Chemosphere 214 (2019) 314–318

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Short Communication

Heavy near-surface $PM_{2.5}$ pollution in Lhasa, China during a relatively static winter period

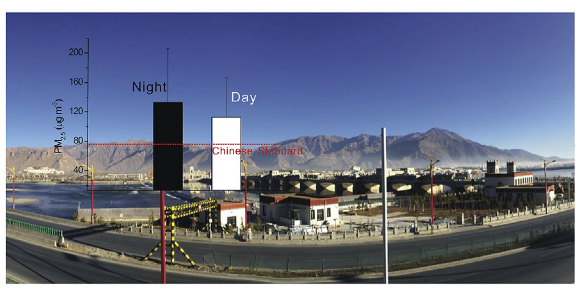
Chaoliu Li [a,e,c,*], Xiaowen Han [a,d], Shichang Kang [b,d,e], Fangping Yan [c], Pengfei Chen [b], Zhaofu Hu [b,d], Junhua Yang [b], Duojie Ciren [a], Shaopeng Gao [a], Mika Sillanpää [c], Yongming Han [f], Yuyan Cui [g,h], Shang Liu [i], Kirk R. Smith [j]

[a] Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China
[b] State Key Laboratory of Cryospheric Sciences, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[c] Laboratory of Green Chemistry, Lappeenranta University of Technology, Sammonkatu 12, FI-50130 Mikkeli, Finland
[d] University of Chinese Academy of Sciences, Beijing 100049, China
[e] CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China
[f] Key Laboratory of Aerosol Chemistry & Physics and SKLLQG, Institute of Earth Environment, Chinese Academy of Sciences, 710061 Xi'an, China
[g] Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO 80309, United States
[h] Chemical Sciences Division, NOAA Earth System Research Laboratory, Boulder, CO 80305, United States
[i] School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui, China
[j] Division of Environmental Health Sciences, School of Public Health, University of California, Berkeley, CA 94720-7360, USA

HIGHLIGHTS

- Near surface $PM_{2.5}$ concentration at Lhasa city during static winter was studied.
- Near surface $PM_{2.5}$ was $118 \pm 60\ \mu g\ m^{-3}$, seriously polluted during studied period.
- $PM_{2.5}$ of Lhasa city was mainly emitted by its local sources.
- Butter lamp lighting during festival cause serious $PM_{2.5}$ pollution of whole city.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 July 2018
Received in revised form
20 September 2018
Accepted 21 September 2018
Available online 22 September 2018

Handling Editor: R. Ebinghaus

ABSTRACT

Fairly high near-surface $PM_{2.5}$ concentrations were found during relatively static winter conditions within Lhasa – a Tibetan Plateau city normally considered to have a clean atmosphere. The average daily $PM_{2.5}$ concentration reached $118 \pm 60\ \mu g\ m^{-3}$ during the study period, was approximately 3.4 times the United States Environmental Protection Agency 24-h standard. $PM_{2.5}$ concentration of Lhasa increased from 20:00 until 23:00, which was probably caused by space heating, waste incineration activities and decreased boundary layer at night. Furthermore, we found traditional religious butter lamp lighting of local Tibetan residents during festivals could cause $PM_{2.5}$ concentration to reach an alarmingly high level, $240 \pm 30\ \mu g\ m^{-3}$. Therefore, to protect the atmosphere of Lhasa, the government may wish to conduct more complete monitoring and find ways to encourage clean heating and cooking fuels, enforce the

* Corresponding author. Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China.

E-mail addresses: lichaoliu@itpcas.ac.cn (C. Li), hanxiaowen@itpcas.ac.cn (X. Han), shichang.kang@lzb.ac.cn (S. Kang), freefly347@126.com (F. Yan), chenpengfeifeifei@126.com (P. Chen), huzf11@lzu.edu.cn (Z. Hu), yangjunhua@lzb.ac.cn (J. Yang), 1051546753@qq.com (D. Ciren), gaoshaopeng@itpcas.ac.cn (S. Gao), mika.sillanpaa@lut.fi (M. Sillanpää), yongming@ieecas.cn (Y. Han), cuiyuyan112@gmail.com (Y. Cui), shangliu@ustc.edu.cn (S. Liu), krksmith@berkeley.edu (K.R. Smith).

https://doi.org/10.1016/j.chemosphere.2018.09.135
0045-6535/

supervision on illegal emission activities such as waste incineration, and guide residents to transfer to more environmentally friendly activities during festivals.

Keywords:
Butter lamp lighting
Festivals
Air pollution
Tibetan Plateau

1. Introduction

Because of its adverse impacts on human health and climate change, airborne particle matter pollution has attracted high attention in the world during the last over decades (Bond et al., 2004; Wang et al., 2011; Rastogi et al., 2014). Most concern has focused on fine particle pollution ($PM_{2.5}$ – particles with an aerodynamic diameter less than or equal to 2.5 μm) because it is an excellent indicator of health hazard (Cohen et al., 2017). In addition, $PM_{2.5}$ can be transported for long distances, potentially producing large climate forcing (Wang et al., 2012). At present, China is experiencing serious $PM_{2.5}$ pollution because of rapid industrialization and urbanization as well as continued use of traditional polluting fuels in households (CNEMC, 2013). Consequently, significant resources have been focused on East China to reduce $PM_{2.5}$ concentration (Zheng et al., 2005; Wang et al., 2006; Tao et al., 2017). However, so far, relatively few studies have focused on $PM_{2.5}$ pollution in Western China, particularly in Tibet.

Lhasa is one of the highest cities in China (3650 m) and is the capital city of the Tibet Autonomous Region as well as the religious center of Tibetan Buddhism. The area and population of Lhasa are around 59 km^2 and 0.55 million. Coal, wood, and liquefied petroleum gas (LPG) are the most important fuels for space heating. Generally, the atmosphere of Lhasa has been considered one of the cleanest in China. For instance, the mean $PM_{2.5}$ concentration in Lhasa from 2013 to 2014 was reported of 26.7 $\mu g\,m^{-3}$ (Li et al., 2016b), which is lower than that of Chinese annual average standard of 35 $\mu g\,m^{-3}$.

In addition, there are sources of pollution in Lhasa due to local fossil burning emissions and customs (Gong et al., 2011; Li et al., 2016a), such as butter lamps, which are generally lighted indoors, may emit a large amount of $PM_{2.5}$ but have not been extensively studied. Such sources may have influence on ground-level concentrations even if not affecting the overall ambient pollution levels. For instance, the $PM_{2.5}$ concentration at a Lhasa roadside was found to be approximately 145 ± 92 $\mu g\,m^{-3}$ (Hu et al., 2017), which was even a little higher than that of Beijing (Song et al., 2012) but around five times higher than that of the ambient concentration of Lhasa (Li et al., 2016b), implying serious $PM_{2.5}$ pollution at the near surface level at some special sites during typical meteorological condition such as weak winds during winter.

Therefore, despite relatively clean general ambient atmosphere in Lhasa, its near surface air may be seriously polluted. Because little precipitation occurs and space heating is more prevalent, $PM_{2.5}$ pollution is more serious during winter than that in summer (Li et al., 2016b). To examine these issues, we conducted winter ground-level measurements at five different sites of Lhasa in 2016, to investigate the concentration, sources and factors influencing $PM_{2.5}$ concentration (Fig. 1).

2. Materials and methods

$PM_{2.5}$ samples were collected on 90 mm pre-burned quartz fiber filters (Whatman Corp) at near surface level (1.5 m above ground) at five separate sites in Lhasa by aerosol sampler (TH150-A, Wuhan Tianhong INST Group) during December 20–27 2016 when the atmosphere is relatively stable (Li et al., 2016b) (Table. S1). The samples were collected at daytime (8:00 a.m.-20:00 (local time)) and nighttime (20:00–8:00 a.m.), respectively every day at each site. Field blank filters were also collected by exposing the filter in the sampler without any air being drawn through. The filters were weighted at least three times by balance with 10 μg precision after being kept in dryer for at least 24 h. The final data of each filter were the average of three weighing values with less than 5% difference. Finally, 23 $PM_{2.5}$ samples and four blank samples were collected. At the same time, hourly $PM_{2.5}$ concentration reported in Lhasa by the China Meteorological Administration (CMA) over this period were adopted for comparision (http://106.37.208.233:20035/). To investigate the relationship between meteorological conditions and $PM_{2.5}$ concentration, we used wind speeds recorded by CMA during study period (Fig. 2). To quantify the influence of butter burning on $PM_{2.5}$, its emission factor was measured using the method of Ni et al. (Ni et al., 2015; see Supplement).

3. Results

3.1. Concentration and diurnal variation of $PM_{2.5}$

The results showed that average 24-h $PM_{2.5}$ concentration in this study reached 118 ± 60 $\mu g\,m^{-3}$. At the same time, the $PM_{2.5}$ level in the China Meteorological Administration (CMA) for Lhasa Environmental Protection Agency (EPA) was 45 ± 35 $\mu g\,m^{-3}$. $PM_{2.5}$ concentration of site E close to CMA was about 4.9 times higher than that of CMA, further implying a high $PM_{2.5}$ concentration at ground level.

Despite higher near-surface $PM_{2.5}$ concentrations and multiple sampling sites of this study, diurnal variations of near surface $PM_{2.5}$ concentrations were significantly related to those of official released data ($p < 0.01$) (Fig. S1), implying their same local sources and the synchronous variations of $PM_{2.5}$ concentrations at different parts of Lhasa city. It needs to point out that the large difference between our data and the official released data caused by lower collecting heights of this study. Meanwhile, $PM_{2.5}$ concentrations were significantly negatively related to the wind speed ($p < 0.01$) (Fig. 2), indicating the diurnal variations of $PM_{2.5}$ concentrations were mainly controlled by wind speed. Lhasa located in Lhasa river valley with high mountains at its south and north sides, so that emitted particles do not easily diffuse when the atmosphere is relatively stable, causing high $PM_{2.5}$ concentration. Diurnally, it is normal to find a small peak during 8:00 to 10:00 a.m. due to rush hour and making breakfast (Fig. 3). Daytime $PM_{2.5}$ concentrations (113 ± 53 $\mu g\,m^{-3}$) were somewhat lower than that of nighttime value (133 ± 73 $\mu g\,m^{-3}$), however. Also, $PM_{2.5}$ concentration always increased after 20:00, peaked around 23:00, then gradually decreased (Fig. 3). This phenomenon was more obvious in winter, which is a different pattern to that of other cities (e.g., Beijing) where peak concentration occurs at 20:00, then gradually decrease until next morning. It is a normal phenomenon that low values appeared at nighttime because of decreased anthropogenic activities and emissions (Zhao et al., 2009; Liu et al., 2015). It is likely that greatly increased local emissions (e.g., space heating and illegal emissions such as waste incineration) after sunset causes this

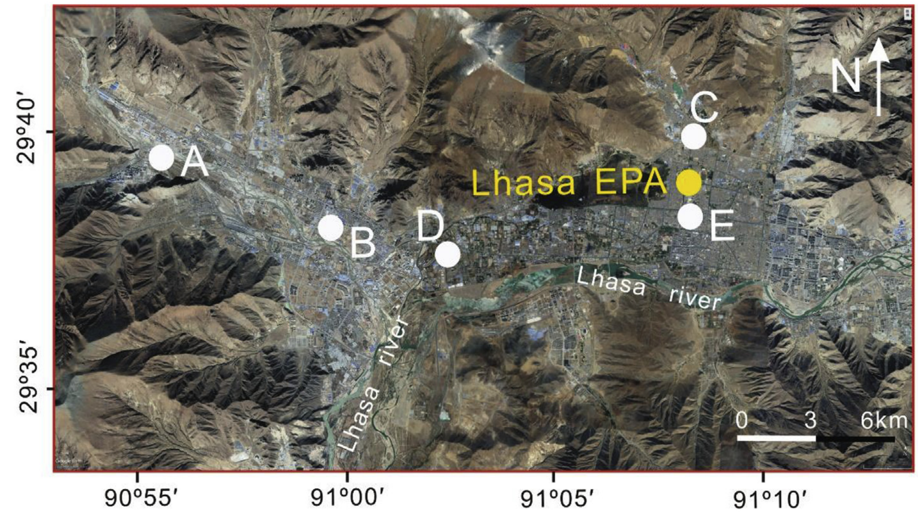


Fig. 1. Sampling sites at Lhasa in this study. The detailed information is shown in Table. S1.

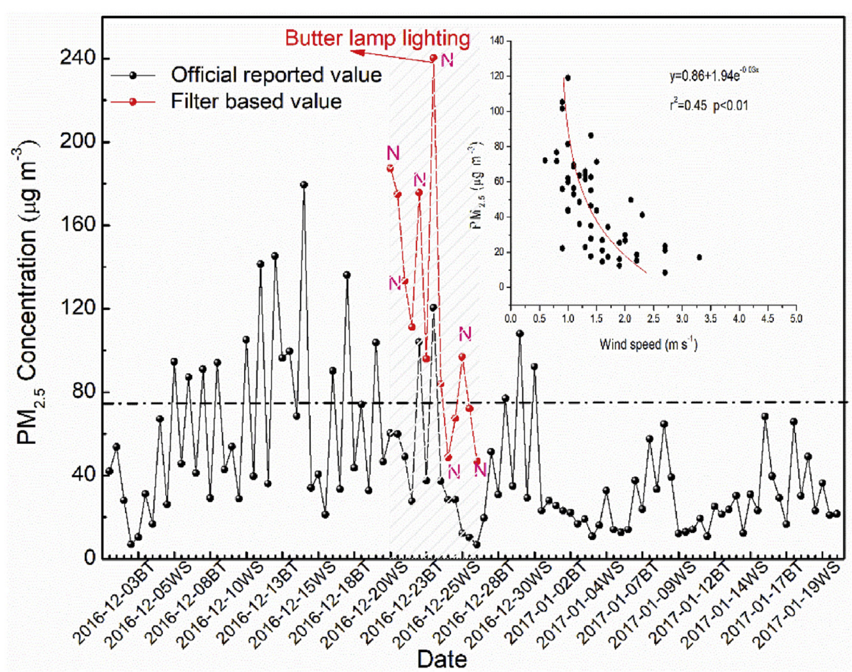


Fig. 2. Daytime and nighttime $PM_{2.5}$ variations of filter based samples at five sites and Lhasa CMA. "N" means value of nighttime, the other point means values of daytime. Meanwhile, The relationship between daily wind speed and $PM_{2.5}$ concentation is shown in the small window.

abnormal diurnal variations of $PM_{2.5}$ concentrations in Lhasa (Cong et al., 2011). At the same time, the decreased height and increased stability of boundary layer during nighttime was another factor causing this phenomenon (Cui et al., 2018). Therefore, we assumed that both local emissions and decreased boundary layer caused the increased trend of $PM_{2.5}$ after 20:00 (Fig. 3).

Meanwhile, two phenomena also need to be mentioned. Firstly, average $PM_{2.5}$ concentration in winter was $46.2 \pm 30.1\ \mu g\ m^{-3}$, much higher than that of summer ($14.2 \pm 4.8\ \mu g\ m^{-3}$). This is because the heavy precipitation in summer removes a large part of $PM_{2.5}$ from the atmosphere. Correspondingly, almost no precipitation happens during winter (Guo et al., 2015). The second phenomenon was that $PM_{2.5}$ concentration increased faster in the morning and night in winter than in summer (Fig. 3), which was mainly contributed by emission of space heating in winter.

3.2. *Peak $PM_{2.5}$ concentation caused by butter lamp lighting*

Special burning activities due to traditional religious practices during some festivals, such as use of lamps, can cause the increase of $PM_{2.5}$ concentration. In this study, the highest urban $PM_{2.5}$ concentration occurred at night of 23rd Dec, 2016, and reached $240 \pm 30\ \mu g\ m^{-3}$, ~1.4 times of that on 22nd. Accordingly, high $PM_{2.5}$ concentration was also recorded from the official released data at the same time, despite that only a small increase was observed (~1.2 times higher than that of the 22nd) because the monitor of official site was put on roof of a building (Fig. 2). Therefore, the high $PM_{2.5}$ concentration happened for the whole city on that night. Because the cooking activities do not increase during the festival, it is proposed that the overlapped influences of normal local emission and butter lamp lighting of local Tibetan

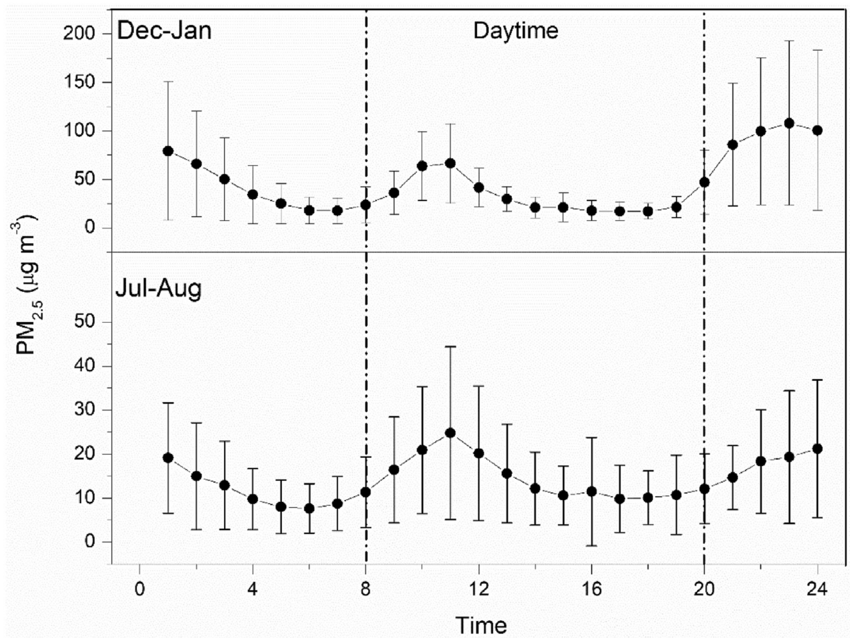


Fig. 3. Average diurnal variations of $PM_{2.5}$ concentation released by CMA from December to January and from July to August, 2016 of Lhasa.

residents caused this pollution pattern. On that day, all the Tibetan families and temples light butter lamps from sunset in memory of Tsongkhapa – one of leaders of the Tibetan Buddhism. The richer a family and a temple, the more lamps will be lighted during that night. Therefore, thousands of butter lamps were lighted at nearly the same time, causing the highest $PM_{2.5}$ concentration during study period (As shown in Fig. S2, the obvious different colors between filter samples collected during the nighttime and daytime also indicate the contribution of butter lamp lighting). According to our study, the emission factor of $PM_{2.5}$ for butter burning was 3.34 ± 0.27 g kg^{-1} (see Supplement). Based on our estimate that there would be more than 40 thousand kg of butter burned that night, we estimate that there could be an increase of $PM_{2.5}$ concentration of around 78 μg m^{-3} from this source alone. (Table. S2).

4. Conclusions and discussion

The near surface $PM_{2.5}$ level during study period (118 μg m^{-3}) is approximately 3.4 times the US EPA standard for 24-h pollution (35 μg m^{-3}), or about 10 times the annual standard (12 μg m^{-3}) (Table. S3). The corresponding ratio is 1.6 and 3.4 times over the Chinese standards. Because many residents of Lhasa are exposed to near surface air, $PM_{2.5}$ concentration at this level is more closely related to health than that of ambient air monitored for official monitors at high level during study period. As a result, the local residents of Lhasa could have a heavier health burdern than that generally considered, based on official released $PM_{2.5}$ concentrations. Additional measurements would be needed, however, to determine the annual average levels of exposure at ground level, where the people live, compared to ambient levels measured by official monitors. Because the illegal waste incineration emissions during nighttime happen frequently at Lhasa, $PM_{2.5}$ concentration seems to peak in the period after sunset until midnight (Fig. 3). Butter lamp lighting of Tibetan residents during their festival can also cause additional serious $PM_{2.5}$ pollution. Therefore, despite relatively clean ambient atmosphere on average, air pollution at the near surface level of Lhasa seems to be serious at some periods in winter. Thus, EPA of Lhasa may wish to strengthen emission controls, especially those illegal waste incineration emissions during nighttime, instead of just caring about the average $PM_{2.5}$ concentration in Lhasa. Meanwhile, it is necessary to do research including measuring chemical characteristics of $PM_{2.5}$ for at least a year to comprehensively understand the fine particle levels and sources at near surface level of Lhasa city and their potential exposure for local residents.

Acknowledges

This work was funded by the NSFC (41675130, 41721091, 41630754) and the State Key Laboratory of Cryospheric Science (SKLCS-ZZ-2017). This study is part of a framework across the HTP: Atmospheric Pollution and Cryospheric Change (APCC). The authors thank a lot for Prof. Yaoming Ma provide meteorological data for this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2018.09.135.

References

Bond, T.C., Streets, D.G., Yarber, K.F., Nelson, S.M., Woo, J.H., Klimont, Z., 2004. A technology-based global inventory of black and organic carbon emissions from combustion. J. Geophys. Res. Atmos. 109.

CNEMC, 2013. China National Environmental Monitoring Centre. Air Quality Report in 74 Chinese Cities in March and the First Quarter 2013 (in Chinese). http://www.cnemc.cn/publish/106/news/news_34605.html. (Accessed 11 June 2013).

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope III, C.A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L., Forouzanfar, M.H., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389, 1907–1918.

Cong, Z., Kang, S., Luo, C., Li, Q., Huang, J., Gao, S., Li, X., 2011. Trace elements and lead isotopic composition of PM10 in Lhasa, Tibet. Atmos. Environ. 45, 6210–6215.

Cui, Y.Y., Liu, S., Bai, Z., Bian, J., Li, D., Fan, K., McKeen, S.A., Watts, L.A., Ciciora, S.J., Gao, R.-S., 2018. Religious burning as a potential major source of atmospheric

fine aerosols in summertime Lhasa on the Tibetan Plateau. Atmos. Environ. 181, 186–191.
Gong, P., Wang, X., Yao, T., 2011. Ambient distribution of particulate- and gas-phase n-alkanes and polycyclic aromatic hydrocarbons in the Tibetan Plateau. Environ. Earth Sci. 64, 1703–1711.
Guo, J., Kang, S., Huang, J., Zhang, Q., Tripathee, L., Sillanpaa, M., 2015. Seasonal variations of trace elements in precipitation at the largest city in Tibet, Lhasa. Atmos. Res. 153, 87–97.
Hu, Z., Kang, S., Li, C., Yan, F., Chen, P., Gao, S., Wang, Z., Zhang, Y., Sillanpaa, M., 2017. Light absorption of biomass burning and vehicle emission-sourced carbonaceous aerosols of the Tibetan Plateau. Environ. Sci. Pollut. Control Ser. 24, 15369–15378.
Li, C., Bosch, C., Kang, S., Andersson, A., Chen, P., Zhang, Q., Cong, Z., Chen, B., Qin, D., Gustafsson, Ö., 2016a. Sources of black carbon to the Himalayan–Tibetan Plateau glaciers. Nat. Commun. 7, 12574.
Li, C., Chen, P., Kang, S., Yan, F., Hu, Z., Qu, B., Sillanpää, M., 2016b. Concentrations and light absorption characteristics of carbonaceous aerosol in PM2.5 and PM10 of Lhasa city, the Tibetan Plateau. Atmos. Environ. 127, 340–346.
Liu, Z., Hu, B., Wang, L., Wu, F., Gao, W., Wang, Y., 2015. Seasonal and diurnal variation in particulate matter (PM10 and PM2.5) at an urban site of Beijing: analyses from a 9-year study. Environ. Sci. Pollut. Control Ser. 22, 627–642.
Ni, H., Han, Y., Cao, J., Chen, L.W.A., Tian, J., Wang, X., Chow, J.C., Watson, J.G., Wang, Q., Wang, P., Li, H., Huang, R.-J., 2015. Emission characteristics of carbonaceous particles and trace gases from open burning of crop residues in China. Atmos. Environ. 123, 399–406.
Rastogi, N., Singh, A., Singh, D., Sarin, M., 2014. Chemical characteristics of PM 2.5 at a source region of biomass burning emissions: evidence for secondary aerosol formation. Environ. Pollut. 184, 563–569.
Song, S., Wu, Y., Jiang, J., Yang, L., Cheng, Y., Hao, J., 2012. Chemical characteristics of size-resolved PM2.5 at a roadside environment in Beijing, China. Environ. Pollut. 161, 215–221.
Tao, J., Zhang, L., Cao, J., Zhang, R., 2017. A review of current knowledge concerning PM2.5 chemical composition, aerosol optical properties and their relationships across China. Atmos. Chem. Phys. 17, 9485–9518.
Wang, K.C., Dickinson, R.E., Su, L., Trenberth, K.E., 2012. Contrasting trends of mass and optical properties of aerosols over the Northern Hemisphere from 1992 to 2011. Atmos. Chem. Phys. 12, 9387–9398.
Wang, M., Ghan, S., Ovchinnikov, M., Liu, X., Easter, R., Kassianov, E., Qian, Y., Morrison, H., 2011. Aerosol indirect effects in a multi-scale aerosol-climate model PNNL-MMF. Atmos. Chem. Phys. 11, 5431.
Wang, Y., Zhuang, G., Zhang, X., Huang, K., Xu, C., Tang, A., Chen, J., An, Z., 2006. The ion chemistry, seasonal cycle, and sources of PM2.5 and TSP aerosol in Shanghai. Atmos. Environ. 40, 2935–2952.
Zhao, X., Zhang, X., Xu, X., Xu, J., Meng, W., Pu, W., 2009. Seasonal and diurnal variations of ambient PM2.5 concentration in urban and rural environments in Beijing. Atmos. Environ. 43, 2893–2900.
Zheng, M., Salmon, L.G., Schauer, J.J., Zeng, L.M., Kiang, C.S., Zhang, Y.H., Cass, G.R., 2005. Seasonal trends in PM2.5 source contributions in Beijing, China. Atmos. Environ. 39, 3967–3976.