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Assessment of PM2.5 concentrations and exposure throughout China using ground observations

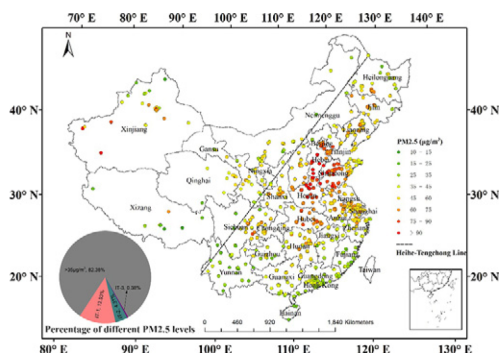
Hong Guo [a], Tianhai Cheng [a,*], Xingfa Gu [a], Ying Wang [a], Hao Chen [a], Fangwen Bao [a,b], Shuaiyi Shi [a,b], Binren Xu [a,b], Wannan Wang [a,b], Xin Zuo [a,b], Xiaochuan Zhang [a,b], Can Meng [a,b]

[a] *State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China*
[b] *University of Chinese Academy of Sciences, Beijing, China*

HIGHLIGHTS

- The assessment of PM2.5 concentrations throughout China in 2015 and 2013 are presented.
- The annual mean PM2.5 concentrations exhibited significant differences in 2015 over China.
- The PM2.5 concentrations decreased from 2013 to 2015 due to the new environmental protection laws.

GRAPHICAL ABSTRACT



Regional distribution of annual mean PM2.5 concentrations throughout China, and the percentage of stations exhibiting annual mean PM2.5 concentrations within various WHO air quality categories in 2015. The Heihe-Tengchong Line divides the territory of China into two roughly equal parts, with ~6% of the population living western less-populated part of the country, while ~94% of the population lived eastern more-populated part of the country in the census.

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ABSTRACT

Exposure to PM2.5 results in negative effects on human health. However, PM2.5 exposure at the national scale is poorly known for China owing to limited spatial and temporal PM2.5 concentration data. In this study, we present analyses of PM2.5 exposure throughout China using high-resolution temporal and spatial ground-level PM2.5 data from 2015. Our results indicated that the annual mean PM2.5 concentration was 52.81 μg/m^3, and that the highest annual mean PM2.5 concentrations primarily appeared in the North China Plain. We also found the lowest and highest monthly mean PM2.5 concentrations appeared in August and January, respectively, while the lowest and highest diurnal mean PM2.5 concentrations occurred at 16:00 and 10:00, respectively. Moreover, comparisons to data from 2013 indicated that the annual mean PM2.5 concentrations decreased by 12.31% from 2013 to 2015, which was likely due to the implementation of environmental protection laws in early 2015. Our findings provide new insights, for not only studies of PM2.5 exposure and human health, but also to inform the implementation of national and regional air pollution reduction policies.

* Corresponding author.
E-mail address: chength@radi.ac.cn (T. Cheng).

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1. Introduction

Exposure to fine particulate matter with aerodynamic diameters less than 2.5 μm (PM2.5) has negative effects on human health and may induce respiratory and cardiovascular problems, lung diseases, and additional health problems (Pope et al., 2004; Thurston et al., 2016; Stieb et al., 2016). In addition to the above illnesses, studies have indicated that exposure to PM2.5 has resulted in more than three million premature deaths of people in 2010 (Lim et al., 2012). PM2.5 is particularly hazardous to human health because it can penetrate deeply into the bronchioles and alveoli.

Spatial and temporal variability of PM2.5 concentrations are key parameters to assess in the evaluation of associations between PM2.5 exposure and human health (Miller et al., 2007; Sarigiannis et al., 2014; Hansen et al., 2016). Positive and significant associations between low birth weight and PM2.5 exposure in the Middle Atlantic, East North Central, and West North Central have been documented in addition to significant negative associations in the Mountain division region (Hao et al., 2016). PM2.5 concentrations can vary over day to year time periods, and increases of up to 10 μg/m^3 PM2.5 concentrations in the same day have been associated with increased pediatric emergency department visits for asthma, wheezing and upper respiratory infections (Strickland et al., 2016).

Several methods using ground data or satellite data have been developed to obtain spatial and temporal data for PM2.5 concentrations (Gupta et al., 2006; Liu et al., 2009, 2012; Lee et al., 2011, 2012; Chudnovsky et al., 2013, 2014; van Donkelaar et al., 2010, 2015; Zhang and Cao, 2015; Kokhanovsky et al., 2015; Guo et al., 2016a; Meng et al., 2016). For example, satellite-based PM2.5 models have been used to estimate ground-level PM2.5 concentrations over three major industrialized regions of China (Zheng et al., 2016). Further, ground-based data were used to analyze spatial and temporal variations in PM2.5 concentrations for 31 provincial capital cities of China during 2013–2014 (Wang et al., 2014a; Zhao et al., 2016).

China has suffered from extremely severe and persistent haze events in recent years, where PM2.5 was the main pollutant (Li et al., 2013; Wang et al., 2014b). Among the five most PM2.5-polluted megacities in the world, three are in China (Cheng et al., 2016). Moreover, China has the largest population in the world, with about 1.3397 billion people in mainland China (http://www.stats.gov.cn/). Thus, it is critically important to understand PM2.5 exposure in order to conduct epidemiological studies of PM2.5 health outcomes in China. However, PM2.5 exposure is poorly known at the national scale in China due to limited PM2.5 spatial and temporal concentration data.

The in-situ measurements of PM2.5 at the ground sites can provide with high temporal and precision of PM2.5 concentrations, which mainly located in the areas with densely population. In this study, we analyzed PM2.5 exposure throughout China using high-resolution temporal and spatial ground-level PM2.5 data that were released by the Ministry of Environmental Protection of China (MEP). First, we present an exposure assessment of PM2.5 concentrations in 2015, and then compare variation in PM2.5 concentrations between 2013 and 2015. The results of our analyses with this extensive dataset at the national-scale level help improve our understanding of PM2.5 exposure throughout China.

2. Data and Methods

2.1. PM2.5 concentrations

MEP has published PM2.5 data in addition to five other air pollutants (PM10, SO_2, NO_2, CO, and O_3) at a national-scale level beginning in January 2013. All ground PM2.5 measurements were obtained using tapered element oscillating microbalances or beta attenuation monitors, both of which are subject to measurement errors due to the loss of semivolatile components. The instrumental operation, maintenance, data assurance and quality control are conducted according to a recent version of the China Environmental Protection Standards such as CAAQS (GB3095–2012). In this study, hourly averaged PM2.5 concentrations from January 2013 to December 2013, and from January 2015 to December 2015 over mainland China were collected from MEP. A total of nearly 800 monitoring stations for 2013, and nearly 1500 monitoring stations for 2015 were used to assess PM2.5 exposure throughout China.

2.2. Population statistics

The Sixth National Population Census Data of China (NPCC) was conducted by the National Bureau of Statistics of China (NBS) with a zero hour of November 1, 2010. The census data included a complete population of the whole country, 31 provinces and centrally administered municipalities. It also included 2872 units at the county level. The contents are categorized by gender, age, nationality, education level, industry and occupation, among other parameters. The total population of China was found to be 1.37 billion, including 1.3397 billion persons in mainland China (http://www.stats.gov.cn/).

The Heihe-Tengchong Line divides the territory of China into two roughly equal parts, with ~6% of the population living western less-populated part of the country (WLPC), while ~94% of the population lived eastern more-populated part of the country (EMPC) in the census (Hu, 1990). Furthermore, three major industrialized city clusters are located in the EMPC: the Beijing-Tianjin-Hebei region (BTH), the Yangtze River Delta region (YRD), and the Pearl River Delta region (PRD), whose populations were 104.41, 215.61 and 104.32 million, respectively.

2.3. Analytical methods

Mean PM2.5 concentrations were calculated by averaging the concentrations at all sites in a region or across the whole country. The 24-h average concentrations of PM2.5 were calculated only when there were valid data for more than 20 h during that day, and the values were greater than zero (Wang et al., 2014a). Finally, annual mean PM2.5 concentrations, monthly mean PM2.5 concentrations and diurnal mean PM2.5 concentrations were calculated for the whole country, EMPC, WLPC, BTH, YRD and PRD.

Populations were considered as the sum of people in a given city. Therefore, to assess exposure, we only use the population at the city level corresponding to the mean PM2.5 concentrations. Rate of change (ROC) was used to compare variance in PM2.5 exposure between 2013 and 2015 throughout China. ROC was defined as follows:

$$\mathrm{ROC} = (x - y)/y \times 100\% \quad (1)$$

where, x and y represent the mean PM2.5 concentrations in 2015 and 2013, respectively. Because there was more PM2.5 data in 2015 than in 2013, we only used PM2.5 data for 2015 that had corresponding location data in 2013.

3. Results and discussion

3.1. Regional mean PM2.5 concentrations and exposures in 2015

Fig. 1 shows the spatial distribution of annual mean PM2.5 concentrations throughout mainland China in 2015. The overall annual mean PM2.5 concentration was 52.81 μg/m^3, and the highest annual mean PM2.5 concentrations primarily occurred in the North China Plain (Beijing, Tianjin, Hebei, Henan and Shandong), which mainly originates from fossil fuel combustion and biomass burning (Zhang et al., 2016). High PM2.5 concentrations were also found in the Xinjiang province, which were primarily the result of mineral dusts from the Taklimakan Desert (Geng et al., 2015; Ma et al., 2016). All of the stations exceeded WHO air quality guidelines (AQG), and only 0.38%, 0.41%, and 12.93%

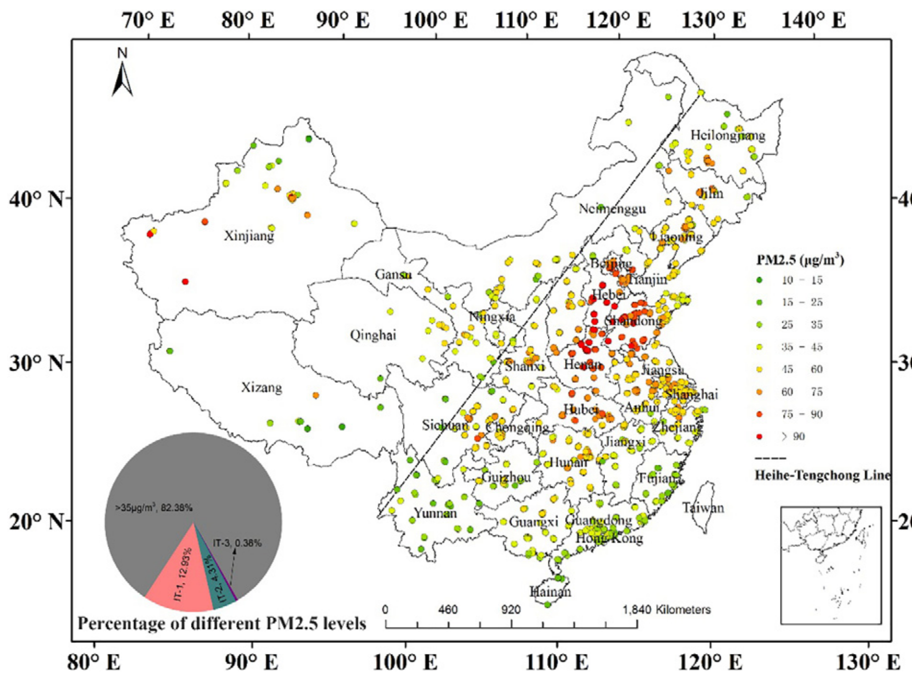

Fig. 1. Regional distribution of annual mean PM2.5 concentrations throughout China, and the percentage of stations exhibiting annual mean PM2.5 concentrations within various WHO air quality categories in 2015. The Heihe-Tengchong Line divides the territory of China into two roughly equal parts, with ~6% of the population living western less-populated part of the country, while ~94% of the population lived eastern more-populated part of the country in the census.

of the stations met WHO interim target-3 (IT-3, 10–15 μg/m^3), interim target-2 (IT-2, 15–25 μg/m^3) and IT-1 thresholds, respectively. These results indicate that 181.08 million people were exposed to annual mean PM2.5 concentrations less than the WHO IT-1 limit of 35 μg/m^3, and 1125.38 million people were exposed to annual mean PM2.5 concentrations exceeding the WHO IT-1 threshold (Fig. 2).

PM2.5 concentrations in WLPC were lower than that in the EMPC, with ~85.5 and ~1254.2 million people exposed to annual mean PM2.5 concentrations of 42.10 μg/m^3 and 54.20 μg/m^3, respectively (Fig. 3a). Numerous studies have reported industrial emissions and biomass burning as the most important contributors to PM2.5 concentrations (Tao et al., 2015; Wang et al., 2014b; Wang et al., 2014c). Thus, our results may be related to increased industrial emissions and biomass burning in the EMPC compared to that of the WLPC. Wang et al. (2014b) reported that domestic and agricultural emissions from Shandong and Henan are non-negligible regional sources of PM2.5.

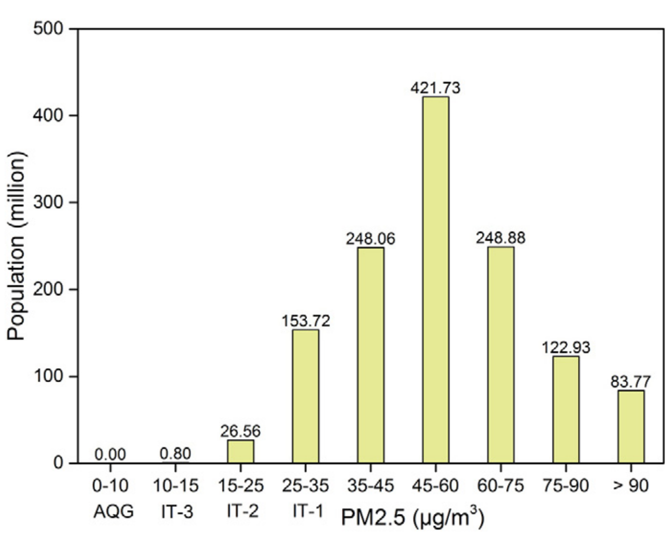

Fig. 2. Population exposure to different annual mean PM2.5 concentrations throughout China in 2015.

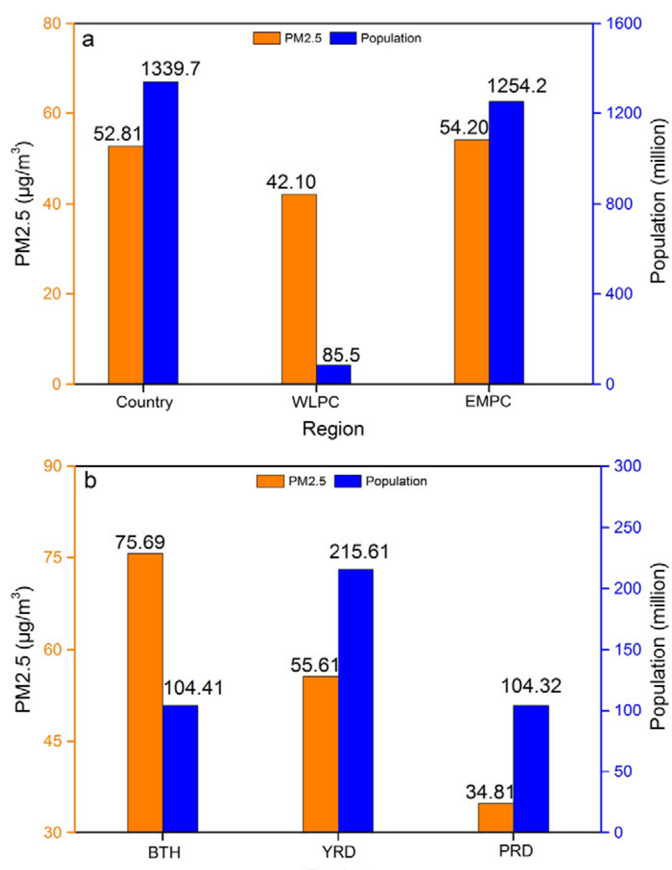

Fig. 3. Annual mean PM2.5 concentrations and population exposure in 2015 for a) WLPC, EMPC and the whole country, and b) BTH, YRD and PRD.

There were obvious significant regional differences among PM2.5 exposures in BTH, YRD and PRD. The highest annual mean PM2.5 concentrations were in BTH, followed by YRD and then PRD, where 104.41, 215.61 and 104.32 million people were exposed to annual mean PM2.5 concentrations of 75.69 μg/m^3, 55.61 μg/m^3 and 34.81 μg/m^3, respectively (Fig. 3b). These differences are mainly related to local emission and meteorological conditions, among other factors. Local emissions such as coal combustion and biomass burning in BTH significantly contribute to PM2.5 concentrations this area (Xiao et al., 2015; Zheng et al., 2016), and air quality can be significantly improved when wind speed is greater than 4 m/s there (Han et al., 2015).

3.2. Monthly mean PM2.5 concentrations in 2015

Fig. 4 shows the monthly mean PM2.5 concentration variation for different regions in China. There was significant monthly variation in PM2.5 concentrations, where the highest monthly mean concentrations occurred in January for YRD and PRD, with PM2.5 values of 86.85 μg/m^3 and 55.34 μg/m^3, respectively. High values for BTH in December (141.08 μg/m^3) may have been caused by more local emission sources such as coal combustion for domestic heating, and adverse meteorological conditions such as weak winds and vertical diffusion in winter that exist in this area (Liang et al., 2015). In contrast, the lowest monthly mean PM2.5 concentrations occurred in June for PRD, July for YRD, and September for BTH (Fig. 4b). These differences may be partially accounted for by different rainfall times (Wei et al., 2015; Guo et al., 2016b). For instance, a rainfall event led to a decrease in PM2.5 concentrations by an average of 56.3% in Beijing (Zheng et al., 2014).

No significant monthly differences of PM2.5 concentrations appeared among comparisons of the whole country, EMPC and WLPC (Fig. 4a) regions where the highest monthly mean PM2.5 concentrations all appeared in January, and the lowest concentrations appeared in August, August and September, respectively. The similarities among these regions is likely due to good diffusion conditions and less anthropogenic emissions including lessened domestic heating in northern China (Liang et al., 2015).

3.3. Diurnal mean PM2.5 concentrations in 2015

Fig. 5 shows the diurnal variability of PM2.5 concentrations for different regions throughout China in 2015. Significant diurnal differences in PM2.5 concentrations were found, with the highest and lowest PM2.5 diurnal mean concentrations at 10:00 and 16:00, respectively, for the whole country and EMPC, while they were found at 11:00 and 17:00, respectively, for WLPC (Fig. 5a).

The lowest diurnal mean PM2.5 concentrations appeared at 15:00, 16:00, and 16:00, while the highest appeared at 0:00, 9:00, and 8:00 for BTH, YRD and PRD, respectively (Fig. 5b). The highest diurnal mean PM2.5 value (81.00 μg/m^3) in daytime appeared at 10:00 for BTH, which was almost equivalent to the highest PM2.5 value (0:00, 81.44 μg/m^3) over 24-h. The diurnal differences in mean PM2.5

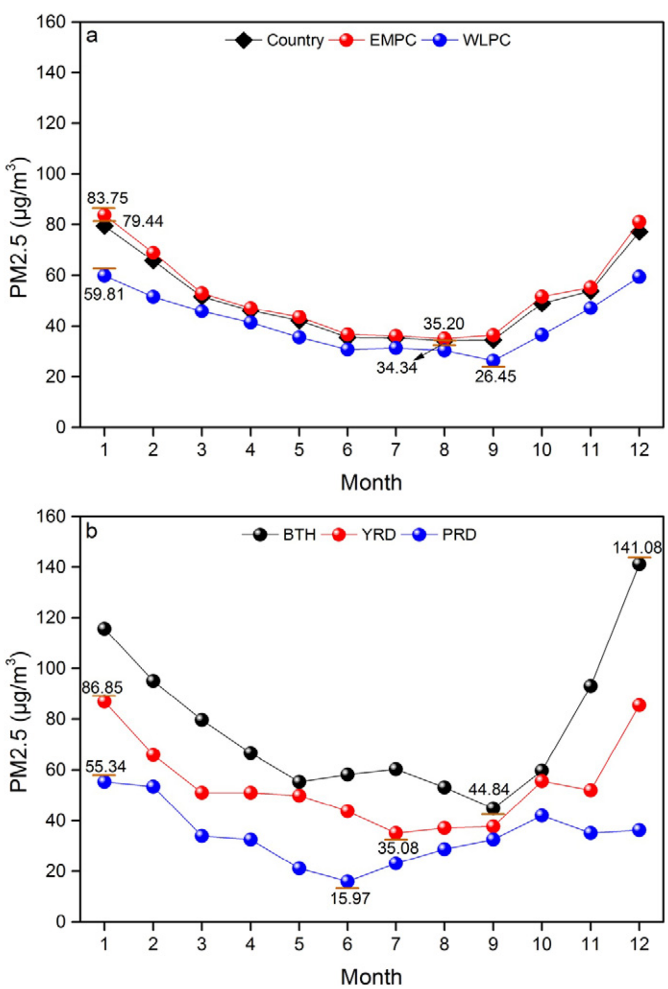

Fig. 4. Monthly mean PM2.5 concentrations in 2015 for a) WLPC, EMPC and the whole country, and b) BTH, YRD and PRD.

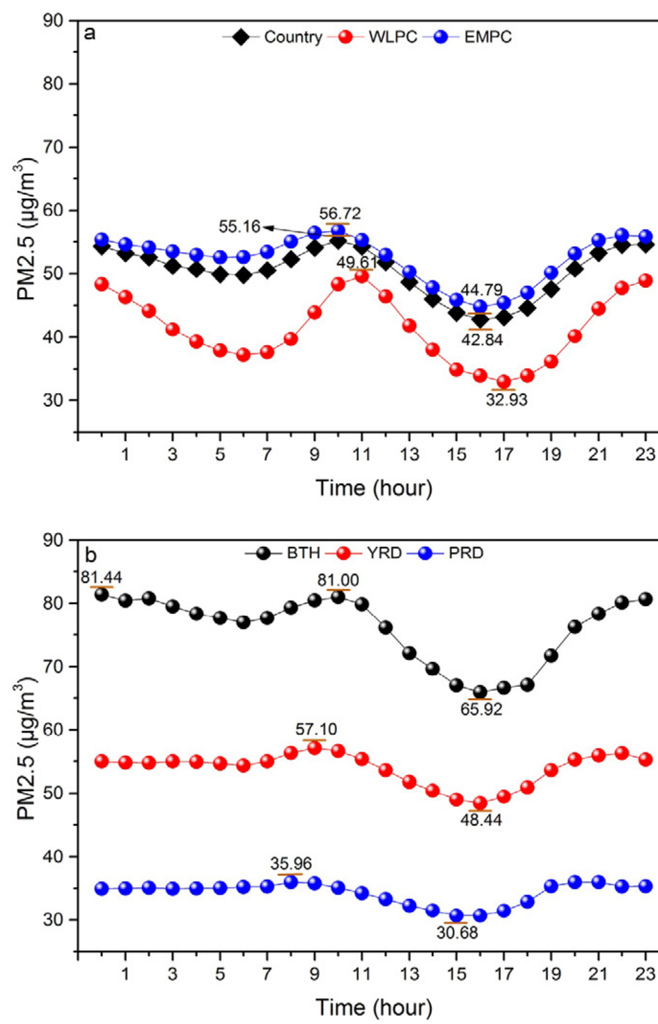

Fig. 5. Diurnal variations in PM2.5 concentrations in 2015 for a) WLPC, EMPC and the whole country, and b) BTH, YRD and PRD.

concentrations remained relatively constant in PRD, with a maximum value of 35.96 μg/m^3 and a minimum value of 30.68 μg/m^3 over 24-h.

The maximum and minimum PM2.5 values in WLPC lagged one hour behind those of EMPC. The same observation was also noted for YRD relative to PRD which may be partly due to differences in vehicle emissions during rush hours (Zhang et al., 2016). Traffic emissions, which were the second largest source of PM2.5 in Wuhan, accounted for 24.4% of locally emitted PM25 according to the China National Environmental Monitoring Center (http://www.cnemc.cn/publish/totalWebSite/news/news_44185.html).

3.4. Regional variation in annual mean PM2.5 concentrations between 2013 and 2015

Figs. 6 and 7 show the regional differences of PM2.5 concentrations between 2013 and 2015. Our results indicate that 82.3% of the stations recorded lower PM2.5 concentrations in 2015 relative to 2013 (Fig. 6). According to the WHO PM2.5 guideline values, number of the stations met WHO IT-3, IT-2 and IT-1 limits have increased from 2013 to 2015. Further, 91.58% of the stations exceeded WHO IT-1 limits in 2013, which was higher than that of 2015 (Fig. 7).

Annual mean PM2.5 concentrations decreased by 12.31% in 2015 compared to that of 2013. EMPC also exhibited similar variation in PM2.5 concentrations, with annual mean PM2.5 values declining 12.64% between 2013 and 2015. However, PM2.5 concentrations in WLPC was nearly invariant (Fig. 8a). Further, significant differences in PM2.5 concentration changes were found for BTH, YRD and PRD. Annual mean PM2.5 concentrations in PRD decreased considerably (−40.51%), which was followed by BTH (−26.86%) (Fig. 8b). The variation in PM2.5 concentrations in YRD was approximately the same as the whole country, with ROC values of −12.31% and −13.00%, respectively. The results indicate that PM2.5 concentrations have been significantly reduced, particularly in PRD and BTH. This decrease is likely due to new stricter environmental protection laws that are aimed at effectively controlling environmental pollution, and which have been enforced in China from 1 January 2015 (http://www.gov.cn/xinwen/2014-04/25/content_2666328.htm).

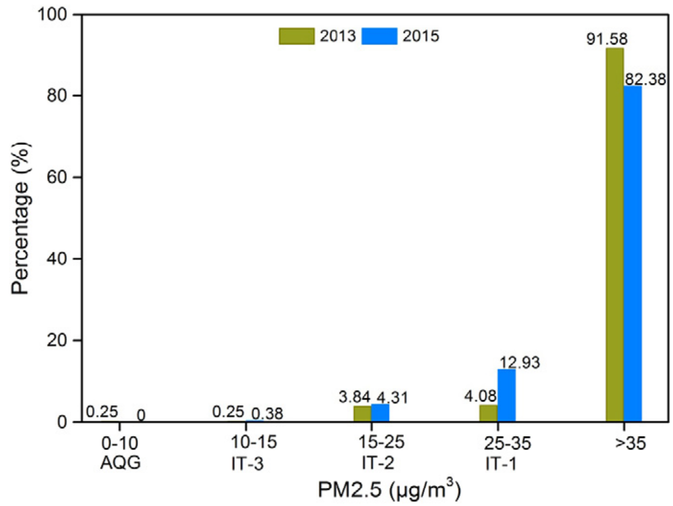

Fig. 7. Percentage of stations recording annual mean PM2.5 levels within various WHO guideline value thresholds for 2013 and 2015.

3.5. Uncertainties in the exposure assessment of PM2.5 concentrations throughout China

Here, we presented an exposure assessment of PM2.5 concentrations throughout China for 2015, and compared regional variation in PM2.5 concentrations between 2013 and 2015. However, it should be noted that uncertainties exist in these calculations.

First, the assessments are based on mean PM2.5 concentrations at the city level, which is an average of all PM2.5 monitoring sites across a city. However, the distribution of PM2.5 monitoring sites may be uneven throughout a city, with most sites in city centers, and few sites existing in countryside areas, which may lead to different PM2.5 concentrations across a city. In addition, populations differ between city centers and the countryside, with the majority of populations living in city centers, and less of the population living in rural areas. Thus, these

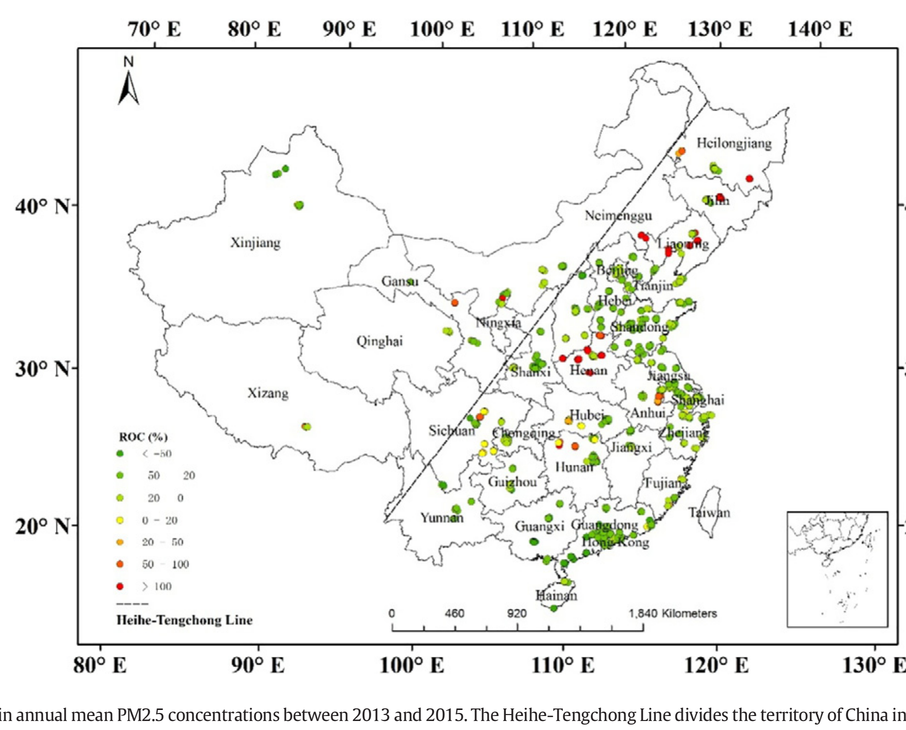

Fig. 6. Regional differences in annual mean PM2.5 concentrations between 2013 and 2015. The Heihe-Tengchong Line divides the territory of China into two roughly equal parts, with ~6% of the population living western less-populated part of the country, while ~94% of the population lived eastern more-populated part of the country in the census.

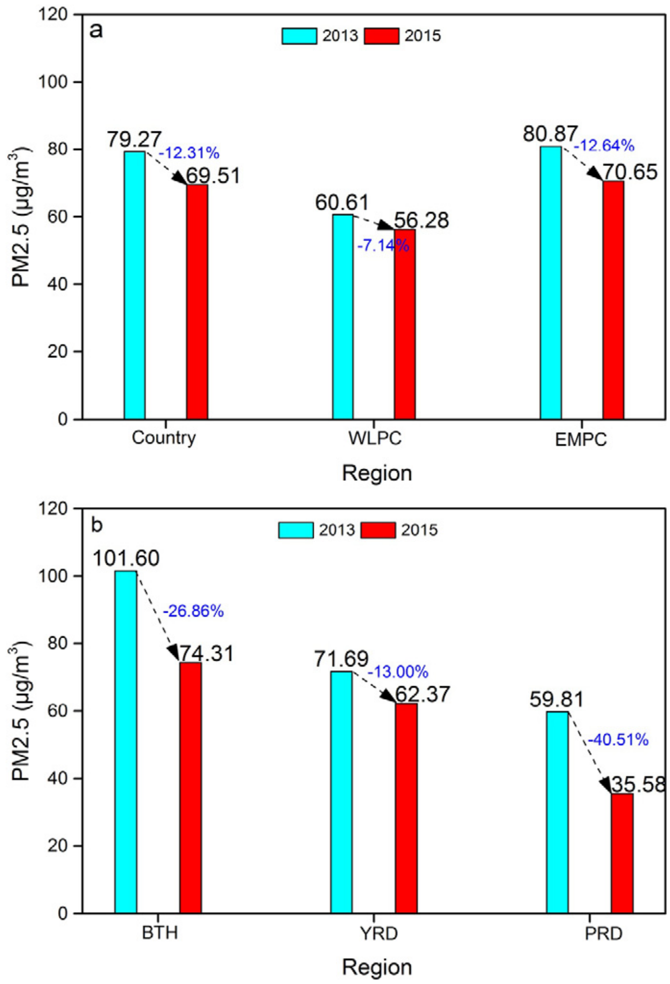

Fig. 8. Variation in annual mean PM2.5 concentrations between 2013 and 2015 for a) WLPC, EMPC and the whole country, and b) BTH, YRD and PRD.

differences may introduce error in the accurate assessment of PM2.5 exposure throughout China.

Second, there are many fewer PM2.5 monitoring sites in WLPC than in EMPC, and there is an inhomogeneous distribution of PM2.5 monitoring sites in WLPC. In addition, the population density is low in WLPC. Thus, there may be error in the assessment of PM2.5 exposure in WLPC, and more PM2.5 monitoring stations in WLPC would provide a better understanding of PM2.5 exposure in this area in future studies. Despite the uncertainties in assessment, our results provide new insights into PM2.5 exposure using high-resolution temporal and spatial ground-level PM2.5 data throughout China.

4. Conclusions

In order to assess PM2.5 exposure throughout China in 2015, this study analyzed the regional, monthly and diurnal variance in PM2.5 exposure using high-resolution temporal and spatial ground-level PM2.5 data. Our results indicated that the annual mean PM2.5 concentration was 52.81 μg/m^3, and the highest PM2.5 concentrations mainly occurred in the North China Plain. Temporally, the lowest and highest monthly mean PM2.5 concentrations occurred in August and January, respectively, while the highest and lowest diurnal mean PM2.5 concentrations occurred at 16:00 and 10:00, respectively. We also found that annual mean PM2.5 concentrations decreased by 12.31% in 2015 compared to 2013. These declines were mainly due to the enforcement of environmental protection laws in China beginning on 1 January 2015.

Compared with van Donkelaar et al. (2015), which used satellite observations for long-term exposure assessment of global PM2.5 concentrations, the annual mean PM2.5 concentrations in 2013 over China was higher than the decadal (2001 − 2010) mean PM2.5 concentrations over France (~12 μg/m^3) and Germany (~16 μg/m^3). However, van Donkelaar et al. (2015) overestimated PM2.5 concentrations and expanded heavily polluted areas over eastern more-populated part of China. Thus, different time and methods may be accounted for the difference between our results and van Donkelaar et al. (2015).

Because PM2.5 exposure at the national scale is poorly known for China in 2015 and 2013, thus our study present analyses of PM2.5 exposure throughout China using high-resolution temporal and spatial ground-level PM2.5 data, and indicated that 82.3% of the stations recorded lower annual mean PM2.5 concentrations in 2015 compared to 2013, therefore, our findings are important, not only for studies of PM2.5 exposure and human health, but also to inform the implementation of national and regional air pollution reduction policies. In future studies, we will incorporate the healthcare datasets with ground-level PM2.5 concentrations to assess PM2.5-induced acute adverse health effects at the city level or at the national scale over China.

Acknowledgments

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