Impacts of COVID-19 on Black Carbon in Two Representative Regions in China: Insights Based on Online Measurement in Beijing and Tibet

Yue Liu1, Yinan Wang2, Yang Cao3, Xi Yang3, Tianle Zhang1, Mengxiao Luan1, Daren Lyu1, Anthony D. A. Hansen4, Baoxian Liu1,5, and Mei Zheng1

1 State Key Joint Laboratory of Environmental Simulation and Pollution Control, College of Environmental Sciences and Engineering, Peking University, Beijing, China, 2 Key Laboratory of Middle Atmosphere and Global Environment Observation, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, 3 Beijing Key Laboratory of Airborne Particulate Matter Monitoring Technology, Beijing Municipal Environmental Monitoring Center, Beijing, China, 4 Magee Scientific, Berkeley, CA, USA, 5 School of Environment, Tsinghua University, Beijing, China

Abstract
Under the influence of Coronavirus Disease 2019 (COVID-19), China conducted a nationwide lockdown (LD) which significantly reduced anthropogenic emissions. To analyze the different impacts of COVID-19 on black carbon (BC) in the two representative regions in China, one-year continuous online measurements of BC were conducted simultaneously in Beijing and Tibet. The average concentration in the LD period was 20% higher than that in the pre-LD period in Beijing, which could be attributed to the increase of transport from southwestern neighboring areas and enhanced aged BC. In contrast to megacity, the average concentration of BC in Tibet decreased over 70% in the LD period, which was mainly the result of the anthropogenic emission reduction in South Asia. Our study clearly showed that BC responded very differently in megacity and background areas to the change of anthropogenic emission under the lockdown intervention.

Plain Language Summary
China has been influenced by Coronavirus Disease 2019 (COVID-19) in 2020 and the nationwide lockdown (LD) caused emission reduction from human activities. As an important component of PM$_{2.5}$, black carbon (BC) can absorb light and effect the climate. It is essential to analyze the different impacts of COVID-19 on BC in the two representative regions in China. In this study, BC was measured simultaneously in Beijing and Tibet. The average concentration in the LD was 20% higher than that in the pre-LD period in Beijing, which could be attributed to the increase of transport from southwestern neighboring areas and enhanced aged BC. In contrast to megacity, the average concentration of BC in Tibet decreased over 70% in the LD period, which was mainly the result of the anthropogenic emission reduction in South Asia. Our study clearly showed that BC responded very differently in megacity and background areas to the change of anthropogenic emission, which could help to form better and more specific control strategies for BC under representative atmospheric environment in China.

1. Introduction
Black carbon (BC) has attracted much attention over the last several decades as it has known impacts on human health and climate. BC in the atmosphere can absorb solar radiation, thus it has positive radiative forcing (Jacobson et al., 2001) and can enhance the melting of snow and ice surface (Twery & Poellot, 2005), which has significant influence on the climate of Tibet Plateau in China (Kang et al., 2019).

From January 2020, China has been fighting Coronavirus Disease 2019 (COVID-19) and multiple measures have been implemented, including a nationwide lockdown (LD) from January 25 to February 20, 2020 (Lv et al., 2020; Xu et al., 2020). The nationwide LD significantly reduced anthropogenic emissions and it is important to investigate the response of atmospheric pollutants to emission reduction in the LD period. Previous studies showed that unlike most cities in China, Beijing has experienced several haze episodes during the LD period due to unfavorable meteorological conditions and reduction of nitrogen oxides (X. Huang et al., 2020; Le et al., 2020). However, as most studies focus on PM$_{2.5}$ in megacities, there still lack of study of how BC responds during the LD period in China.
Different from Beijing, a typical urban site and a megacity, Tibet is a representative background area which is largely influenced by the cross-border regional transport from South Asia, especially during non-monsoon seasons (November–May) (Cong et al., 2015; Kang et al., 2019). Previous studies reported that primary emission in India decreased significantly during the LD period from March to May, resulting in reduction of BC concentration (Kalluri et al., 2021; Panda et al., 2021). Under the nationwide LD in South Asia in 2020, it is essential to investigate the sensitivity of BC in Tibet to the emission reduction, which has not been investigated to our best knowledge.

In this study, 1-year continuous online measurement of BC was conducted simultaneously in Beijing and Tibet. The aethalometer model was used for two sites while the receptor model (Positive Matrix Factorization [PMF]) was applied for Beijing. This is mainly because more online measurements for different chemical components could be carried out in Beijing, while it is very hard to deploy multiple instruments in Tibet. The aim of the study is to investigate the different response of BC in Beijing and Tibet under the impact of COVID-19 as well as the major factors impacting BC concentration and temporal variation during the LD period, which could help to understand the sensitivity of urban and background areas to the change of anthropogenic emission under the LD intervention.

2. Methods

2.1. BC Measurement in Beijing and Tibet

To analyze the different influence of COVID-19 on BC in megacity and remote areas in China, Beijing and Tibet were selected as two representative sites in this study. The online measurement of BC by a multi-wavelength Aethalometer (AE33, Magee Scientific) was conducted simultaneously at two sites from November 2019 to October 2020. The sampling site in Beijing is located at the Beijing Municipal Environmental Monitoring Center (the BJMEMC site; 39°55′N, 116°21′E; 52 m mean sea level [MSL]) site in the northwestern urban area of Beijing city. The online measurement in Tibet was conducted in Yangbajain (the YBJ site; 30°12′N, 90°28′E; 4,300 m MSL), which was about 90 km northwest of Lhasa and close to the Himalayas (Figure S1). The BC mass concentration by AE33 is calculated based on the change of optical attenuation at 880 nm with a time resolution of 1 min (Drinovec et al., 2015). The detailed information of AE33 measurement can be found in Drinovec et al. (2015).

2.2. Supporting Data in Beijing

2.2.1. Measurement of Chemical Components at the BJMEMC Site

As other online measurements of multiple chemical species can be carried out at the Beijing site, the receptor model could be applied for BC source apportionment in Beijing. The online measurements of other PM$_{2.5}$ components include multiple elements by the Xact™ 625 (Cooper Environmental Services LLC), water soluble ions by the URG-9000 ambient ion monitor, and organic carbon (OC) by the Semi-continuous OCEC Carbon Aerosol Analyzer (Sunset Laboratory Inc.). These online measurements were conducted simultaneously with BC at the BJMEMC site. The detailed information of instruments could be found in Liu et al. (2019) and Manigrasso et al. (2010). The quality control was discussed in the supporting information.

The operation and maintenance of the above multiple online instruments is very challenging at the YBJ site, especially during the LD period. Therefore, only AE33 measurement was made in Tibet.

2.2.2. Online Measurement in Previous Years at Another Urban Site in Beijing

To compare the diurnal variation of BC and the correlation between BC and secondary inorganic aerosol (including sulfate, nitrate, ammonium; hereafter SNA) in 2020 with those in previous years, the long-term online measurements of BC by AE33 and SNA by the In-situ Gas and Aerosol Composition monitoring system (Model S-611, Fortelice International Co., Ltd.) at the Peking University site (the PKU site, 39°59′N, 116°18′E; 52 m MSL) from January 2016 to November 2019 were used for this analysis. The PKU and BJMEMC sites are both representative urban site of Beijing, and two sites are 7 km apart. The BC data from these two urban sites are comparable (see Figure S2).
2.3. Source Apportionment Method

2.3.1. The Aethalometer Model

The aethalometer model was applied for source apportionment of BC in both Beijing and Tibet. It is assumed that BC absorption can be attributed to fossil and non-fossil combustion. Therefore,

\[ b_{\text{abs,880}}(\text{BC}) = b_{\text{abs,880}}(\text{BC}_{\text{fossil}}) + b_{\text{abs,880}}(\text{BC}_{\text{non-fossil}}) \]  

(1)

The wavelength dependence of absorption coefficient is proportional to \( \lambda^{-\alpha} \), where \( \lambda \) is the wavelength and \( \alpha \) is the angstrom exponent (AAE).

\[ b_{\text{abs}} = \lambda^{-\alpha} \]  

(2)

The contribution of BC from fossil fuel and non-fossil fuel can be derived as follows:

\[ \frac{b_{\text{abs,BC}}(370\text{nm})_{\text{fossil}}}{b_{\text{abs,BC}}(880\text{nm})_{\text{fossil}}} = \left( \frac{370}{880} \right)^{-\alpha_{\text{fossil}}} \]  

(3)

\[ \frac{b_{\text{abs,BC}}(370\text{nm})_{\text{non-fossil}}}{b_{\text{abs,BC}}(880\text{nm})_{\text{non-fossil}}} = \left( \frac{370}{880} \right)^{-\alpha_{\text{non-fossil}}} \]  

(4)

where \( \alpha_{\text{fossil}} \) and \( \alpha_{\text{non-fossil}} \) represents the AAE for BC from fossil fuel (\( \alpha_{\text{fossil}} = 1.0 \)) and BC from non-fossil fuel (\( \alpha_{\text{non-fossil}} = 2.0 \)). How to determine \( \alpha \) values can be found in the supporting information.

2.3.2. The PMF Model

The PMF model requires input of source tracers, which were not measured in Tibet in this study. Therefore, PMF was only applied to investigate BC sources in Beijing. The principle and detailed information of this model could be found in Paterson et al. (1999). Source profiles of PMF are shown in Figure S3. The identification of each factor can be found in the supporting information.

Both two models were applied in Beijing. The fossil fuel sources of BC mainly includes traffic emission and coal combustion in China (Q. Zhang et al., 2009). However, the AAE of BC from coal combustion was larger than 1.0 (Liu et al., 2018), thus the fossil fuel contribution apportioned by the aethalometer model mainly includes traffic source (Sandradewi et al., 2008). Therefore, the contribution of traffic source by the PMF model and fossil fuel combustion source by the aethalometer model were compared (seen in Figure S4 and Table S1). It could be seen that the two models agreed well with each other with \( R^2 \) over 0.9.

The total potential source contribution function (TPSCF) method was conducted for potential source region analysis and the detailed information of TPSCF is provided in the supporting information.

2.4. Definition of Time Periods

To investigate the influence of COVID-19 on BC in Beijing and Tibet, different periods were defined according to the timeline of government regulations. On December 31, 2019, the new coronavirus was found and reported in Wuhan, China. The first LD of city started on January 23 and the first level response to major public health emergencies was issued in all 31 provinces from January 29, 2020. Different from China, which experienced a recovery period in March 2020, the lockdown of India started on March 25 and lasted until the end of May 2020 (Chatterjee et al., 2021). Therefore, five special period was defined as follows: pre-LD (before the lockdown in China, November 15, 2019–January 19, 2020), Spring Festival (Spring Festival in China, 20–25 January), LD (the lockdown in China, January 26–February 19), Recovery (February 20–March 24) and LD-IN (the lockdown in India, March 25–May 31).
3. Results and Discussion

3.1. BC Concentration During Lockdown Period at Urban and Background Site

3.1.1. Temporal Variation of BC

The temporal variations of BC concentration in Beijing and Tibet from November 2019 to October 2020 are shown in Figure 1a. Figure 1b shows the average BC concentration in different periods and the log-normal distributions are shown in Figure S5. It could be seen that the influence of COVID-19 on BC were significantly different in megacity and plateau background site.

In Beijing, the average concentration of BC in the LD period was 2.22 ± 1.66 μg/m³, which was higher than that in the pre-LD period by about 20%. The log-normal distribution also showed similar variation trend, with the mean value increased from 0.09 in pre-LD period to 0.20 in LD period (Figure S5). Unlike the decrease of BC in other cities (Chen et al., 2020; Xu et al., 2020), the increase of BC average concentration in the LD period in Beijing could be mainly attributed to high concentrations during two haze episodes. Without the two haze episodes, BC in the LD period was actually lower than that in the pre-LD period by about 25% (Figure S6). Three haze episodes (HP) and two non-haze periods (NHP) were selected with daily PM2.5 concentration larger than 75 μg/m³ for HP and less than 75 μg/m³ for NHP (Figure S7). As shown in Figure 1c, HP1 and NHP1 were selected for the pre-LD period while HP2, HP3, and NHP2 were selected for the LD period. The date and the average, maximum, and minimum concentration of BC during different episodes are listed in Table S2. It could be seen that BC in NHP2 during the LD period was lower than that in NHP1 during the pre-LD period. Compared with the pre-LD period, the haze episodes in the LD period were characterized by longer duration with lower maximum value of BC.

In contrast to Beijing, the average concentration of BC in Tibet decreased over 70% from pre-LD (0.81 ± 1.16 μg/m³) to LD period (0.23 ± 0.17 μg/m³). Moreover, BC concentration showed an increasing trend after the LD-IN period, with an average concentration two times higher than that in the LD period.
The monthly variation of BC in our study was different from previous studies in Tibet. Figure 1d showed the monthly variation of BC at the YBJ site in this study and at Lulang in 2008 and Namco site in 2013 in Tibet (X. Zhang et al., 2017; Zhao et al., 2013). In 2013, BC concentration increased significantly from November to May and decreased from June to September (X. Zhang et al., 2017). Similar temporal variation could also be found in Lulang in 2008 (Zhao et al., 2013). The relatively high BC from January to March in previous years could be attributed to the regional transport from highly polluted South Asia. However, instead of an increasing trend seen in previous years, BC in our study decreased from December to March (abnormal low in 2020) while slightly increased after June. This was probably due to low BC concentration in South Asia in 2020, providing supporting evidence that Tibet was very sensitive to the impact of COVID-19 and emission reduction in the source region in 2020.

3.1.2. Influence of Meteorological Conditions

The variation of meteorological conditions was different during the LD period in Beijing and Tibet. As reported in several studies, the unfavorable meteorological conditions during the LD period in Beijing could enhance the accumulation of atmospheric pollutants (Su et al., 2020). Lv et al. (2020) found that the relative humidity (RH) increased during the LD period, especially in the two haze episodes with highest RH exceeding 80%, while the wind speed and the highest boundary layer height decreased to around 1.0 m/s and 1 km, respectively.

In contrast to Beijing, the variation of meteorological conditions was not significant during the LD period in Tibet. As shown in Figure S8, the RH in Tibet was the lowest in January and February, and only increased in the end of February due to snow. During the LD period, the highest RH was around 40%, which was only half of that in Beijing. Moreover, the wind speed in Tibet remained rather constant than that in Beijing, with slight fluctuation around 2.0 m/s.

3.2. Influence of COVID-19 on BC in Beijing

3.2.1. Sources and Regional Transport in the Pre-LD and LD Period

Seven sources of BC were identified by the PMF model, including industrial, dust, traffic, biomass burning, coal combustion, firework, and aged BC. It has been reported that BC could be coated with secondary species in winter in Beijing (D. Liu et al., 2015), thus the aged BC factor in our study was defined with high loadings of BC and SNA.

The temporal variation of BC sources in Beijing from November 2019 to March 2020 is shown in Figure 2a. It could be seen that before the LD, traffic and industrial source were predominant. After January 23, the contribution of primary source decreased due to the strict regulation. Instead, the increase of BC concentration in the LD period could be mainly attributed to aged BC, especially during haze episodes. Figures 2b–2d showed the temporal variation of sources in HP1 in the pre-LD period, HP2 and HP3 in the LD period. HP1 was mainly influenced by traffic source with average contribution of 60%. In HP2, which was close to the Spring Festival, traffic source contribution decreased while the influence of firework was important. As for HP3, the contribution of aged BC increased significantly, with the average contribution two times higher than that in HP1. The absolute concentration of aged BC increased from 0.77 ± 0.62 μg/m³ in HP1 to 1.61 ± 0.59 μg/m³ in HP3.

The high BC concentration in HP3 during the LD period could be influenced by regional transport from neighboring province. As shown in Figures 2e and 2f, HP1 in the pre-LD period was mainly influenced by local emission, while the contribution of regional transport to BC in HP3 during the LD period was more significant and was mainly originated from Hebei province. As reported by Li et al. (2017), 80% of SNA in Beijing in rapid increasing stage of a haze episode was from emissions in Hebei province. Therefore, the regional transport from the southwestern areas in the LD period could be the reason for the enhanced contribution of aged BC to high BC concentration in HP3.

3.2.2. Significant Aged BC Contribution in Haze Episodes During LD in Beijing

The less impact of primary sources to BC in the LD period could be found in the diurnal variation. As shown in Figure 3a, the diurnal variation of BC in 2016, 2017, and 2019 showed more significant peaks in
the morning rush-hour and in the evening, suggesting the impact of traffic source, especially heavy-duty trucks in Beijing. However, the diurnal variation in 2020 was not as significant as previous years, indicating lower contribution of primary traffic source to BC. The diurnal variation in 2018 was minor as well due to the strict policy control and favorable meteorological conditions in that year (Cheng et al., 2019).

The associations of BC with SNA in the LD periods in 5 years are presented in Figure 3b. It could be seen that SNA and BC were best correlated in 2020 ($R^2 = 0.77$) with the highest slope of 19.6, suggesting that BC was more associated or coated with SNA in 2020. As shown in Figure 2, aged BC contribution increased during the LD period based on the PMF model. A previous study used a single particle soot photometer (SP2) to analyze the relative coating thickness ($Dp/Dc$) of aged BC and BC from primary sources by the PMF model (B. Zhang, 2019). The results showed that aged BC was characterized by larger $Dp/Dc$ compared to primary sources, indicating the aging and mixing of BC with secondary species.
3.3. Influence of COVID-19 on BC in Tibet

As shown in Figure 4a, BC in Tibet exhibited a clear reduction from January to March within the LD periods, which was abnormally low compared to previous years. It is important to understand the reason for BC reduction in Tibet based on source apportionment analysis.

As only AE33 was able to be deployed continuously for 1 year in Tibet in our study, BC sources were investigated by the aethalometer model. Figures 4b and 4c showed the monthly variation of fossil fuel contribution and the AAE at the YBJ site. It could be seen that although BC concentration decreased abnormally, the relative contribution of non-fossil fuel (mainly biomass burning) and AAE increased during the LD and LD-IN periods. That increasing trend was similar with previous years in Tibet, in which higher biomass burning contribution was found in February and April (Cong et al., 2015; J. Huang et al., 2010).

The increased biomass burning contribution indicated that BC in Tibet during the LD periods was still quite influenced by regional transport, which was similar to previous years (Cong et al., 2015; Kang et al., 2019; Wan et al., 2017; Yang et al., 2021). It was reported that biomass burning activities were significant in South Asia with the highest intensity during February–May (Bhardwaj et al., 2016) and polluted air mass from biomass burning in South Asia could be transported over the Himalayas to Tibet (Cong et al., 2015). The regional transport from South Asia influenced the spatial distribution of BC sources in Tibet, with non-fossil fuel contribution higher in Himalayas close to South Asia and lower in Northern Tibet (66% ± 16%) (Kang et al., 2019). The TPSCF method was applied in this study to analyze the potential source region of BC in the pre-LD and LD period in 2020. As shown in Figure S9, the potential source region during the LD period was more concentrated in the south of Tibet, including Nepal and Northern India, where biomass was burned extensively (Bhardwaj et al., 2016). Overall, the impact of regional transport from South Asia was significant during the LD periods in Tibet.

However, as the main source region of BC in Tibet, South Asia was also influenced by COVID-19 and its anthropogenic emission significantly decreased, resulting in lower concentration of atmospheric pollutants (Panda et al., 2021). Figure S9 showed the BC surface mass concentration derived by the NASA GIOVANNI tool (https://giovanni.gsfc.nasa.gov/giovanni/) during the pre-LD and LD periods. It could be seen that the BC concentration level significantly decreased during the LD period in South Asia, with the highest concentration reduced by half. Based on the satellite data, it can be seen that there were fewer fire spots in South Asia during the LD-IN period in 2020 than the same period in 2019 (Figure S10). Therefore, the abnormal
reduction of BC in Tibet during the LD periods could be attributed to high sensitivity of plateau background areas to the emission reduction in South Asia. The results suggested that the investigation and control of cross-border transport was essential to reduce BC concentration in Tibet.

4. Conclusions

In this study, 1-year continuous online measurement of BC was conducted simultaneously in Beijing and Tibet from November 2019 to October 2020. The results showed that the influence of COVID-19 on BC was significantly different in Beijing and Tibet. Due to the two haze episodes in the LD period in Beijing, the average concentration in the LD period was 20% higher than that in pre-LD period. In contrast to Beijing, the average concentration of BC in Tibet decreased over 70% from pre-LD to LD period, which exhibited very different seasonal variation pattern compared to those in previous years.

For Beijing, the PMF results showed higher aged BC contribution during haze episodes in the LD period. Moreover, BC and SNA were best correlated in 2020 compared with 2016–2019. The results indicated that although the local emission from primary sources was reduced, higher BC during the LD period could be attributed to the contribution of aged BC and transport from southwestern neighboring areas.

Figure 4. Monthly variation of (a) BC concentration, (b) the percentage of fossil fuel contribution, and (c) angstrom exponent (AAE) at the Yangbajain (YBJ) site. Similar to previous years, the contribution from biomass burning source increased during spring (pre-monsoon season) although BC concentration was abnormally low during lockdown (LD) and LD-IN periods in 2020.
As for Tibet, although BC concentration decreased, the increased relative contribution of biomass burning in spring indicated impact of regional transport from South Asia during the LD periods in Tibet. Due to COVID-19, the anthropogenic emissions and fire spots reduced significantly in South Asia. Therefore, the decrease of BC in Tibet confirmed high sensitivity of plateau background areas to the anthropogenic emission reduction in South Asia. Overall, this study helps to better understand different sensitivity of BC in megacity and background areas in China to change of anthropogenic activities due to COVID-19.

Nevertheless, there is still space for improvement in the study. In the future, the mixing state of BC could be measured simultaneously, which could help better understand aging of BC. In addition, as BC has significant effects on radiative forcing, especially in Tibet, the radiative forcing model could be combined with source apportionment results to further study the impacts on radiative forcing due to anthropogenic emission reduction during COVID-19.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The associated data can be downloaded online (10.6084/m9.figshare.13668905).

Acknowledgments

This study was supported by funding from the second Tibetan Plateau Scientific Expedition and Research Program (2019QZEK0105, 2019QZEK0204), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA17010103), the Beijing Municipal Science & Technology Commission (Z181100005418003), and the National Natural Science Foundation of China (91743310). The authors would like to thank the assistance of Yuejian Xuan (91744310). The authors would like to thank the assistance of Yuejian Xuan from Chinese Academy of Sciences, Beijing Saak-Mar Environmental Instrument Ltd. and Yazhen Wu from Peking University.

References

Bhardwaj, P., Naja, M., Kumar, R., & Chandola, H. C. (2016). Seasonal, interannual, and long-term variabilities in biomass burning activity over South Asia. *Environmental Science & Pollution Research*, 23, 4397–4410. https://doi.org/10.1007/s11356-015-5620-6

Chatterjee, A., Mukherjee, S., Dutta, M., Ghosh, A., Ghosh, S. K., & Roy, A. (2021). High rise in carbonaceous aerosols over very low anthropogenic emissions over eastern Himalaya, India: Impact of lockdown for COVID-19 outbreak. *Atmospheric Environment*, 244, 117947. https://doi.org/10.1016/j.atmosenv.2020.117947

Chen, Y., Zhang, S., Peng, C., Shi, G., Tian, M., Huang, R., et al. (2020). Impact of the COVID-19 pandemic and control measures on air quality and aerosol light absorption in southwestern China. *Science of the Total Environment*, 749, 141419. https://doi.org/10.1016/j.scitotenv.2020.141419

Cheng, J., Su, J., Cui, T., Li, X., Dong, X., Sun, F., et al. (2019). Dominant role of emission reduction in PM2.5 air quality improvement in Beijing during 2013–2017: A model-based decomposition analysis. *Atmospheric Chemistry and Physics*, 19(9), 6125–6146. https://doi.org/10.5194/acp-19-6125-2019

Cong, Z., Kang, S., Kawamura, K., Liu, B., Wan, X., Wang, Z., et al. (2015). Carbonaceous aerosols on the south edge of the Tibetan Plateau: Concentrations, seasonality and sources. *Atmospheric Chemistry and Physics*, 15(3), 1573–1584. https://doi.org/10.5194/acp-15-1573-2015

Drinovec, L., Močnik, G., Zotter, P., Prévôt, A. S. H., Ruckstuhl, C., Coz, E., et al. (2015). The 'dual-spot' Aethalometer: An improved measurement of aerosol black carbon with real-time loading compensation. *Atmospheric Measurement Techniques*, 8(5), 1965–1979. https://doi.org/10.5194/amt-8-1965-2015

Huang, J., Kang, S., Shen, C., Cong, Z., Liu, K., Wang, W., & Liu, L. (2010). Seasonal variations and sources of ambient fossil and biogenic-derived carbonaceous aerosols based on 13C measurements in Lhasa, Tibet. *Atmospheric Research*, 96(4), 553–559. https://doi.org/10.1016/j.atmosres.2010.01.003

Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., et al. (2020). Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. *National Science Review*, 0, 1–9. https://doi.org/10.1093/nsr/nwaa137

Jacobson, M. Z. (2001). Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature*, 409(6821), 695–697. https://doi.org/10.1038/35055518

Kalluri, R. O. R., Gugamsetty, B., Tandule, C. R., Kotalo, R. G., Thotli, L. R., Rajuru, R. R., & Palle, S. N. R. (2021). Impact of aerosols on surface ozone during COVID-19 pandemic in southern India: A multi-instrumental approach from ground and satellite observations, and model simulations. *Journal of Atmospheric and Solar-Terrestrial Physics*, 212, 105491. https://doi.org/10.1016/j.jastp.2020.105491

Kang, S., Zhang, Q., Qian, Y., Ji, Z., Li, C., Cong, Z., et al. (2019). Linking atmospheric pollution to cryospheric change in the third pole region: Current progress and future prospects. *National Science Review*, 6(4), 796–809. https://doi.org/10.1093/nsr/nwz031

Le, T., Wang, Y., Liu, L., Yang, J., Yung, Y. L., Li, G., & Seinfeld, J. H. (2020). Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. *Science*, 369(6504), 702–706. https://doi.org/10.1126/science.abb7431

Li, J., Du, H., Wang, Z., Sun, Y., Yang, W., Li, J., et al. (2017). Rapid formation of a severe regional winter haze episode over a mega-city cluster on the north China plain. *Environmental Pollution*, 221, 605–615. https://doi.org/10.1016/j.envpol.2017.01.063

Liu, D., Joshi, R., Wang, J., Yu, C., Allan, J. D., Coe, H., et al. (2015). Contrasting physical properties of black carbon in urban Beijing between winter and summer. *Atmospheric Chemistry and Physics*, 19, 6749–6769.

Liu, Y., Yan, C., & Zheng, M. (2018). Source apportionment of black carbon during winter in Beijing. *Science of the Total Environment*, 618, 531–541. https://doi.org/10.1016/j.scitotenv.2017.11.053

Liu, Y., Zheng, M., Yu, M., Cai, X., Du, H., Li, J., et al. (2019). High-time-resolution source apportionment of PM2.5 in Beijing with multiple models. *Atmospheric Chemistry and Physics*, 19(9), 6595–6609. https://doi.org/10.5194/acp-19-6595-2019

Lv, Z., Wang, X., Deng, F., Ying, Q., Archibald, A. T., Jones, R. L., et al. (2020). Source-Receptor relationship revealed by the halted traffic and aggravated haze in Beijing during the COVID-19 lockdown. *Environmental Science & Technology*, 54(24), 15660–15670. https://doi.org/10.1021/acs.est.0c04841
Manigrasso, M., Abballe, F., Jack, R. F., & Avino, P. (2010). Time-resolved measurement of the ionic fraction of atmospheric fine particulate matter. *Journal of Chromatographic Science*, 48(7), 549–552. https://doi.org/10.1093/jcms/jcs077

Panda, S., Malik, C., Nath, J., Das, T., & Ramasamy, B. (2021). A study on variation of atmospheric pollutants over Bhurbaneswar during imposition of nationwide lockdown in India for the COVID-19 pandemic. *Air Quality, Atmosphere & Health*, 14(1), 97–108. https://doi.org/10.1007/s11869-020-00916-5

Paterson, K. G. (1999). Analysis of air quality data using positive matrix factorization. *Environmental Science & Technology*, 33(18), 3283. https://doi.org/10.1021/es990217r

Sandradewi, J., PréVôt, A. S. H., Szigatid, S., Perron, N., Alfarr, M. R., Lanz, V. A., et al. (2008). Using aerosol light absorption measurements for the quantitative determination of wood burning and traffic emission contributions to particulate matter. *Environmental Science & Technology*, 42(9), 3316–3323. https://doi.org/10.1021/es0702253m

Su, T., Li, Z., Zheng, Y., Luan, Q., & Guo, J. (2020). Abnormally shallow boundary layer associated with severe air pollution during the COVID-19 lockdown in China. *Geophysical Research Letters*, 47(20), e2020GL090041. 10.1029/2020GL090041

Twohy, C. H., & Poellot, M. R. (2005). Chemical characteristics of ice residual nuclei in anvil cirrus clouds: Evidence for homogeneous and heterogeneous ice formation. *Atmospheric Chemistry and Physics*, 5(8), 2289–2297. https://doi.org/10.5194/acp-5-2289-2005

Wan, X., Kang, S., Li, Q., Rupakheti, D., Zhang, Q., Guo, J., et al. (2017). Organic molecular tracers in the atmospheric aerosols from Lumbini, Nepal, in the northern Indo-Gangetic plain: Influence of biomass burning. *Atmospheric Chemistry and Physics*, 17(14), 8867–8885. https://doi.org/10.5194/acp-17-8867-2017

Xu, L., Zhang, J., Sun, X., Xu, S., Shan, M., Yuan, Q., et al. (2020). Variation in concentration and sources of black carbon in a megacity of China during the COVID-19 pandemic. *Geophysical Research Letters*, 47(23), e2020GL090444. 10.1029/2020GL090444

Yang, J., Ji, Z., Kang, S., & Tripathee, L. (2021). Contribution of South Asian biomass burning to black carbon over the Tibetan Plateau and its climatic impact. *Environmental Pollution* 270. https://doi.org/10.1016/j.envpol.2020.116195

Zhang, B. (2019). Effects of black carbon with different sources and mixing states on respiratory inflammatory response (Master’s thesis). Location: Peking University.

Zhang, Q., Streets, D. G., Carmichael, G. R., He, K. B., Huo, H., Kannari, A., et al. (2009). Asian emissions in 2006 for the NASA INTEX-B mission. *Atmospheric Chemistry and Physics*, 9(14), 5131–5153. https://doi.org/10.5194/acp-9-5131-2009

Zhang, X., Chen, Y., Ming, J., Li, Z., Wang, F., & Zhang, G. (2017). The online measured black carbon aerosol and source orientations in the Nam Co region, Tibet. *Environmental Science & Pollution Research*, 24(32), 25021–25033. https://doi.org/10.1007/s11356-017-1651-5

Zhao, Z., Cao, J., Shen, Z., Xu, B., Zhu, C., Chen, L., et al. (2013). Aerosol particles at a high-altitude site on the Southeast Tibetan Plateau, China: Implications for pollen transport from South Asia. *Journal of Geophysical Research: Atmospheres*, 118(19), 11360–11375. https://doi.org/10.1002/jgrd.50599

---

**References From the Supporting Information**

**AE33 Guide (2015). Aethalometer® model AE33 user manual. Aerosol doo.**

Amato, F., Schaap, M., van der Gon, H. A. C. D., Pandolfi, M., Alastuey, A., Keukken, M., & Querol, X. (2013). Short-term variability of mineral dust, metals and carbon emission from road dust resuspension. *Atmospheric Environment*, 74, 134-140.

Cheng, M., Hopke, D. P. K., Barrie, L., Rippe, A., Olson, M., & Landsberger, S. (1993). Qualitative determination of source regions of aerosol in Canadian high Arctic. *Environmental Science & Technology*, 27(10), 2063–2071.

Duan, F., Liu, X., Yu, T., & Cachier, H. (2004). Identification and estimate of biomass burning contribution to the urban aerosol organic carbon concentrations in Beijing. *Atmospheric Environment*, 38(9), 1275–1282.

Fuller, G. W., Tremer, A. H., Baker, T. D., Yttri, K. E., & Butterfield, D. (2014). Contribution of wood burning to PM<sub>2.5</sub> in London. *Atmospheric Environment*, 87, 87–94.

Gao, J., Peng, X., Chen, G., Xu, J., Shi, G., Zhang, Y., & Feng, Y. (2016). Insights into the chemical characterization and sources of PM<sub>2.5</sub> in Beijing at a 1-h time resolution. *Science of the Total Environment*, 542, 162–171.

Guo, Q., Hu, M., Guo, S., Wu, Z., Hu, W., Peng, J., et al. (2015). The identification of source regions of black carbon at a receptor site off the eastern coast of China. *Atmospheric Environment*, 100, 78–84.

Hu, Y., Lin, J., Zhang, S., Kong, L., Fu, H., & Chen, I. (2015). Identification of the typical metal particles among haze, fog, and clear episodes in the Beijing atmosphere. *Science of the Total Environment*, 511, 369–380.

Jia, Y., Kahn, K. A., He, K., Wen, T., & Wang, Y. (2008). A novel technique for quantifying the regional component of urban aerosol solely from its sawtooth cycles. *Journal of Geophysical Research*, 113(D21), D21309. https://doi.org/10.1029/2008JD001039

Kedia, S., Ramachandran, S., Rajesh, T. A., & Srivastava, R. (2012). Aerosol absorption over Bay of Bengal during winter: Variability and sources. *Atmospheric Environment*, 54, 738–745.

Li, Y., Chang, M., Ding, S., Wang, S., Ni, D., & Hu, H. (2017). Monitoring and source apportionment of trace elements in PM<sub>1</sub>, Implications for local air quality management. *Journal of Environmental Management*, 196, 16–25.

Liu, Y., Zheng, M., Yu, M., Cai, X., Du, H., Li, J., et al. (2019). High-time-resolution source apportionment of PM<sub>2.5</sub> in Beijing with multiple models. *Atmospheric Chemistry and Physics*, 19(9), 6595–6609.

Lv, Z., Wang, X., Deng, F., Ying, Q., Archibald, A. T., Jones, R. L., et al. (2020). Source-Receptor relationship revealed by the halted traffic and aggravated haze in Beijing during the COVID-19 lockdown. *Environmental Science & Technology*, 54(24), 15660–15670.

Norris, G., Duvall, R., Brown, S., & Bai, S. (2014). *EPA Positive Matrix Factorization (PMF) 5.0 Fundamentals and User Guide*. EPA United States Environmental Protection Agency Search.

Olson, M. R., Garcia, M. V., Robinson, M. A., Van Rooy, P., Dieterenberger, M. A., Bergin, M., & Schauer, J. J. (2015). Investigation of black carbon and wavelength-dependent light absorption from biomass and fossil fuel combustion source emissions. *Journal of Geophysical Research: Atmospheres*, 120(13), 6682–6697. https://doi.org/10.1002/2014JD022970

Paatiero, R., Eberly, S., Brown, S. G., & Norris, G. A. (2014). Methods for estimating uncertainty in factor analytic solutions. *Atmospheric Measurement Techniques*, 7(3), 781–797.

Pant, P., & Harrison, R. M. (2013). Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review. *Atmospheric Environment*, 77, 78–97.

Ran, L., Deng, Z., Wang, P., & Xia, X. (2016). Black carbon and wavelength-dependent aerosol absorption in the north China plain based on two-year aethalometer measurements. *Atmospheric Environment*, 142, 132–144.
Sandradewi, J., Prevot, A. S. H., Szidat, S., Perron, N., Alfarra, M. R., Lanz, V. A., et al. (2008). Using aerosol light absorption measurements for the quantitative determination of wood burning and traffic emission contributions to particulate matter. *Environmental Science & Technology*, 42(9), 3316–3323.

Shen, Z., Sun, J., Cao, J., Zhang, L., Zhang, Q., Lei, Y., et al. (2016). Chemical profiles of urban fugitive dust PM$_{2.5}$ samples in Northern Chinese cities. *Science of the Total Environment*, 569, 619–626.

Shi, G., Xu, J., Peng, X., Xiao, Z., Chen, K., Tian, Y., et al. (2017). pH of aerosols in a polluted atmosphere: Source contributions to highly acidic aerosol. *Environmental Science & Technology*, 51(8), 4269–4276.

Tao, J., Gao, J., Zhang, L., Zhang, R., Che, H., Zhang, Z., et al. (2014). PM$_{2.5}$ pollution in a megacity of southwest China: Source apportionment and implication. *Atmospheric Chemistry and Physics*, 14(16), 8679–8699.

Tsai, H. H., Chien, L. H., Yuan, C., Lin, Y., Jen, Y., & Ie, I. E. (2012). Influences of fireworks on chemical characteristics of atmospheric fine and coarse particles during Taiwan’s Lantern Festival. *Atmospheric Environment*, 62, 256–264.

Watson, J. G., & Chow, J. C. (2001). Estimating middle-, neighborhood-, and urban-scale contributions to elemental carbon in Mexico City with a rapid response aethalometer. *Journal of the Air and Waste Management Association*, 51(11), 1522–1528.

Yu, X., Shi, C., Ma, J., Zhu, B., Li, M., Wang, J., et al. (2013). Aerosol optical properties during firework, biomass burning and dust episodes in Beijing. *Atmospheric Environment*, 81, 475–484.

Zhang, B., Zhou, T., Liu, Y., Yan, C., Li, X., Yu, J., et al. (2019). Comparison of water-soluble inorganic ions and trace metals in PM$_{2.5}$ between online and offline measurements in Beijing during winter. *Atmospheric Pollution Research*, 10(6), 1755–1765.

Zhang, Q., Streets, D. G., Carmichael, G. R., He, K., Hue, H., Kannari, A., et al. (2009). Asian emissions in 2006 for the NASA INTEX-B mission. *Atmospheric Chemistry and Physics*, 9(14), 5131–5153.