCEP, F.2000. National Centers for Environmental Prediction/National Weather Service/NOAA/US Department of Commerce. 2000, updated daily. NCEP FNL Operational Model Global Tropospheric Analyses, continuing from July 1999. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory.
- Qiao, X., Guo, H., Tang, Y., Wang, P., Deng, W., Zhao, X., Hu, J., Ying, Q., Zhang, H., 2019. Local and regional contributions to fine particulate matter in the 18 cities of Sichuan Basin, southwestern China. *Atmos. Chem. Phys.* 19 (9), 5791–5803.
- Rahman, A., Luo, C., Khan, M.H.R., Ke, J., Thilakanayaka, V., Kumar, S., 2019. Influence of atmospheric PM_{2.5}, PM₁₀, O₃, CO, NO₂, SO₂, and meteorological factors on the concentration of airborne pollen in Guangzhou, China. *Atmos. Environ.* 212, 290–304.
- Richter, A., Burrows, J.P., Nüß, H., Granier, C., Niemeier, U., 2005. Increase in tropospheric nitrogen dioxide over China observed from space. *Nature* 437 (7055), 129–132.
- Shi, C., Yuan, R., Wu, B., Meng, Y., Zhang, H., Zhang, H., Gong, Z., 2018. Meteorological conditions conducive to PM_{2.5} pollution in winter 2016/2017 in the Western Yangtze River Delta, China. *Sci. Total Environ.* 642, 1221–1232.
- Sun, Y., Wang, Z., Wild, O., Xu, W., Chen, C., Fu, P., Du, W., Zhou, L., Zhang, Q., Han, T., Wang, Q., Pan, X., Zheng, H., Li, J., Guo, X., Liu, J., Worsnop, D.R., 2016. "APEC Blue": secondary aerosol reductions from emission controls in Beijing. *Sci. Rep.* 6, 20668.
- Wang, G., Cheng, S., Wei, W., Yang, X., Wang, X., Jia, J., Lang, J., Lv, Z., 2017. Characteristics and emission-reduction measures evaluation of PM_{2.5} during the two major events: APEC and Parade. *Sci. Total Environ.* 595, 81–92.
- Wang, H., Li, J., Peng, Y., Zhang, M., Che, H., Zhang, X., 2019a. The impacts of the meteorology features on PM_{2.5} levels during a severe haze episode in central-east China. *Atmos. Environ.* 197, 177–189.
- Wang, H., Zhao, L., Xie, Y., Hu, Q., 2016. "APEC blue"—The effects and implications of joint pollution prevention and control program. *Sci. Total Environ.* 553, 429–438.
- Wang, M., Cao, C., Li, G., Singh, R.P., 2015. Analysis of a severe prolonged regional haze episode in the Yangtze River Delta, China. *Atmos. Environ.* 102, 112–121.
- Wang, P., Guo, H., Hu, J., Kota, S.H., Ying, Q., Zhang, H., 2019b. Responses of PM_{2.5} and O₃ concentrations to changes of meteorology and emissions in China. *Sci. Total Environ.* 662, 297–306.
- Wang, S., Xing, J., Jang, C., Zhu, Y., Fu, J.S., Hao, J., 2011. Impact assessment of ammonia emissions on inorganic aerosols in East China using response surface modeling technique. *Environ. Sci. Technol.* 45 (21), 9293–9300.
- Wang, Y., Ying, Q., Hu, J., Zhang, H., 2014. Spatial and temporal variations of six criteria air pollutants in 31 provincial capital cities in China during 2013–2014. *Environ. Int.* 73, 413–422.
- Wei, Y., Li, J., Wang, Z.-F., Chen, H.-S., Wu, Q.-Z., Li, J.-J., Wang, Y.-L., Wang, W., 2017. Trends of surface PM_{2.5} over Beijing-Tianjin-Hebei in 2013–2015 and their causes: emission controls vs. meteorological conditions. *Atmos. Ocean. Sci. Lett.* 10 (4), 276–283.
- WHO. 2020. Coronavirus disease 2019 (COVID-19): situation report, 36.
- Wiedinmyer, C., Akagi, S., Yokelson, R.J., Emmons, L., Al-Saadi, J., Orlando, J., Soja, A., 2011. The Fire Inventory from NCAR (FINN): A high resolution global model to estimate the emissions from open burning. *Geoscientific Model. Dev.* 4 (3), 625.
- Wu, L., Sun, J., Zhang, X., Zhang, Y., Wang, Y., Zhong, J., Yang, Y., 2019. Aqueous-phase reactions occurred in the PM_{2.5} cumulative explosive growth during the heavy pollution episode (HPE) in 2016 Beijing wintertime. *Tellus B* 71 (1).
- Xu, J., Chang, L., Qu, Y., Yan, F., Wang, F., Fu, Q., 2016. The meteorological modulation on PM_{2.5} interannual oscillation during 2013 to 2015 in Shanghai, China. *Sci. Total Environ.* 572, 1138–1149.
- Xu, W., Song, W., Zhang, Y., Liu, X., Zhang, L., Zhao, Y., Liu, D., Tang, A., Yang, D., Wang, D., Wen, Z., Pan, Y., Fowler, D., Collett Jr, J.L., Erisman, J.W., Goulding, K., Li, Y., Zhang, F., 2017. Air quality improvement in a megacity: implications from 2015 Beijing Parade Blue pollution control actions. *Atmos. Chem. Phys.* 17 (1), 31–46.
- Xu, W., Sun, Y., Chen, C., Du, W., Han, T., Wang, Q., Fu, P., Wang, Z., Zhao, X., Zhou, L., 2015. Aerosol composition, oxidation properties, and sources in Beijing: results from the 2014 Asia-Pacific Economic Cooperation summit study. *Atmos. Chem. Phys.* 15 (23), 13681–13698.
- Xue, Y., Wang, Y., Li, X., Tian, H., Nie, L., Wu, X., Zhou, J., Zhou, Z., 2018. Multi-dimension apportionment of clean air "parade blue" phenomenon in Beijing. *J. Environ. Sci. (China)* 65, 29–42.
- Yang, J., Ji, Z., Kang, S., Zhang, Q., Chen, X., Lee, S.Y., 2019. Spatiotemporal variations of air pollutants in western China and their relationship to meteorological factors and emission sources. *Environ. Pollut.* 254 (Pt A), 112952.
- Zhang, H., Li, J., Ying, Q., Yu, J., Wu, D., Cheng, Y., He, K., Jiang, J., 2012a. Source apportionment of PM_{2.5} nitrate and sulfate in China using a source-oriented chemical transport model. *Atmos. Environ.* 62, 228–242.
- Zhang, Q., He, K., Huo, H., 2012b. Cleaning China's air. *Nature* 484 (7393), 161–162.
- Zhang, Q., Zheng, Y., Tong, D., Shao, M., Wang, S., Zhang, Y., Xu, X., Wang, J., He, H., Liu, W., Ding, Y., Lei, Y., Li, J., Wang, Z., Zhang, X., Wang, Y., Cheng, J., Liu, Y., Shi, Q., Yan, L., Geng, G., Hong, C., Li, M., Liu, F., Zheng, B., Cao, J., Ding, A., Gao, J., Fu, Q., Huo, J., Liu, B., Liu, Z., Yang, F., He, K., Hao, J., 2019. Drivers of improved PM_{2.5} air quality in China from 2013 to 2017. *Proc Natl Acad Sci U S A* 116 (49), 24463–24469.
- Zhao, B., W. Wu, S. Wang, J. Xing, X. Chang, K.-N. Liou, J. H. Jiang, Y. Gu, C. Jang, and J. Fu. 2017. A modeling study of the nonlinear response of fine particles to air pollutant emissions in the Beijing-Tianjin-Hebei region.
- Zhao, X., Zhao, P., Xu, J., Meng, W., Pu, W., Dong, F., He, D., Shi, Q., 2013. Analysis of a winter regional haze event and its formation mechanism in the North China Plain. *Atmos. Chem. Phys. Discuss.* 13 (1).
- Zhao, Y., Nielsen, C.P., Lei, Y., McElroy, M.B., Hao, J., 2011. Quantifying the uncertainties of a bottom-up emission inventory of anthropogenic atmospheric pollutants in China. *Atmos. Chem. Phys.*
- Zheng, J., Zhang, L., Che, W., Zheng, Z., Yin, S., 2009. A highly resolved temporal and spatial air pollutant emission inventory for the Pearl River Delta region, China and its uncertainty assessment. *Atmos. Environ.* 43 (32), 5112–5122.