Difference in PM$_{2.5}$ Variations between Urban and Rural Areas over Eastern China from 2001 to 2015

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Abstract: To more effectively reduce population exposure to PM$_{2.5}$, control efforts should target densely populated urban areas. In this study, we took advantage of satellite-derived PM$_{2.5}$ data to assess the difference in PM$_{2.5}$ variations between urban and rural areas over eastern China during the past three Five-Year Plan (FYP) periods (2001–2015). The results show that urban areas experienced less of a decline in PM$_{2.5}$ concentration than rural areas did in more than half of the provinces during the 11th FYP period (2006–2010). In contrast, most provinces experienced a greater reduction of PM$_{2.5}$ concentration in urban areas than in rural areas during the 10th and 12th FYP periods (2001–2005 and 2011–2015, respectively). During the recent 12th FYP period, the rates of decline in PM$_{2.5}$ concentration in urban areas were more substantial than in rural areas by as much as 1.5 µg·m^{-3}·year^{-1} in Beijing and 2.0 µg·m^{-3}·year^{-1} in Tianjin. These results suggest that the spatial difference in PM$_{2.5}$ change was conducive to a reduction in the population exposure to PM$_{2.5}$ in most provinces during recent years.

Keywords: PM$_{2.5}$; China; urban; rural; exposure

1. Introduction

Long-term exposure to ambient PM$_{2.5}$ (particulate matter with an aerodynamic diameter of smaller than 2.5 µm) is associated with a range of adverse health effects [1–7]. As one of the fastest developing and most heavily polluted countries in the world, China is suffering from much more severe PM$_{2.5}$ exposure problems than the U.S. and Europe [8]. The population-weighted mean PM$_{2.5}$ concentration in China was estimated to be 52 µg/m^3 in 2014 [9]. In addition, in 2013, more than 96% of Chinese people lived in areas where PM$_{2.5}$ concentrations exceeded the World Health Organization (WHO) Interim Target 1 (IT-1, 35 µg/m^3, which is also the current Chinese National Ambient Air Quality Standard (NAAQS)) [10].

A decline in the mean PM$_{2.5}$ concentration level is conducive to a reduction of the population's exposure to PM$_{2.5}$. During recent Five-Year Plan (FYP) periods, the Chinese government promulgated a series of control measures to reduce the PM$_{2.5}$ concentration level in China [11–13]. Lin et al. [14] assessed the long-term variation in PM$_{2.5}$ concentration over China during the past three FYP periods

(2001–2015). Their results showed that the mean $PM_{2.5}$ concentration increased in most provinces in southern China during the 10th FYP period (2001–2005) and then declined in most provinces in China during the 11th and 12th FYP periods (2006–2010 and 2011–2015, respectively).

For a more effective reduction in the population's exposure to $PM_{2.5}$, control efforts should target densely populated urban areas [15]. As a result, $PM_{2.5}$ in urban areas will experience a more substantial reduction than in rural areas. This type of spatial difference in $PM_{2.5}$ change helps to reduce the population's exposure to $PM_{2.5}$. To better guide future policy formulation, it is thus essential to assess the difference in $PM_{2.5}$ variations between urban and rural areas in China.

To monitor the change in $PM_{2.5}$ concentration, traditional studies have mostly relied on observations from ground monitoring networks [16]. However, such monitors are not able to fully capture the spatial variability in $PM_{2.5}$ concentrations on a large scale [17]. In addition, national fixed-site monitoring of $PM_{2.5}$ concentration in China has only been conducted since 2013. Satellite remote sensing of $PM_{2.5}$ concentration has large spatial and temporal coverages and thus is an important step toward filling this data gap [18–24]. Han et al. [25] analyzed the $PM_{2.5}$ data derived from satellite observations and demonstrated that $PM_{2.5}$ concentrations in urban areas experienced a higher increase than those in rural areas in China from 1999 to 2011.

The lack of long-term spatially explicit $PM_{2.5}$ data limits the assessment of $PM_{2.5}$ concentrations in China. It is therefore of great value to derive more results using independent $PM_{2.5}$ data. As many improved control measures have been enforced in China during the most recent FYP period, it is necessary to extend the assessment to the most recent FYP period. In the present study, we took advantage of a new satellite-derived $PM_{2.5}$ dataset to characterize the long-term variation in $PM_{2.5}$ concentration over eastern China. We then assessed the differences in $PM_{2.5}$ trends between urban and rural areas for different provinces during the past three FYP periods (2001–2015).

2. Materials and Methods

2.1. Study Region

The study region, shown in Figure 1, covered a major part of the Greater China region. It contained 17 provinces (Hebei, Henan, Shandong, Shanxi, Shaanxi, Jiangsu, Zhejiang, Anhui, Hubei, Hunan, Jiangxi, Fujian, Guangdong, Guangxi, Sichuan, Guizhou, and Hainan) and four municipalities (Beijing, Tianjin, Shanghai, and Chongqing) in eastern China; two special administrative regions (Hong Kong and Macau); and Taiwan. We considered all 24 administrative regions as "provinces in eastern China" in this study.
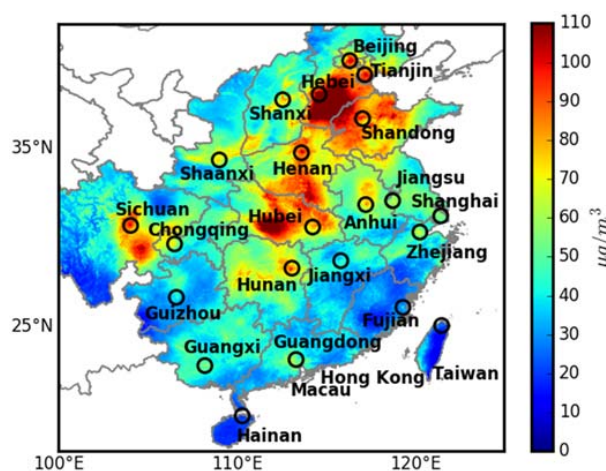

Figure 1. The 24 provinces in the study region. The figure also plots the spatial distribution of the 15-year mean of $PM_{2.5}$ concentration at a resolution of $0.01° \times 0.01°$ in the study region. The locations of the provinces' capital cities are marked by circles.

2.2. Satellite-Derived PM$_{2.5}$

Lin et al. [14] built a long-term PM$_{2.5}$ dataset at a spatial resolution of $0.01° \times 0.01°$ in the study region from 2001 to 2015 (http://envf.ust.hk/dataview/aod2pm/current). We took advantage of this satellite dataset to characterize the long-term variation of PM$_{2.5}$ concentration in eastern China. Two steps were required to construct this satellite PM$_{2.5}$ dataset. First, spectral data from the two Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the Terra and Aqua satellites were used to build aerosol optical depth (AOD) data at a resolution of $0.01° \times 0.01°$ in eastern China [26]. Second, an observational data-driven algorithm, which took the ground-observed visibility and relative humidity data as inputs, was developed to derive the ground-level PM$_{2.5}$ concentration from the AOD [14,27]. To validate the long-term satellite-derived PM$_{2.5}$ concentration, we applied a method used in similar studies [28,29]. We obtained the available ground observations of PM$_{2.5}$ concentration from multiple sources (e.g., national and regional ground monitoring networks, observations by the U.S. consulate, and a series of published papers) in the study region from 2001 to 2015. Evaluation of the satellite-derived PM$_{2.5}$ concentration against the ground observations obtained a correlation coefficient of >0.9 and a mean absolute percentage error within $\pm$20% [14]. In addition, the satellite-derived PM$_{2.5}$ concentrations experienced consistent long-term variations with the ground observations in multiple metropolises (e.g., Beijing, Shanghai, Guangzhou, Hong Kong, and Taipei). Figure 1 plots the spatial distribution of the 15-year mean of PM$_{2.5}$ concentration at a resolution of $0.01° \times 0.01°$ in the study region. The 15-year mean PM$_{2.5}$ concentrations in northern China were much higher than those in southern China, even exceeding 100 μg/m^3.

2.3. Urban and Rural Areas

It is extremely difficult, if not impossible, to find a truly objective criterion to classify a geographical area as urban or rural. All classification methods require a choice of threshold, which is subjective to a certain extent. Thresholds of population size or population density, either as the sole criterion or in conjunction with others, have been used to identify urban areas in many countries. An elaborate approach has been proposed by the Organization for Economic Co-operation and Development (OECD). The OECD approach uses population size cutoffs (50,000 or 100,000 people depending on the country) and population density cutoffs (1000 or 1500 people/km^2 depending on the country) to define urban cores [30]. The government of China has modified the standards for rural/urban classification many times. In 1999, the National Bureau of Statistics of China issued the "Stipulations on Statistical Classification for Rural and Urban Areas (Trial)" to classify urban and rural areas. This approach used a population density threshold of 1500 people/km^2 together with other criteria (http://www.stats.gov.cn/tjsj/pcsj/rkpc/5rp/html/append7.htm). The ongoing stipulations for rural–urban classification in China were issued in 2008. The new approach was mainly based on criteria for functional urban areas, and was conceptually close to the method proposed by the OECD [30].

The use of a threshold based on population density has the obvious benefit of simplicity and performs well for many applications [30]. Following the OECD approach, we used the population density threshold of 1500 people/km^2 for the classification of urban and rural areas in this study. The national census provides systematic population data by administrative region. However, the spatial matching of the census data and the gridded pollution data is difficult. Using gridded population data derived from a spatialization of the census data is an effective method to solve this issue. These gridded population data play an important role in social, economic, and environmental studies [31]. We acquired the gridded population density data at a spatial resolution of 1 km over the study region in 2008 from the LandScan population database, which was developed by the Oak Ridge National Laboratory (http://web.ornl.gov/sci/landscan/). The algorithm for the construction of the LandScan population data uses spatial data and imagery analyses to disaggregate census counts within administrative boundaries. The year 2008 was chosen as a representative year because it was in the middle of the study period and the population data for this year can be considered to represent the averaged population distribution during the study period. Figure 2 plots the spatial distribution of population density in

the study region in 2008 at a resolution of $0.01° \times 0.01°$. Overall, the north China plain had higher population densities compared to southern China. The population densities in several capital cities of these northern provinces exceeded 10^4 people/km^2.
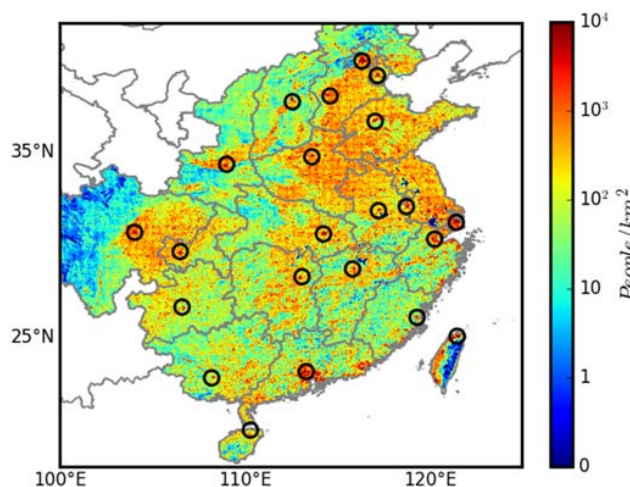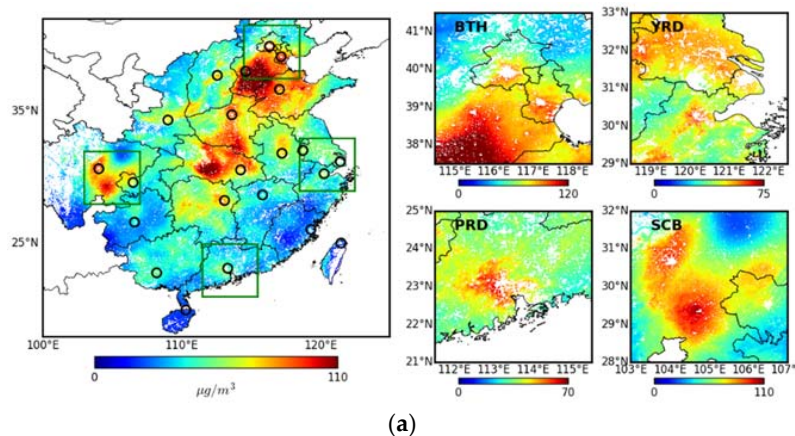

Figure 2. Spatial distribution of population density at a resolution of $0.01° \times 0.01°$ in the study region in 2008. The locations of the capital cities of the provinces are marked by circles.

Areas such as remote mountains are not ideal residential locations and thus have low population densities. In this study, our assessments focused only on areas with population densities of >10 people/km^2. Therefore, areas with population densities of <10 people/km^2 (e.g., those in the eastern part of Taiwan and the western part of Sichuan) were not taken into account in our assessments. An area was classified as urban if its population density was $\geq$1500 people/km^2 and rural if its population density was $\geq$10 people/km^2 and <1500 people/km^2. Figure 3 plots the spatial distributions of the 15-year means of PM$_{2.5}$ concentrations in (Figure 3a) rural and (Figure 3b) urban areas in the study region and four major city clusters. The Beijing-Tianjin-Hebei (BTH) region contains Beijing, Tianjin, and Hebei; the Yangtze River Delta (YRD) region contains Jiangsu, Zhejiang, and Shanghai; the Pearl River Delta (PRD) region contains Guangdong, Hong Kong, and Macau; and the Sichuan Basin (SCB) region contains Sichuan and Chongqing. The urban and rural areas accounted for 5.1% (147,260 pixels) and 75.4% (2,192,736 pixels) of the study region, respectively. The remainder was identified as non-residential and was not taken into account in this study. The population density threshold explicitly distinguishes urban areas from rural areas.
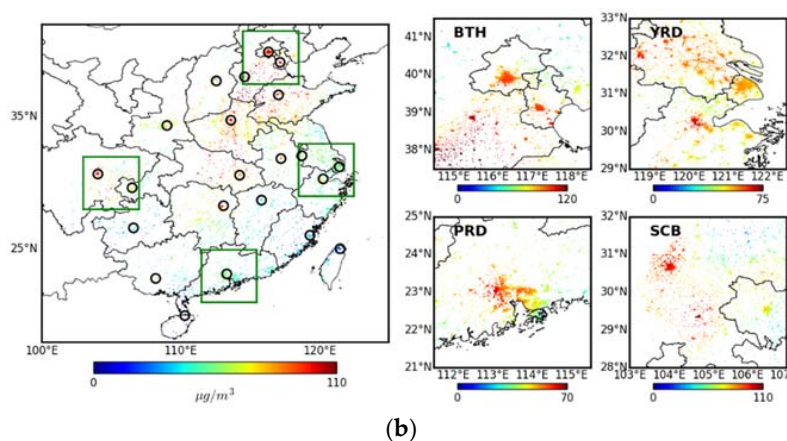

(**a**)

Figure 3. *Cont.*

(**b**)

Figure 3. Spatial distributions of the 15-year means of PM$_{2.5}$ concentrations in (**a**) rural and (**b**) urban areas in the study region and four major city clusters (BTH (Beijing-Tianjin-Hebei), YRD (Yangtze River Delta), PRD (Pearl River Delta), and SCB (Sichuan Basin) regions). The locations of the capital cities of the provinces are marked by circles.

3. Results

3.1. PM$_{2.5}$ in Urban and Rural Areas

The blue and green bars in Figure 4 represent the 15-year averages of PM$_{2.5}$ concentrations in rural (c_r) and urban (c_u) areas over the entire study region and in different provinces. The red bars show the differences between c_r and c_u. The 15-year averages of c_r and c_u for the entire study region were estimated to be about 52.7 μg/m^3 and 61.0 μg/m^3, respectively. The mean PM$_{2.5}$ concentrations in both rural and urban areas for the study region were much higher than the WHO IT-1 (35 μg/m^3).
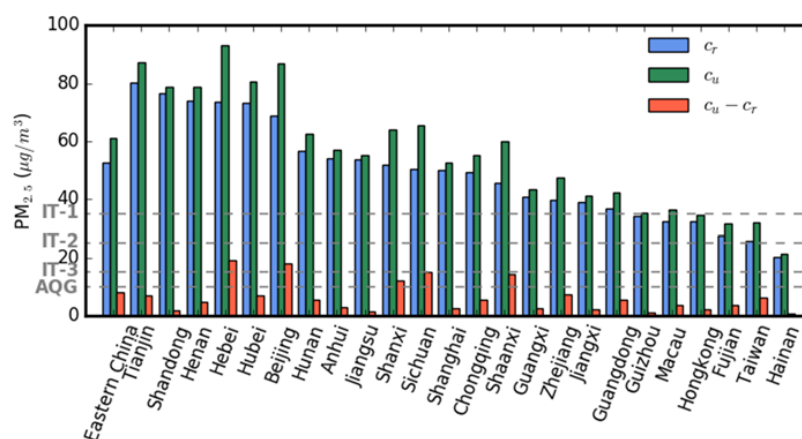

Figure 4. Fifteen-year averages of PM$_{2.5}$ concentrations in rural (c_r, blue bars) and urban (c_u, green bars) areas of the entire study region and in different provinces. The red bars show the difference between c_r and c_u. Provinces are ordered by their c_r value. The WHO air-quality standards (IT-1, IT2, IT-3, and AQG (air quality guideline)) for annual PM$_{2.5}$ are indicated by the dashed lines.

Tianjin had the highest level of c_r (80.2 μg/m^3). The highest levels of c_u were found in provinces in the BTH region: Beijing (c_u = 87.0 μg/m^3), Tianjin (c_u = 87.3 μg/m^3), and Hebei (c_u = 93.1 μg/m^3). PM$_{2.5}$ concentrations in urban areas were higher than in rural areas in all provinces. The difference between c_r and c_u was >15 μg/m^3 in Beijing ($c_u - c_r$ = 18.1 μg/m^3), Hebei ($c_u - c_r$ = 19.4 μg/m^3), and Sichuan ($c_u - c_r$ = 15.3 μg/m^3). The higher PM$_{2.5}$ concentrations in urban areas are due to more human activities, greater energy consumption, and higher emissions of air pollutants [32,33].

The mean PM$_{2.5}$ concentrations in both rural and urban areas exceeded the WHO IT-1 (35 µg/m^3) and IT-2 (25 µg/m^3) in most provinces and exceeded the WHO IT-3 (15 µg/m^3) and air quality guideline (AQG, 10 µg/m^3) in all provinces.

3.2. PM$_{2.5}$ Trends in Urban and Rural Areas

Figure 5 shows the spatial distributions of PM$_{2.5}$ trends in the residential areas of the study region during the 10th (2001–2005), 11th (2006–2010), and 12th (2011–2015) FYP periods. PM$_{2.5}$ concentrations declined substantially in northern China but increased extensively in southern China during the 10th FYP period. During the 11th FYP period, PM$_{2.5}$ concentrations declined extensively in the study region. During the 12th FYP period, PM$_{2.5}$ concentrations reduced substantially in the study region particularly in the BTH region and central China (e.g., Hubei and Hunan). Overall, northern China experienced a greater reduction in PM$_{2.5}$ concentration than southern China did during the 10th and 12th FYP periods.
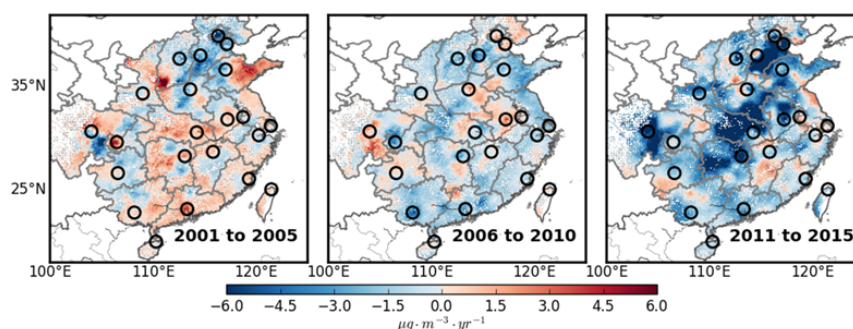

Figure 5. Spatial distributions of PM$_{2.5}$ trends in the residential area of the study region during the 10th, 11th, and 12th FYP periods. The locations of the capital cities of the provinces are marked by circles.

The blue and green bars in Figure 6 represent the averages of the PM$_{2.5}$ trends in the rural (dc_r/dt) and urban (dc_u/dt) areas of the entire study region during the three FYP periods. The PM$_{2.5}$ concentrations in rural areas remained steady during the 10th FYP period and declined by -0.68 µg·m^{-3}·year^{-1} and -2.41 µg·m^{-3}·year^{-1} during the 11th and 12th FYP periods, respectively. The PM$_{2.5}$ concentrations in urban areas declined by -0.11 µg·m^{-3}·year^{-1}, -0.68 µg·m^{-3}·year^{-1}, and -2.70 µg·m^{-3}·year^{-1} during the 10th, 11th, and 12th FYP periods, respectively. The red bars show the differences in the averaged PM$_{2.5}$ trends between rural and urban areas ($D = dc_u/dt - dc_r/dt$) during the three FYP periods. Urban areas experienced greater reductions in PM$_{2.5}$ than rural areas during the 10th and 12th FYP periods. During the 11th FYP period, the averaged PM$_{2.5}$ reduction rates in the rural and urban areas of the entire study region were similar.

Figure 7a,b shows the averaged PM$_{2.5}$ trends in rural and urban areas in different provinces during the three FYP periods. Figure 7c shows the differences in the averaged PM$_{2.5}$ trends between rural and urban areas in different provinces during the three FYP periods. Despite a similar trend, substantial differences remained between PM$_{2.5}$ trends in rural and urban areas. During the 10th FYP period, urban areas experienced more reductions in PM$_{2.5}$ than rural areas in most provinces (17 out of 24). PM$_{2.5}$ reductions in urban areas were more substantial than in rural areas in Beijing (by as much as 1.9 µg·m^{-3}·year^{-1}). During the 11th FYP period, PM$_{2.5}$ in urban areas showed less of a reduction than in rural areas in more than half of the provinces (15 out of 24). During the 12th FYP period, PM$_{2.5}$ in urban areas had more reductions than in rural areas in most provinces (19 out of 24). The rates of decline in PM$_{2.5}$ concentration in urban areas were more substantial than in rural areas by as much as 1.5 µg·m^{-3}·year^{-1} in Beijing and 2.0 µg·m^{-3}·year^{-1} in Tianjin. In contrast, PM$_{2.5}$ reductions in urban areas were less substantial than in rural areas by as much as 0.36 µg·m^{-3}·year^{-1} in a few provinces such as Henan.
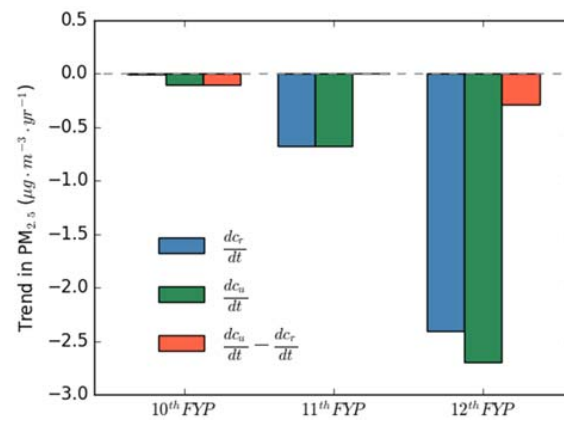
Figure 6. Averages of PM$_{2.5}$ trends in rural (dc_r/dt) and urban (dc_u/dt) areas (blue and green bars, respectively) across the entire study region during the three FYP periods. The red bars represent the difference in the averaged PM$_{2.5}$ trends between rural and urban areas ($D = dc_u/dt - dc_r/dt$) during the three FYP periods.
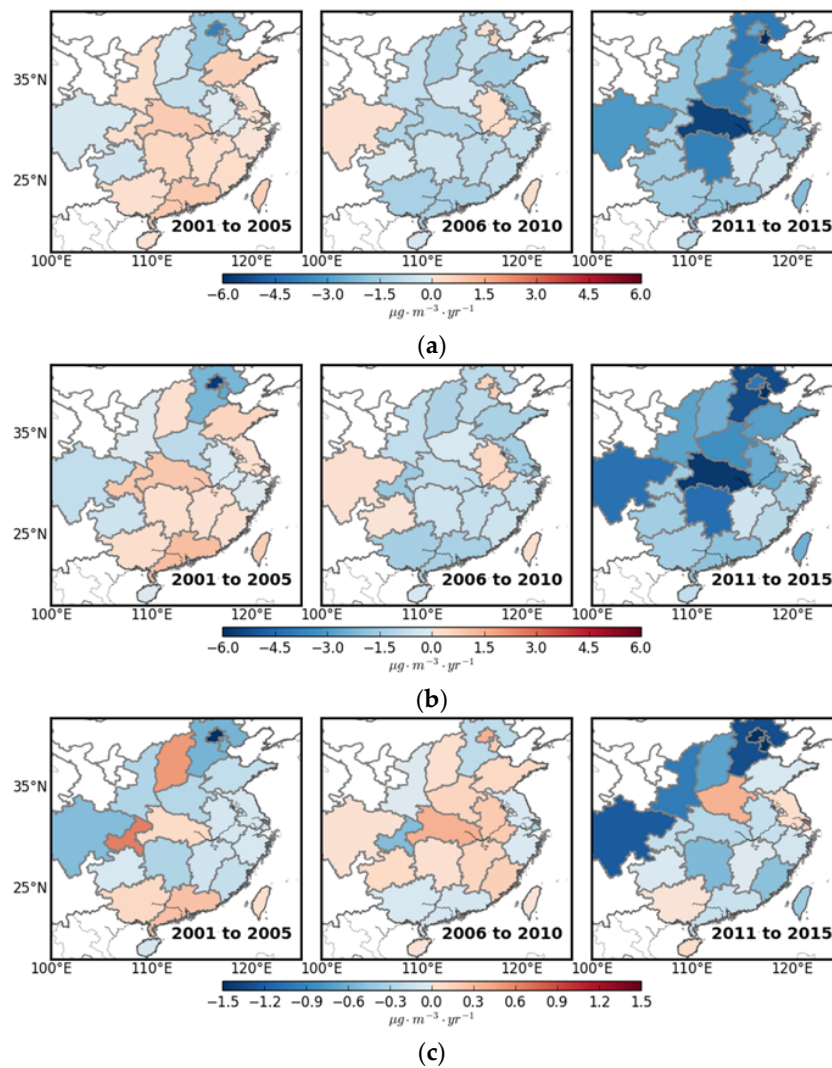

Figure 7. Averaged PM$_{2.5}$ trends in (**a**) rural and (**b**) urban areas in different provinces during the three FYP periods. (**c**) The differences in the averaged PM$_{2.5}$ trends between rural and urban areas in different provinces during the three FYP periods.

4. Discussion

Beyond the change in mean $PM_{2.5}$ concentration, spatial differences in $PM_{2.5}$ change also play an important role in reducing the population's exposure to $PM_{2.5}$. During the most recent FYP period, the spatial difference in $PM_{2.5}$ change helped to reduce exposure to $PM_{2.5}$ in most provinces. In contrast, the spatial difference in $PM_{2.5}$ change remained unfavorable in a few provinces, such as Henan. We suggest that control efforts further target densely populated urban areas in these provinces.

Control strategies targeted at urban areas should be more cost effective than trying to reduce $PM_{2.5}$ concentrations everywhere. The reduction of mean $PM_{2.5}$ concentration will become more difficult when the mean $PM_{2.5}$ concentration has dropped to a lower level. By that time, the targeted efforts will be more important in $PM_{2.5}$ exposure management. The $PM_{2.5}$ concentration in urban areas can be reduced through the control of anthropogenic emissions such as those from traffic and industrial sources and domestic fuel consumption. Beyond the control of emissions, we can also consider city planning measures such as moving pollution sources (e.g., industrial sources) away from densely populated urban areas and improving ventilation in street canyons surrounded by high-rise buildings.

The evaluation of satellite-derived $PM_{2.5}$ concentrations against ground observations showed a mean percentage error within $\pm 20\%$. This deviation is likely to result from the uncertainties of the satellite-based AOD and ground meteorological data (e.g., visibility and relative humidity) and from the assumption of steady aerosol characteristics (e.g., aerosol extinction efficiency). In addition, the satellites provide observations only during the daytime. This temporal limitation also contributed to the deviation of the satellite-derived $PM_{2.5}$ concentration.

With the use of high-resolution data, further research can be conducted to make assessments at city or even district scales over China. Population exposure to $PM_{2.5}$ is also affected by demographic change. Population exposure to $PM_{2.5}$ declines if city planning moves people away from heavily polluted areas. However, because of the rapid urbanization in China during the past decade, many people have moved into polluted urban areas. This rural-to-urban migration tends to increase population exposure to $PM_{2.5}$ in China. Further study could delineate these types of effect on population exposure to $PM_{2.5}$.

5. Conclusions

This study assessed the difference in $PM_{2.5}$ variations between urban and rural areas over eastern China during the past three FYP periods (2001–2015). The results of our analyses provide crucial information about pollution exposure over China. In addition, this long-term assessment is of great value in the formulation of future environmental policies and city planning. To better protect public health, it is suggested that control efforts further target densely populated urban areas and that city planning moves some pollution sources away from urban areas.

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