LETTER

The rationality of PM2.5 monitoring sites’ locations based on exposure level across eastern China

Chang Yan¹, Guangming Shi¹² and Fumo Yang¹²

¹ Department of Environmental Science and Engineering, Sichuan University, Chengdu, People’s Republic of China
² National Engineering Research Center on Flue Gas Desulfurization, Chengdu, People’s Republic of China

E-mail: shigm@scu.edu.cn

Keywords: PM2.5, exposure level, monitoring stations

Supplementary material for this article is available online

Abstract

Due to the heterogeneity of PM2.5 and population distribution, the representativeness of existing monitoring sites is questionable when the monitored data were used to assess the population exposure. By comparing the PM2.5 concentration from a satellite-based dataset named the China High Air Pollutants (CHAP), population and exposure level in urban areas with monitoring stations (UWS) and without monitoring stations (UNS), we discussed the rationality of the current spatial coverage of monitoring stations in eastern China. Through an analysis of air pollution in all urban areas of 256 prefectural-level municipalities in eastern China, we found that the average PM2.5 concentration in UNS in 2015 and 2018 were 52.26 μg m⁻³ and 41.32 μg m⁻³, respectively, which were slightly lower than that in UWS (52.98 μg m⁻³ and 41.48 μg m⁻³). About 12.1% of the prefectural-level municipalities had higher exposure levels in certain UNS than those in UWS. With the faster growth of UNS population, the gap between exposure levels of UNS and UWS were narrowing. Hence, currently prevalent administration-based principle of site location selection might have higher risk of missing the non-capital urban areas with relatively higher PM2.5 exposure level in the future.

1. Introduction

In the past decades, the acceleration of urbanization and industrialization brought severe air pollution problems in China (Li et al. 2016, Hao et al. 2020). PM2.5 (particulate matter with aerodynamic diameter less than 2.5 μm) is one of the major air pollutants, which has serious impacts on human health and global climate change (Cao et al. 2012, 2016).

To effectively monitor and assess PM2.5 pollution, a large amount of monitoring stations managed directly by central government (state-controlled-stations for short) were established. The first batch of cities, including 74 key prefecture-level cities, started monitoring PM2.5 routinely and listed the concentration of PM2.5 as an elementary index of air quality in 2013. By 2015, the number of these cities expanded to 338. As the PM2.5 concentration is closely related to human activities, much attentions were focused on the central downtown area of key cities. The monitoring network greatly enhanced the nationwide monitoring ability and played an important role in the control of PM2.5 pollution (You 2014, Chen et al. 2015, Wang et al. 2019).

The primary principle of selecting the location of a state-controlled-station was administrative division. The current monitoring network covers the capital urban area of prefectural-level municipalities. And the minimum number of stations in each capital urban area depends on the urban size and population of the downtown area. However, the representativeness of the administration-based stations is questionable because of the heterogeneous distribution of PM2.5 and population. For example, the assessment of site locations in Beijing showed that the monitoring stations were mainly located in the city centre. But there were few stations in the suburbs despite a large proportion of the population living there (Li et al. 2018, Yu et al. 2018). And during the
rapid urbanization process, the urban environment had a more and more negative impact on the surrounding areas (Han et al. 2015b). On the other hand, the polycentric urban development, accompanied by consistent growth of population, caused tight environmental stress in the outskirts of the city centres (Sun et al. 2012, Han et al. 2015a, Wu et al. 2018, Sun and Lv 2020). Lin et al. found that the decline rate of PM$_{2.5}$ in most urban areas was higher than that in other areas (Lin et al. 2018).

Although massive monitoring stations managed by lower level governments, such as provincial and prefectural-level governments, have been established and are routinely operating, the state-controlled stations were the main data source for most studies on PM$_{2.5}$ concentration distribution and health risk assessment on national scale (Huang et al. 2018, Ye et al. 2018, Fan et al. 2020). Hence, it is worth evaluating whether the administration-based state-controlled-stations have appropriate representativeness. The purpose of this study is to explore the rationality of the spatial coverage of current administration-based PM$_{2.5}$ monitoring stations by comparing the PM$_{2.5}$ concentration from a gridded satellite-based dataset, population and exposure level between urban areas with and without monitoring stations. This information has implications for further improving the air quality surveillance network in the future.

2. Data and methods

2.1. Study region and urban identification

This study covered 256 prefectural-level municipalities in eastern China as shown in figure 1. The urban areas, representing the residential areas scattered in a certain prefecture-level municipality, were identified using Global Urban Boundaries (GUB) dataset generated based on Global Artificial Impervious Area (GAIA) data (Li et al. 2020). The spatial resolution of GUB dataset is 30 meters and the year of GAIA data collection are 2015 and 2018. In total, 2210 urban areas were identified and the belonging prefectural-level municipalities of these urban areas were also labelled. To simplify the expressions, the four direct-administrated municipalities, including Beijing, Shanghai, Tianjin and Chongqing, were also presented as prefectural-level municipalities.

Among the identified urban areas in each prefectural-level municipality, the one where the administration is located was named ‘capital downtown’ and the remaining ones consist of county-level downtown and other lower administrative level settlements. These urban areas were categorized into two groups according to the existence of state-controlled-station within the identified urban areas, noted as UWS for urban areas with station(s) and UNS for those without station, respectively. Most capital downtowns (578 out of 858) were in UWS group, while only 41 out of 1352 other urban areas were in UWS group.

2.2. PM$_{2.5}$ and population data

Annually average PM$_{2.5}$ mass concentrations data from China High Air Pollutants (CHAP) dataset (https://weijing-rs.github.io/product.html) with the grid resolution of 1 km $\times$ 1 km in 2015 and 2018 were used to analyze the PM$_{2.5}$ concentration distribution and its variation trend in the identified urban areas. The PM$_{2.5}$ concentrations in this dataset were predicted by a space–time extremely randomized trees (STET) model using revised MAIAC AOD product combining meteorological parameters, land coverage, surface topography, and
population distribution data (Lyapustin et al 2011, Wei et al 2020). Evaluation results showed high correlation between the predicted concentrations and the ground-level observations (Wei et al 2021).

The population data from LandScan dataset (https://landsan.ornl.gov/) with the grid resolution of 1 km × 1 km in 2015 and 2018 were used to analyze the distribution of population density and PM$_{2.5}$ exposure (Bhaturi et al 2007, Graesser et al 2012). The LandScan dataset was generated by a Global Population Distribution Model using the sub-national census data, land cover, road density, urban distribution, settlements locations, etc. The gridded PM$_{2.5}$ concentrations and population were collocated with the GUB dataset by Nearest resampling algorithm. For each identified urban area, the annually mean PM$_{2.5}$ concentration and total population were determined by calculating the average of PM$_{2.5}$ concentrations and summations of population in all the grids located in this urban area. In a certain prefectural-level municipality, the average PM$_{2.5}$ concentrations (total population) of UWS and UNS were calculated by averaging (summing) the mean PM$_{2.5}$ concentrations and total population of all urban areas categorized as UWS and UNS, respectively.

2.3. Exposure level

The method of calculating the population’s PM$_{2.5}$ exposure level (PPME) was similar to the model used in Kousa et al (2002). In each identified urban area, the PPME was calculated by multiplying mean PM$_{2.5}$ concentration and total population with unit of persons μg m$^{-3}$. Both larger population and higher PM$_{2.5}$ concentration could lead to higher PPME in an urban area.

3. Results

3.1. PM$_{2.5}$ in UWS and UNS urban areas

The average PM$_{2.5}$ concentrations of each prefectural-level municipalities in UWS and UNS were shown in figure 2. Similar spatial distribution characteristics were observed between concentrations in UWS and UNS. Heavily polluted areas were mainly concentrated in Beijing-Tianjin-Hebei, Yangtze River Delta and Sichuan Basin, which were consistent with the ground-level observations (Shen et al 2020). The trend variations of PM$_{2.5}$ concentrations in UWS were similar to those in UNS from 2015 to 2018. Average PM$_{2.5}$ concentrations across eastern China decreased from 53.0 μg m$^{-3}$ and 52.3 μg m$^{-3}$ to 41.5 μg m$^{-3}$ and 41.3 μg m$^{-3}$ in UWS and UNS, respectively. But the reduction amount showed large regional disparity. The reduction of PM$_{2.5}$ concentration in Beijing-Tianjin-Hebei was the largest among the city agglomerations, about 17.7 μg m$^{-3}$ and 18.9 μg m$^{-3}$ in UNS and UWS, respectively. The PM$_{2.5}$ concentration in Sichuan Basin decreased in a relatively slighter degree, only 6.9 μg m$^{-3}$ and 7.9 μg m$^{-3}$ in UNS and UWS, respectively. The reduction amount of PM$_{2.5}$ concentration in Yangtze River Delta was close to the average value across eastern China, about 11.5 μg m$^{-3}$ and 12.3 μg m$^{-3}$ in UNS and UWS, respectively.

Figure 3 presented the differences between average PM$_{2.5}$ concentrations of UWS and UNS in the same prefectural-level municipalities (DPM) and a positive DPM value means higher PM$_{2.5}$ concentration in UWS. On average, the PM$_{2.5}$ concentrations of UWS were slightly higher than those of UNS. And the discrepancies narrowed significantly from 2015 to 2018. The average DPM in all the prefectural-level municipalities was 0.72 μg m$^{-3}$ in 2015 and decreased to 0.16 μg m$^{-3}$ in 2018. The DPM concentrated between −2 μg m$^{-3}$ and 4 μg m$^{-3}$ and the distribution of municipality numbers peaked at DPM range of 0−2 μg m$^{-3}$. The comparison between DPMs in 2015 and 2018 showed that the gaps in PM$_{2.5}$ concentrations between UWS and UNS were narrowing rapidly. As a result, the municipalities with absolute DPMs less than 2 μg m$^{-3}$ increased significantly and the municipalities with absolute DPMs larger than 10 μg m$^{-3}$ almost disappeared. Specifically, the number of prefectural-level municipalities where PM$_{2.5}$ concentrations in UNS were higher than those in UWS (DPM < 0) increased from 92 in 2015 to 98 in 2018.

3.2. Population in UWS and UNS urban areas

Like PM$_{2.5}$ concentrations, the differences of population between UWS and UNS were also decreasing. In total, the population in all UNS increased by 16.7% (from 156 million to 182 million) from 2015 to 2018, which was exceeding two times larger than the rising proportion of population in all UWS (6.5%, from 185 million to 197 million). At provincial level, figure 4 presented the total population in UWS and UNS of each province. The population in UWS were higher than those in UNS in most provinces except Henan, Hebei, Fujian and Liaoning. The differences of population between UWS and UNS were 29 million in 2015 and 15 million in 2018, respectively. At municipality level, about 122 prefectural-level municipalities had more population in UNS in 2015, accounting for 47.7% of all the municipalities. But in 2018, the proportion of these municipalities increased to 51.2%.
Figure 2. Average PM$_{2.5}$ concentrations of each prefectural-level municipalities in UWS in 2015 (a); UWS in 2018 (b); UNS in 2015 (c); UNS in 2018 (d). The PM$_{2.5}$ concentrations were obtained from the CHAP dataset.

Figure 3. The distribution of the number of prefectural-level municipalities with respect to the DPM.
3.3. PPME in UWS and UNS urban areas

The exposure level of an urban area was determined by ambient PM$_{2.5}$ concentration and population together. Hence, comparing the PM$_{2.5}$ concentration or population between UWS and UNS individually was insufficient to assess the exposure level. In about 31 prefectural-level municipalities, exposure levels of UWS were not the largest among all the urban areas in the same prefectural-level municipality in 2015. This revealed that about 12.1% of the municipalities had higher exposure levels in certain UNS than those in UWS. And the number of municipalities with this feature expanded to 32 in 2018 (figure S1 (available online at stacks.iop.org/ERC/4/011001/mmedia)). As to all the identified areas, we sorted the exposure levels of all the urban areas from the largest value to the smallest and the results were shown in figure 5. In the high exposure level region, although the UWS had much higher exposure levels than the UNS, several tens of UNS also confronted serious exposure and these urban areas mainly consisted of the suburbs of mega-cities, such as Beijing, Shanghai and Guangzhou, and some county-level cities. The decrease of UNS exposure level was much lower than that of UWS. As a result, in the low exposure level region the exposure levels in UWS were lower than those in UNS when the ranking of urban areas larger than about 450. These UWS with lower exposure levels were mostly the downtown areas of smaller prefectural-level municipalities with less population.
4. Discussion and conclusions

The differences between PM$_{2.5}$ concentrations in capital downtown areas (mainly UWS) and non-capital urban areas (mainly UNS) of same prefectural-level municipalities were unexpectedly small. This might be caused by the transportation of pollutants from relatively polluted downtown areas to surrounding areas (Wang et al 2014). And these differences of PM$_{2.5}$ concentrations decreased significantly from 2015 to 2018. One reason of this phenomenon might be the acceleration of urbanization process in the non-capital urban areas, which could be supported by the increase of population as shown in section 3.2. The population in the non-capital urban areas grew at a faster rate than those in the capital downtown areas. This led to growing pollutant emissions from vehicles, energy consumption (Lin and Zhu 2018) and construction (Xu and Lin 2016). Furthermore, widespread transfer of industries from capital downtown areas to non-capital areas very likely increased the potential emissions in latter areas (Fang et al 2019). Moreover, in non-capital areas usually there were lower proportions of clean energy usage (Zhao et al 2018, Chen and Chen 2019), more poorly managed small factories, less usage of emission reduction techniques with poorer efficiency (Cheng et al 2020) and even looser governmental supervision (Liu et al 2018).

As to the PM$_{2.5}$ exposure level, in most prefectural-level municipalities the exposure levels in capital downtowns were higher than the non-capital urban areas and the differences were more obvious than the PM$_{2.5}$ concentration differences. This were mainly caused by less population in non-capital urban areas. Still, the gaps of exposure levels were narrowing in most prefectural-level municipalities because of the faster growing rate of population in the non-capital urban areas. The number of prefectural-level municipalities with higher PM$_{2.5}$ exposure levels in non-capital urban areas than those in capital areas was increasing. This might be caused by the transfer of industries from capital areas to non-capital areas and the migration of population from rural areas to non-capital areas. Along with the rapid and sustained development of economy, these processes will be promoted in more cities. Therefore, it is expected that the PM$_{2.5}$ exposure levels in non-capital urban areas would to be of the same importance as those in capital areas in the future.

Considering that the primary purpose of monitoring PM$_{2.5}$ is assessing the population exposure, and that the current administration-based state-controlled-stations cover the most exposed areas in exceeding 87.9% of the prefectural-level municipalities, we concluded that the spatial coverage of current administration-based PM$_{2.5}$ monitoring stations are good enough. However, in the future, the administration-based selection principle of site locations might miss substantial urban areas with relatively high PM$_{2.5}$ exposure. Thus, we suggest that more monitoring stations should be established based on the exposure level rather than simply based on the administrative level.

Acknowledgments

This research was supported by the National Key R&D Program of China (2018YFC0214002 and 2018YFC0214001), the Key S&T Program of Sichuan Province (2018SZDZX0023 and 2019YFS0495), the National Natural Science Foundation of China (41875162 and 22076129), the Fundamental Research Funds for the Central Universities (YJ201871 and YJ201891), the Young Talent Team Science and Technology Innovation Project of Sichuan Province (2020JDTD0005).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Guangming Shi  https://orcid.org/0000-0001-5866-537X

References

Bhaduri B, Bright E, Coleman P and Urban M L 2007 LandScan USA: a high-resolution geospatial and temporal modeling approach for population distribution and dynamics Geoforum 69 103–17
Cao G, Lee X, Liu S, Schultz N, Xiao W, Zhang M and Zhao L 2016 Urban heat islands in China enhanced by haze pollution Nat. Commun. 7 12509
Cao J, Xu H, Xu Q, Chen B and Kan H 2012 Fine particulate matter constituents and cardiopulmonary mortality in a heavily polluted chinese city Environ. Health Perspect. 120 373–8
Chen H and Chen W 2019 Potential impact of shifting coal to gas and electricity for building sectors in 28 major northern cities of China Appl. Energy 236 1049–61
Chen W, Wang F, Xiao G, Wu K and Zhang S 2015 Air quality of Beijing and impacts of the new ambient air quality standard Atmosphere 6 1243–58
Cheng Z, Li L and Liu J 2020 The impact of foreign direct investment on urban PM2.5 pollution in China J. Environ. Manage. 265 110532
Fan H, Zhao C and Yang Y 2020 A comprehensive analysis of the spatio-temporal variation of urban air pollution in China during 2014–2018 Atmos. Environ. 220 117066
Fang D, Chen B, Hubacek K, Ni R, Chen L, Feng K and Lin J 2019 Clean air for some: unintended spillover effects of regional air pollution policies Sci. Adv. 5 eava4707
Graesser J, Cheriyadat A, Vatsavai R R, Chandola V, Long J and Bright E 2012 Image based characterization of formal and informal neighborhoods in an urban landscape IEEE J. Sel. Top. Appl. Earth Observations Remote Sensing 5 1164–76
Han H, Yang C, Wang E, Song J and Zhang M 2015a Evolution of jobs-housing spatial relationship in Beijing metropolitan area: a job accessibility perspective Chin. Geogr. Sci. 25 375–88
Han L, Zhou W and Li W 2015b Increasing impact of urban fine particles (PM2.5) on areas surrounding Chinese cities Sci Rep. 5 12467
Hao Y, Zheng S, Zhao M, Wu H, Guo Y and Li Y 2020 Reexamining the relationships among urbanization, industrial structure, and environmental pollution in China—New evidence using the dynamic threshold panel model Energy Reports 6 28–39
Huang J, Pan X, Guo X and Li G 2018 Health impact of China’s air pollution prevention and control action plan: an analysis of national air quality monitoring and mortality data The Lancet Planetary Health 2 e313–23
Kousa A, Kukkonen J, Karpipinen A, Aarnio P and Koskentalo T 2002 A model for evaluating the population exposure to ambient air pollution in an urban area Atmos. Environ. 36 2109–19
Li G, Fang C, Wang S and Sun S 2016 The effect of economic growth, urbanization, and industrialization on fine particulate matter (PM 2.5) concentrations in China Environ. Sci. Technol. 50 11452–9
Li T, Zhou X C, Ikhumhen H O and Difei A 2018 Research on the optimization of air quality monitoring station layout based on spatial grid statistical analysis method Environ. Technol. 39 1271–83
Li X et al 2020 Mapping global urban boundaries from the global artificial impervious area (GAIA) data Environ. Res. Lett. 15 094044
Lin B and Zou J 2018 Changes in urban air quality during urbanization in China J. Clean. Prod. 188 312–21
Lin C, Lau A, Li Y, Fung J, Li C, Lu X and Li Z 2018 Difference in PM2.5 variations between urban and rural areas over eastern china from 2001 to 2015 Atmosphere 9 312
Liu B et al 2018 Effectiveness evaluation of temporary emission control action in 2016 in winter in Shijiazhuang, China Atmos. Chem. Phys. 18 7019–39
Lyapustin A, Wang Y, Laszlo I, Kahn R, Korkin S, Remer L, Levy R and Reid JS 2011 Multiscale implementation of atmospheric correction (MAIAC): 2. Aerosol algorithm J. Geophys. Res. 116 D03211
Shen F, Zhang L, Jiang L, Tang M, Gui X, Chen M and Ge X 2020 Temporal variations of six ambient criteria air pollutants from 2015 to 2018, their spatial distributions, health risks and relationships with socioeconomic factors during 2018 in China Environ. Int. 137 105556
Sun T, Han Z, Wang L and Li G 2012 Suburbanization and subcentering of population in Beijing metropolitan area: A nonparametric analysis Chin. Geogr. Sci. 22 472–82
Sun T and Lv Y 2020 Employment centers and polycentric spatial development in Chinese cities: A multi-scale analysis Cities 99 102617
Wang K, Yin H and Chen Y 2019 The effect of environmental regulation on air quality: A study of new ambient air quality standards in China J. Clean. Prod. 215 268–79
Wang Z et al 2014 Modeling study of regional severe hazes over mid-eastern China in January 2013 and its implications on pollution prevention and control Sci China. Earth. Sci. 57 3–13
Wei J et al 2020 Improved 1 km resolution PM 2.5 estimates across China using enhanced space–time extremely randomized trees Atmos. Chem. Phys. 20 5273–89
Wei J, Li Z, Lyapustin A, Sun L, Peng Y, Xue W, Su T and Cribb M 2021 Reconstructing 1-km-resolution high-quality PM2.5 data records from 2000 to 2018 in China: spatiotemporal variations and policy implications Remote Sens. Environ. 252 112136
Wu Y, Fan P and You H 2018 Spatial evolution of producer service sectors and its influencing factors in cities: a case study of hangzhou China Sustainability 10 975
Xu B and Lin B 2016 Regional differences of pollution emissions in China: contributing factors and mitigation strategies J. Clean. Prod. 112 1434–63
Ye W F, Ma Z Y and Ha X Z 2018 Spatial–temporal patterns of PM2.5 concentrations for 338 Chinese cities Sci. Total Environ. 631–632 524–33
You M 2014 Addition of PM 2.5 into the national ambient air quality standards of china and the contribution to air pollution control: the case study of Wuhan, China The Scientific World Journal 2014 1–10
Yu T, Wang W, Ciren P and Sun R 2018 An assessment of air-quality monitoring station locations based on satellite observations Int. J. Remote Sens. 39 6463–78
Zhao B et al 2018 Change in household fuels dominates the decrease in PM 2.5 exposure and premature mortality in China in 2005–2015 Proc. Natl. Acad. Sci. U.S.A. 115 12401–6