Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-1191
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 23 November 2018

Atmospheric Chemistry and Physics
Discussions

Effects of air pollution control policies on $PM_{2.5}$ pollution improvement in China from 2005 to 2017: a satellite based perspective

Zongwei Ma [1], Riyang Liu [1], Yang Liu [2], Jun Bi [1, 3, *]

[1] State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing, Jiangsu, China

[2] Department of Environmental Health, Rollins School of Public Health, Emory University, Atlanta, GA, USA

[3] Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment Technology (CICAEET), Nanjing University of Information Science & Technology, Nanjing, Jiangsu, China

*** Correspondence to:**

Dr. Jun Bi, School of the Environment, Nanjing University, 163 Xianlin Avenue, Nanjing 210023, P. R. China. Tel.: +86 25 89681605. E–mail address: jbi@nju.edu.cn.

ABSTRACT

Understanding the effectiveness of air pollution control policies is important for future policy making. China implemented strict air pollution control polices since 11th Five Year Plan (FYP). There is still a lack of overall evaluation of the effects of air pollution control policies on $PM_{2.5}$ pollution improvement in China since FYP. In this study, we aimed to assess the effects of air pollution control policies from 2005 to 2017 on $PM_{2.5}$ from the view of satellite remote sensing. We used the satellite derived $PM_{2.5}$ of 2005-2013 from one of our previous studies. For the data of 2014-2017, we developed a two-stage statistical model to retrieve satellite $PM_{2.5}$ data. Results show that the Energy Conservation and Emissions Reduction (ECER) policy, implemented in 11th FYP period and focused on SO_2 emissions control, had co-benefits on $PM_{2.5}$ reductions. The increasing trends of $PM_{2.5}$ pollutions was suppressed after 2007, and the $PM_{2.5}$ in Central and South China showed significant decreasing trends. The ECER policy during 12th FYP period were basically the extension of 11th FYP policy. However, the emissions control oriented policies reached it bottleneck. The $PM_{2.5}$ concentrations did not decrease from 2010 to 2013 in polluted areas. China implemented two stricter policies: 12th FYP on Air Pollution Prevention and Control in Key Regions (APPC-KR) in 2012, and Action Plan of Air Pollution Prevention and Control (APPC-AP) in 2013. The goal of air quality improvement (especially $PM_{2.5}$ concentration improvement) was proposed for the first time. The air quality improvement oriented polices had led to dramatic decreases of $PM_{2.5}$ after 2013.

1 Introduction

Fine particulate matter ($PM_{2.5}$, particulate matter with aerodynamic diameter less than 2.5 μm) is a major atmospheric pollutant, which has been shown to be strongly associated with adverse health effects (e.g., cardiovascular and respiratory morbidity and mortality) in many epidemiological studies (Crouse et al., 2012;Dominici et al., 2006;Pope et al., 2002). With the rapid economic development and industrialization in the past decades, $PM_{2.5}$ pollution has gradually become a major environmental issue in China (Liu et al., 2017b). However, the Chinese government did not realize the $PM_{2.5}$ issues until 2012. Therefore, air pollution control policies implemented before 2012 mainly focus on SO_2, industrial dust and soot emission control. The air pollution control policies of China started to pay attention to $PM_{2.5}$ since late 2012.

Understanding the effectiveness of air pollution controls policies is important for future air pollution control in China. Several studies have examined the historical air pollution control policies and their association with the trends of SO_2, NO_2, and PM_{10} (Jin et al., 2016;Chen et al., 2011;Hu et al., 2010). Since the national $PM_{2.5}$ monitoring network was established in late 2012, few studies have evaluated the effects of air pollution control policies on $PM_{2.5}$ concentrations before 2013 due to the lack of historical ground monitoring data. Therefore, it is difficult to understand whether the air pollution control policies had synergistic effects on $PM_{2.5}$ reductions before 2012.

In recent years, estimating ground $PM_{2.5}$ using satellite aerosol optical depth (AOD) data has been shown an effective way to fill the spatiotemporal $PM_{2.5}$ gaps left by ground monitoring network (Liu, 2013, 2014;Hoff and Christopher, 2009). There are two major methods to estimate ground $PM_{2.5}$ concentration using AOD data, the scaling method and statistical approach (Liu, 2014). Boys et al. (2014) and van Donkelaar et al. (2015) estimated the global satellite $PM_{2.5}$ time series using the scaling method. Compared to the scaling method, statistical models have greater prediction accuracy but require large amount ground-measured $PM_{2.5}$ data to develop the statistical models (Liu, 2014). By taking advanced of the newly established ground $PM_{2.5}$ monitoring network, we developed a two-stage statistical model to estimate historical monthly mean $PM_{2.5}$ concentrations using Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 AOD data in one of our previous study(Ma et al., 2016). Validation results shows that this monthly $PM_{2.5}$ dataset has high prediction accuracy ($R^2 = 0.73$). This accurate historical $PM_{2.5}$ dataset from 2004 to 2013 allowed us to examined the effects of pollution control policies on $PM_{2.5}$ concentrations. In this previous study(Ma et al., 2016), we preliminary analyzed the effects of Energy Conservation and Emissions Reduction (ECER) policy in 11th five year plan (2006-2010). We found an inflection point around 2008, after which $PM_{2.5}$ concentration showed slight decreasing trend, showing the co-benefits of the ECER policy. From 2013 to 2017, China implemented the Action Plan of Air Pollution Prevention and Control (APPC-AP), which focused on $PM_{2.5}$ pollutions. Currently, there is still a lack of overall evaluation of the effects of air pollution control policies on $PM_{2.5}$ pollution improvement in China from 2005 to 2017.

In this study, we aimed to assess the effects of air pollution control policies from 2005 to 2017 on $PM_{2.5}$ from the view of satellite remote sensing. We used the satellite-derived $PM_{2.5}$ dataset developed in our previous study (Ma et al., 2016). Since this data set was from 2004 to 2013 and data after 2014 has been lacking, we extended the dataset to 2017 in the present work. To keep consistent with our previous satellite $PM_{2.5}$ dataset, we used the same method as described in our previous study (Ma et al., 2016).

2 Overview of air pollution control policies in China from 2005 to 2017

During 2005 to 2017, China implemented a series air pollution prevention and control policies, including 11th Five Year Plan (FYP) on Environmental Protection (2006-2010), ECER Policy during 11th FYP period, 12th FYP on Environmental Protection (2011-2015), 12th FYP on ECER, The 12th FYP on Air Pollution Prevention and Control in Key Regions (APPC-KR), and APPC-AP (2013-2017). The base year, implementation period, major goals, and major measures are listed in Table 1.

During 11th FYP period, there was no specific air pollution control policies. Air pollution prevention and control measures were incorporated in the whole environmental protection plan or policy (i.e., 11th FYP on Environmental Protection and ECER policy). From Table 1 we can see that the air pollution policies during 11th FYP mainly focused on total emission reduction. In this period, environmental management mode in China is emission control oriented. The 12th FYP on Environmental Protection and ECER policy were basically the extension of the 11th FYP policies, which mainly focused on emission reduction.

The 12th FYP on APPC-KR is the first special plan for air pollution prevention and control. This plan proposed the idea of unification of total emission reduction and air quality improvement. And it proposed the goals of air pollutant concentration control for the first time. $PM_{2.5}$ pollution control was also incorporated in this plan. Although the implementation period of 12th FYP on APPC-KR is 2011-2015, it was issued in October 29, 2012. After that, China issued the APPC-AP (2013-2017) in September 10, 2013, which strengthened the air pollution control and the goals of air quality improvement. In addition, during this period, China issued the new air quality standard, which incorporated $PM_{2.5}$ as a major control pollutant. These policies indicated that the air pollution control in China began to focus on air quality improvement.

3 Data and method

3.1 Satellite-based $PM_{2.5}$ from 2004 to 2013

The monthly satellite-based $PM_{2.5}$ data at 0.1 °resolution were obtained from our previous study (Ma et al., 2016). Briefly, we developed a two-stage statistical model using MODIS Collection 6 AOD and assimilated meteorology, land use data, and ground monitored $PM_{2.5}$ concentrations in 2013. The overall model cross-validation R^2 was 0.79 (daily estimates) for the model year. Since ground monitor data before 2013 has been lacking and therefore it is unable to develop statistical models before 2013 to estimate historical $PM_{2.5}$ concentrations. Thus, the historical $PM_{2.5}$ concentrations (2004-2012) were then estimated using the model developed based on 2013 model. Validation results indicated that it accurately predicted $PM_{2.5}$ concentrations with little bias at the monthly level ($R^2 = 0.73$, slope = 0.91). Currently, this historical monthly $PM_{2.5}$

dataset has been widely used in environmental epidemiological (Liu et al., 2016;Liu et al., 2017a;Chen et al., 2016;Wang et al., 2018a), health impact (Liu et al., 2017c;Wang et al., 2018b), and social economic impact (Chen and Chen, 2017;Chen and Jin, 2019;Yang and Zhang, 2018) studies in China.

3.2 Satellite-based $PM_{2.5}$ from 2014 to 2017

Unlike historical estimates from 2004 to 2012, we have sufficient ground monitored $PM_{2.5}$ data to develop statistical models after 2013, which allowed us to estimate daily $PM_{2.5}$ concentrations accurately. Therefore, we developed a separate $PM_{2.5}$-AOD statistical model for each year of 2014-2017 to estimate the spatially-resolved (0.1 °resolution) $PM_{2.5}$ concentrations. To keep satellite $PM_{2.5}$ estimates of 2014-2017 consistent with our previous satellite $PM_{2.5}$ dataset, we used the same method as described in our previous study (Ma et al., 2016). The data, model development, and model validation are briefly introduced as follows. Details can be found in our previous study (Ma et al., 2016).

The data used in this study include ground monitored $PM_{2.5}$ concentrations (μg/m^3), Aqua MODIS Collection 6 Dark Target (DT) AOD and Deep Blue (DB) AOD data, planetary boundary layer height (PBLH, 100 m), wind speed (WS, m/s) at 10 m above the ground, mean relative humidity in PBL (RH_PBLH, %), surface pressure (PS, hPa), precipitation of the previous day (Precip_Lag1; mm), MODIS active fire spots, urban cover (%), and forest cover (%). Ground monitored $PM_{2.5}$ data were collected from China Environmental Monitoring Center (CEMC), environmental protection agencies of Hong Kong and Taiwan. Figure 1 shows the ground $PM_{2.5}$ monitors used in this study. AOD were downloaded from the Level 1 and Atmospheric Archive and Distribution System (https://ladsweb.modaps.eosdis.nasa.gov/). Meteorological data were extracted from Goddard Earth Observing System Data Assimilation System GEOS-5 Forward Processing (GEOS 5-FP, ftp://rain.ucis.dal.ca) meteorological data. MODIS fire spots were from the NASA Fire Information for Resource Management System (https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms). Land use information were downloaded from Resource and Environment Data Cloud Platform of Chinese Academy of Science (http://www.resdc.cn/data.aspx?DATAID=184). DT and DB AOD were combined using inverse variance weighting method to improve the spatial coverage of AOD data (Ma et al., 2016). All data were assigned to a predefined 0.1 °grid. Then all of the variables in were matched by grid cell and day-of-year for model fitting.

A two-stage statistical model was developed for each year separately from 2014 to 2017. The first-stage linear mixed-effects (LME) model included day-specific random intercepts and slopes for AOD, season-specific random slopes for meteorological variables, and fixed slope for precipitation and fire spots. The first-stage model was fitted for each province separately. The second-stage generalized additive model (GAM) established the relationship between the residuals of the first-stage model and smooth terms of geographical coordinates, forest and urban cover. Details about model structure can be found elsewhere (Ma et al., 2016). Statistical indicators of coefficient of determination (R^2), mean prediction error (MPE), and root mean squared prediction error (RMSE) were calculated and compared between model fitting and 10-fold cross validation (CV) to assess model performance and over-fitting. Daily satellite $PM_{2.5}$ concentrations were predicted using the two-stage model.

3.3 Time series analysis

Monthly mean $PM_{2.5}$ concentrations for each grid cell were calculated to perform the time series analysis. Following our previous study (Ma et al., 2016), we required at least six daily $PM_{2.5}$ predictions in each month to calculate the monthly mean $PM_{2.5}$. We deseasonalized the monthly $PM_{2.5}$ time series by calculating the monthly $PM_{2.5}$ anomaly time series for each grid cell to remove the seasonal effect. $PM_{2.5}$ trend for each grid cell was calculated using least squares regression (Weatherhead et al., 1998). We analyzed the $PM_{2.5}$ trend for different periods to examine the effects of air pollution control policies on $PM_{2.5}$ pollution improvement.

4. Results and discussion

4.1 Validation of satellite-based $PM_{2.5}$ concentrations from 2014 to 2017

Table S1 (Supplemental Materials, SM) summarized the statistics of all variables for the modeling dataset from 2014 to 2017. Overall, there are 95,649, 110,805, 113,490, and 123,652 matchups for the model fitting datasets for years of 2014, 2015, 2016, and 2017, respectively. The average $PM_{2.5}$ concentration decreases year by year, from 65.66 μg/m^3 in 2014 to 48.32 μg/m^3 in 2017. Correspondingly, the average AOD also shows a decreasing trend from 0.67 in 2014 to 0.50 in 2017.

Figure 2 shows the model fitting and cross validation results for each year's model. The model fitting R^2 ranges from 0.75 (2015) to 0.80 (2017) and CV R^2 ranges from 0.72 (2015) to 0.77 (2017), which is similar to the 2013 model (0.82 for model fitting and 0.79 for CV) developed in our previous study (Ma et al., 2016). The model prediction accuracy is different among years, which is consistent with previous studies. Hu et al. (2014) studied the 10-year spatial and temporal trends of $PM_{2.5}$ concentrations in the southeastern US from 2001 to 2010. They developed a separate two-stage statistical model for each year and found the CV R^2 ranged from 0.62 in 2009 to 0.78 in 2005 and 2006. Kloog et al. conducted two studies in Northeast US and also found that the validation R^2 varied among years (Kloog et al., 2011;Kloog et al., 2012). Compared to the model fitting R^2, the CV R^2 only decreases 0.02 in 2016 and 0.03 in 2014, 2015, and 2017, showing that our models were not substantially over-fitted. For the monthly mean concentrations calculated from at least six daily $PM_{2.5}$ predictions, the validation R^2 values ranges from 0.75 to 0.81 (Figure 3). The results show that the overall prediction accuracy of the models from 2014 to 2017 is satisfying.

4.2 Overall spatial and temporal trend of $PM_{2.5}$ concentrations in China from 2004 to 2017

Figure 4 shows the spatial distribution characteristics of annual mean $PM_{2.5}$ concentrations are similar among the years from 2004 to 2017. The most polluted area was North China Plain (including south of Jingjinji Region, Henan, and Shandong Provinces), which was also the largest polluted area. The Sichuan Basin (including east of Sichuan and western Chongqing) is another polluted area. The cleanest areas were mainly located in Tibet, Hainan, Taiwan, Yunnan, and the north of Inner Mongolia. The spatial distributions of satellite-derived $PM_{2.5}$ concentrations from 2013 to 2017 are consistent with the spatial characteristics of ground monitored $PM_{2.5}$ (Figure S2, SM)

Figure 5 shows the spatial distributions of $PM_{2.5}$ trends and significance levels in China from 2004 to 2017. Over all, the $PM_{2.5}$ pollution level of most area in China showed a decreasing trend ($p<0.05$). Table S2 shows that the overall trends of 2004-2017 for entire China, Jingjinji, Yangtze River Delta (YRD), Pearl River Delta (PRD) Regions were -1.27, -1.55, -1.60, and -1.27 μg/m^3/year (all $p<0.001$), respectively. Back to Figure 4, we can see that the decrease of $PM_{2.5}$ mainly happened after 2013. $PM_{2.5}$ concentrations had an obvious increase from 2004 to 2007. The area with $PM_{2.5}$ concentrations higher than 100 μg/m^3 continuously expanded during this period. From 2008 to 2013, the pollution levels plateaued in most areas. After 2013, the $PM_{2.5}$ concentrations obviously decreased.

4.3 Effect of ECER policy during 11th Five Year Plan period

To assess the effect of ECER policy during 11th FYP, we calculated the trends of $PM_{2.5}$ for 2005-2010, 2004-2007, and 2007-2010 for each grid cell (Figure 6) and entire China and key regions (Table S2, SM).

Compared to the base year (2005) of the 11th FYP period, the overall $PM_{2.5}$ pollution of 2010 did not have obvious change. Some of the area had decreasing trends (Figure 6(a)) but the trends were insignificant (Figure 6(b)). Some regions (Shandong, Henan, Jiangsu Provinces, and Northeast China) had slight increasing trend (~1-2 μg/m^3/year, $p<0.001$). Overall, the trends of entire China, Jingjinji, YRD, and PRD Regions were all insignificant (0.41, 0.26, 0.61, and -1.26 μg/m^3/year, and all $p>0.1$) during 11th FYP period.

However, when separating this period into two periods, we can see that before 2007, the $PM_{2.5}$ concentrations generally had significant increasing trends (Figure 6(c, d)), especially in South of Jingjinji Region, Henan, Shandong, and Hubei Provinces. The overall trends of entire China and Jingjinji Region are 1.88 ($p<0.001$) and 3.14 ($p<0.005$) μg/m^3/year (Table S2, SM). The trends of YRD and PRD Regions are insignificant.

Compared to the period before 2007, and period of 2007 to 2010 had different trend characteristics. The $PM_{2.5}$ concentrations of Central and South China decreased significantly, with highest trend of around -9 μg/m^3/year (Figure 6(e, f), $p<0.01$). For south of Jingjinji Region, Henan, Shandong, and Hubei Provinces, which had significantly increased before 2007, showed insignificant trends (Figure 6(f), $p>0.05$). Table S2 shows that the overall trends of entire China, Jingjinji, and YRD Regions were not significant during the latter half of 11th FYP period. And $PM_{2.5}$ concentrations in PRD Region had a big drop (-4.81 μg/m^3/year, $p<0.001$). The results show that the increasing trend of $PM_{2.5}$ had been suppressed. 11th FYP for National Economic and Social Development of China released in 2006 first proposed the ECER goals. However, China did not achieve the annual goal of 2006, which had led to the release of Comprehensive Working Plan on ECER (http://www.gov.cn/zwgk/2007-06/03/content_634545.htm) in 2007 and strengthened the ECER measures. After 2007, the increasing trend of $PM_{2.5}$ pollutions was suppressed. Results show that although ECER policy was not for $PM_{2.5}$ prevention and control, it still had co-benefits on $PM_{2.5}$ pollution control.

4.4 Effect of air pollution control policies in 12th Five-Year Plan period (2011–2015)

Figure 7(a) and (b) show that most of the areas of China show significant decreasing trend during 12th FYP period. $PM_{2.5}$ concentrations of entire China, Jingjinji, and YRD had dropped by 2.89, 3.63, and 3.33 μg/m^3/year ($p<0.001$). When considering the years from 2010 to 2013, although overall trend of entire China was -1.03 μg/m^3/year ($p<0.05$, Table S2, SM), the decreasing trend mainly happened in Xinjiang and Central Inner Mongolia. Most of the polluted area in China did not had obvious change (Figure 7(c) and (d)). As we mentioned above, The ECER policy during 12th FYP period was basically the extension of the policy in 11th FYP, which mainly focused on emissions reduction. As the further development of social economic, the ECER policy had shown its bottleneck for $PM_{2.5}$ reductions.

Therefore, China issued the 12th FYP on APPC-KR in late 2012, which is the first special plan for air pollution prevention and control and focused on air quality improvement. $PM_{2.5}$ is one of the major pollutants under control in this policy. After that, $PM_{2.5}$ pollution in China had shown dramatic drops. Table 2 shows $PM_{2.5}$ concertation improvement goals and final accomplishments for key regions (see Figure S1, SM) of 12th FYP on APPC-KR calculated from satellite $PM_{2.5}$.

Results show that all key regions had accomplished the goals except for Yinchuan. The changes in population weighted averages also show similar results. Overall, the 12th FYP on APPC-KR accomplished its air pollution control goals. And the decrease of $PM_{2.5}$ concentrations was mainly attributable to the decrease after 2013.

4.5 Effect of Action Plan for Air Pollution Prevention and Control (2013-2017)

China issued the APPC-AP (2013-2017) in late 2013, which further strengthened the air pollution control measures and air quality improvement goals. The implementation of APPC-AP, together with 12th FYP on APPC-KR, had led to dramatic drop in $PM_{2.5}$ concentrations from 2013 to 2017 (Figure 7(e) and (f)). $PM_{2.5}$ trends of 2013-2017 for entire China, Jingjinji, YRD, and PRD Regions were -4.27, -6.77, -6.36, and -2.11 μg/m^3/year (all p<0.05), respectively (Table S2, SM). Table 3 shows $PM_{2.5}$ concertation improvement goals and final accomplishments for APPC-AP. The goals required $PM_{2.5}$ concentrations in Jingjinji, YRD, and PRD Regions in 2017 should decreased by 25%, 20%, and 15% compared to 2012, and the annual mean $PM_{2.5}$ of Beijing should reach at around 60 μg/m^3. Since there were no ground measurements in 2012, the Ministry of Ecology and Environment (MEE) of China used 2013 as the base year to assess the performance of APPC-AP (http://www.mee.gov.cn/gkml/sthjbgw/stbgth/201806/t20180601_442262.htm). To maintain consistency with the official performance assessment, we also used 2013 as the base year. Results show that the arithmetic average of satellite $PM_{2.5}$ concentrations for Jingjinji, YRD, and PRD Regions were decreased by 36.9%, 37.1%, and 14.0%, respectively. And annual mean $PM_{2.5}$ of Beijing was 44.67 μg/m^3 in 2017. From the view of satellite, Jingjinji, YRD, and Beijing had accomplished their goals, and PRD was very closed to the goal.

According to the official results of APPC-AP performance assessment, $PM_{2.5}$ of Jingjinji, YRD, and PRD Regions were decreased by 39.6%, 34.3%, and 27.7%, respectively. And annual mean $PM_{2.5}$ of Beijing was 58 μg/m^3 in 2017. Compared to the arithmetic average, the populations weighted average results (Table 3) are more closed to the official results. The main reason is that official performance assessment used ground measurements. However, the spatial distribution of ground monitors is uneven. Most of the sites are distributed in populated urban areas and only a few are located in rural areas. Compared to ground monitors, satellite remote sensing has more comprehensive spatial coverage. Figure S3 shows the spatial distribution of satellite and ground $PM_{2.5}$ concentrations of 2017 in Beijing. It can be seen that the ground monitors are clustered in polluted urban centers. The cleaner north and northwest of Beijing have few sites. Thus the population weighted results of satellite $PM_{2.5}$ are closer to the official results, but still have differences. Since satellite $PM_{2.5}$ have better spatial coverage than ground monitors, satellite $PM_{2.5}$ can better represent the spatial variation of $PM_{2.5}$ pollutions. The population weighted average satellite $PM_{2.5}$ can better represent the health impact of $PM_{2.5}$ pollutions. When using ground monitors to calculate the regional mean concentrations, the weights of area and population for each site should be considered.

5 Discussion and Conclusions

This paper reviewed the air pollution control policies from 2005 to 2017. For the first time we gave an overall evaluation of the effects of these policies on $PM_{2.5}$ pollution improvement in China from the perspective of satellite remote sensing. Results show that our satellite $PM_{2.5}$ dataset is a good source to evaluate the performance of air pollution policies. The trends of satellite-derived $PM_{2.5}$ concentrations is consistent with the implementation of air pollution control policies in different periods.

The ECER policy implemented in 11th FYP period had co-benefits on $PM_{2.5}$ pollution control. The overall $PM_{2.5}$ pollution had certain decrease after 2007, but the effects were limited. The Environmental Protection Plan and ECER policy during 12th FYP period were basically the extension of 11th FYP policy, with additional total emission control on NO_x. However, the total emission control oriented policy had reached it bottleneck. The $PM_{2.5}$ concentrations of polluted areas did not decrease from 2010 to 2013.

To addressed the $PM_{2.5}$ pollution issue, China implemented two strict policies: the 12th FYP on APPC-KR in 2012 and APPC-AP in 2013. The goal of air quality improvement was proposed for the first time. Besides, China incorporated $PM_{2.5}$ as a major control pollutant into the National Ambient Air Quality Standard. All these polices had led to dramatic decreases of $PM_{2.5}$ after 2013. And the implementation of these policies was also an important mark that environmental management in China began to change from total emission control oriented mode to environmental quality improvement oriented mode. To ensure that the goals could be accomplished, MEE adopted a temporal measure in 2017, i.e., the intensified supervision for air pollution control in Jinjinji and around area (http://www.gov.cn/hudong/2017-07/14/content_5210588.htm). This temporal action ensured the accomplishment of APPC-AP goals.

The air pollution control in China has achieved a periodic victory. However, $PM_{2.5}$ concentrations in many areas are still much higher than Level 2 annual $PM_{2.5}$ standard of 35 μg/m^3 of the National Ambient Air Quality Standard of China, which is corresponding to World Health Organization (WHO) Air Quality Interim Target-1 level. China has implemented a new air pollution control policy from 2018, i.e., the Three-year Action Plan to Win Battle for Blue Skies (2018-2020). China’s air quality is expected to be further improved in the next three years.

This study extended the satellite $PM_{2.5}$ dataset in our previous study (Ma et al., 2016) to the year of 2017 and obtained longer time series of satellite $PM_{2.5}$ data, which can provide more spatially-resolved and high accurate $PM_{2.5}$ data for epidemiological, health impact assessment, and social economic impact studies in China.

Authors contributions

J. B. conceived and designed the study. R. L. collected and processed the data. Z. M. and Y. L. performed statistical modeling for satellite $PM_{2.5}$ predictions. Z. M. analyzed the spatiotemporal trends of $PM_{2.5}$ concentrations. J. B. prepared and analyzed the air pollution control policies. Z. M. prepared the manuscript with contributions from all co-authors.

Acknowledgment

This work was supported by the National Key Research and Development Program of China (2016YFC0207603), the National Natural Science Foundation of China (71433007, 91644220, and 41601546), and the Fundamental Research Funds for the Central Universities of China (0211-14380078).

References

Boys, B., Martin, R., van Donkelaar, A., MacDonell, R., Hsu, C., Cooper, M., Yantosca, R., Lu, Z., Streets, D. G., Zhang, Q., and Wang, S.: Fifteen-year global time series of satellite-derived fine particulate matter, Environ. Sci. Technol., 48, 11109-11118, 2014.

Chen, B., Kan, H., Chen, R., Jiang, S., and Hong, C.: Air pollution and health studies in China—policy implications, J. Air Waste Manag. Assoc., 61, 1292-1299, 2011.

Chen, D., and Chen, S.: Particulate air pollution and real estate valuation: Evidence from 286 Chinese prefecture-level cities over 2004–2013, Energy Policy, 109, 884-897, 2017.

Chen, K., Zhou, L., Chen, X., Ma, Z., Liu, Y., Huang, L., Bi, J., and Kinney, P. L.: Urbanization level and vulnerability to heat-related mortality in Jiangsu Province, China, Environ. Health Perspect., 124, 1863, 2016.

Chen, S., and Jin, H.: Pricing for the clean air: Evidence from Chinese housing market, J. Clean. Prod., 206, 297-306, 2019.

Crouse, D. L., Peters, P. A., van Donkelaar, A., Goldberg, M. S., Villeneuve, P. J., Brion, O., Khan, S., Atari, D. O., Jerrett, M., and Pope, C.: Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: a Canadian national-level cohort study, Environ. Health Perspect., 120, 708-714, 2012.

Dominici, F., Peng, R. D., Bell, M. L., Pham, L., McDermott, A., Zeger, S. L., and Samet, J. M.: Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases, JAMA-J. Am. Med. Assoc., 295, 1127-1134, 2006.

Hoff, R. M., and Christopher, S. A.: Remote sensing of particulate pollution from space: have we reached the promised land?, J. Air Waste Manag. Assoc., 59, 645-675, 2009.

Hu, H., Yang, Q., Lu, X., Wang, W., Wang, S., and Fan, M.: Air Pollution and Control in Different Areas of China, Crit. Rev. Env. Sci. Technol., 40, 452-518, 2010.

Hu, X., Waller, L., Lyapustin, A., Wang, Y., and Liu, Y.: 10-year spatial and temporal trends of $PM_{2.5}$ concentrations in the southeastern US estimated using high-resolution satellite data, Atmos. Chem. Phys., 14, 6301-6314, 2014.

Jin, Y., Andersson, H., and Zhang, S.: Air pollution control policies in China: a retrospective and prospects, Int. J. Environ. Res. Public Health, 13, 1219, 2016.

Kloog, I., Koutrakis, P., Coull, B. A., Lee, H. J., and Schwartz, J.: Assessing temporally and spatially resolved $PM_{2.5}$ exposures for epidemiological studies using satellite aerosol optical depth measurements, Atmos. Environ., 45, 6267-6275, 2011.

Kloog, I., Nordio, F., Coull, B. A., and Schwartz, J.: Incorporating local land use regression and satellite aerosol optical depth in a hybrid model of spatiotemporal $PM_{2.5}$ exposures in the Mid-Atlantic states, Environ. Sci. Technol., 46, 11913-11921, 2012.

Liu, C., Yang, C., Zhao, Y., Ma, Z., Bi, J., Liu, Y., Meng, X., Wang, Y., Cai, J., and Kan, H.: Associations between long-term exposure to ambient particulate air pollution and type 2 diabetes prevalence, blood glucose and glycosylated hemoglobin levels in China, Environ. Int., 92, 416-421, 2016.

Liu, C., Chen, R., Zhao, Y., Ma, Z., Bi, J., Liu, Y., Meng, X., Wang, Y., Chen, X., and Li, W.: Associations between ambient fine particulate air pollution and hypertension: a nationwide cross-sectional study in China, Sci. Total Environ., 584, 869-874, 2017a.

Liu, M., Bi, J., and Ma, Z.: Visibility-based $PM_{2.5}$ concentrations in China: 1957–1964 and 1973–2014, Environ. Sci. Technol., 51, 13161-13169, 2017b.

Liu, M., Huang, Y., Ma, Z., Jin, Z., Liu, X., Wang, H., Liu, Y., Wang, J., Jantunen, M., Bi, J., and Kinney, P. L.: Spatial and temporal trends in the mortality burden of air pollution in China: 2004–2012, Environ. Int., 98, 75-81, 2017c.

Liu, Y.: New Directions: Satellite driven $PM_{2.5}$ exposure models to support targeted particle pollution health effects research, Atmos. Environ., 68, 52-53, 2013.

Ma, Z., Hu, X., Sayer, A. M., Levy, R., Zhang, Q., Xue, Y., Tong, S., Bi, J., Huang, L., and Liu, Y.: Satellite-Based Spatiotemporal Trends in $PM_{2.5}$ Concentrations: China, 2004–2013, Environ. Health Perspect., 124 184-192, 2016.

Pope, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., and Thurston, G. D.: Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, JAMA-J. Am. Med. Assoc., 287, 1132-1141, 2002.

van Donkelaar, A., Martin, R. V., Brauer, M., and Boys, B. L.: Use of satellite observations for long-term exposure assessment of global concentrations of fine particulate matter, Environ. Health Perspect., 123, 135-143, 2015.

Wang, C., Xu, J., Yang, L., Xu, Y., Zhang, X., Bai, C., Kang, J., Ran, P., Shen, H., and Wen, F.: Prevalence and risk factors of chronic obstructive pulmonary disease in China (the China Pulmonary Health [CPH] study): a national cross-sectional study, The Lancet, 391, 1706-1717, 2018a.

Wang, Q., Wang, J., He, M. Z., Kinney, P. L., and Li, T.: A county-level estimate of $PM_{2.5}$ related chronic mortality risk in China based on multi-model exposure data, Environ. Int., 110, 105-112, 2018b.

Weatherhead, E. C., Reinsel, G. C., Tiao, G. C., Meng, X. L., Choi, D., Cheang, W. K., Keller, T., DeLuisi, J., Wuebbles, D. J., and Kerr, J. B.: Factors affecting the detection of trends: Statistical considerations and applications to environmental data, J. Geophys. Res. Atmos., 103, 17149-17161, 1998.

Yang, J., and Zhang, B.: Air pollution and healthcare expenditure: Implication for the benefit of air pollution control in China, Environ. Int., 120, 443-455, 2018.

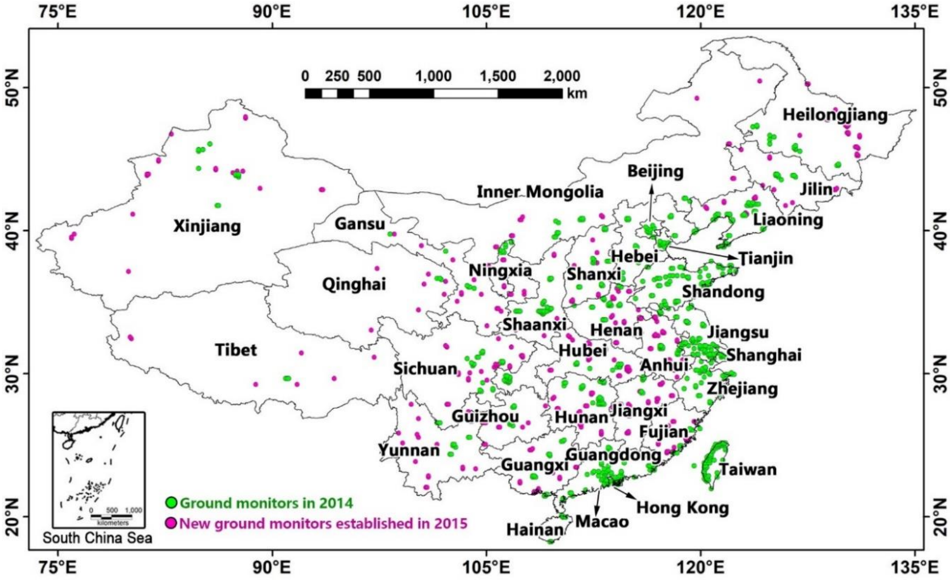

Figure 1. Spatial distributions of ground $PM_{2.5}$ monitors involved in model fitting and validation. Red circles denote the ground monitor in 2014. Pink circles denote new ground monitors established in 2015.

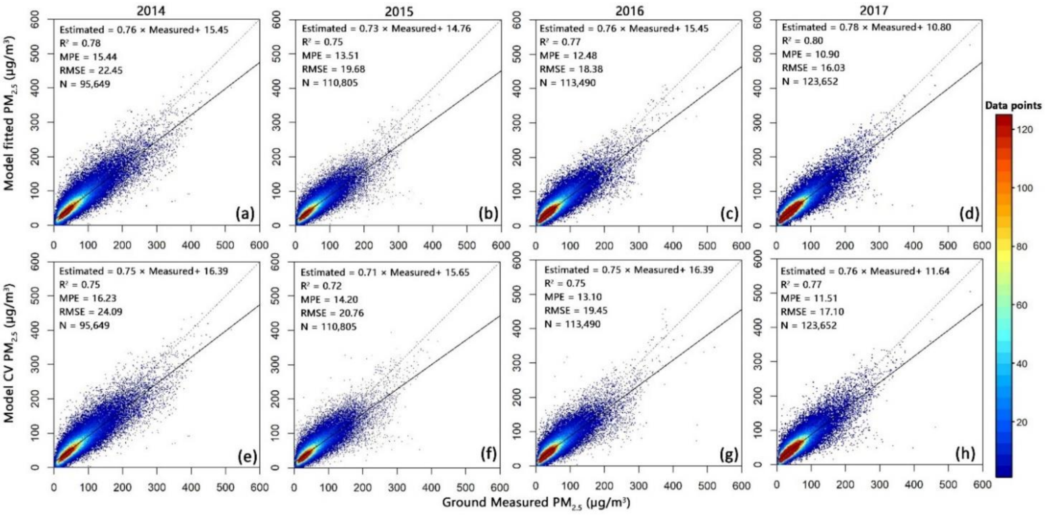

Figure 2. Model fitting and CV results for satellite $PM_{2.5}$ prediction models from 2014 to 2017.

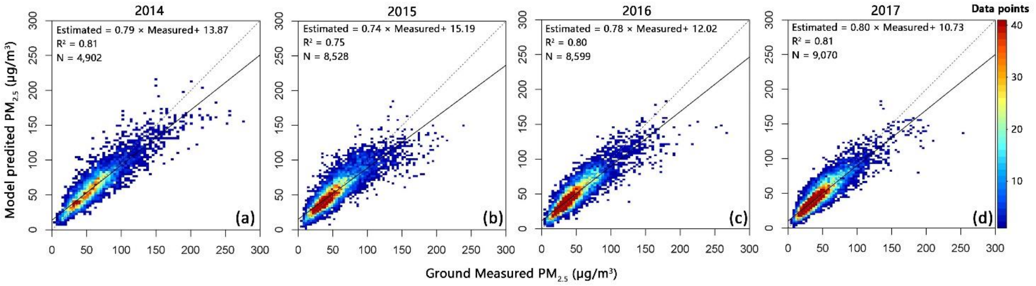

Figure 3. Validation of monthly mean $PM_{2.5}$ predictions from 2014 to 2017.

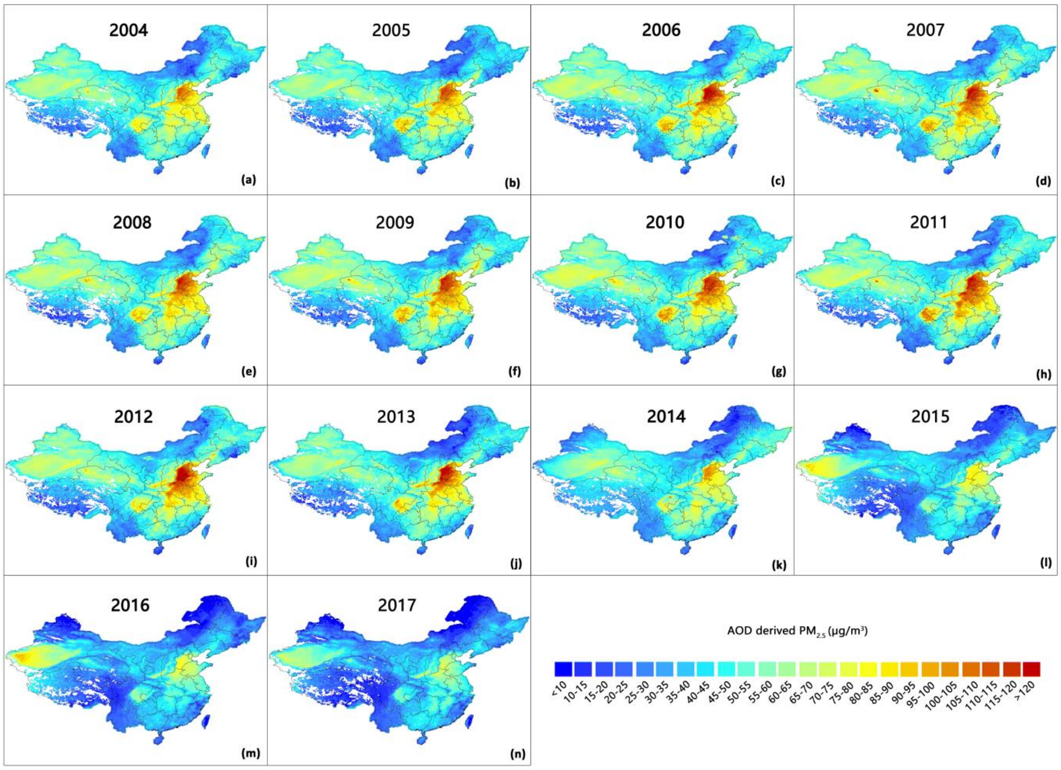

Figure 4. Spatial distributions of annual mean satellite-derived $PM_{2.5}$ concentrations from 2004 to 2017.

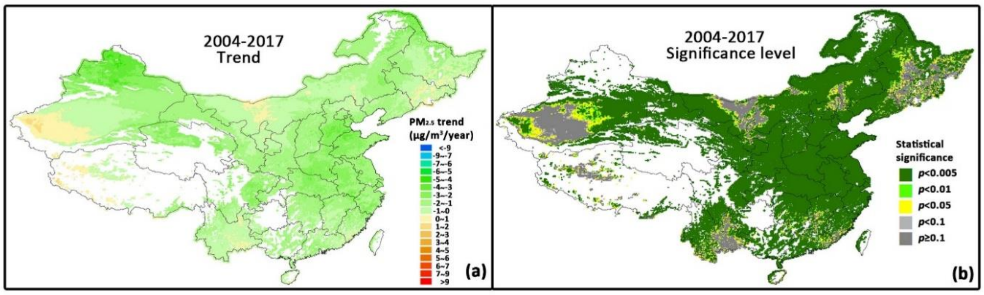

Figure 5. Spatial distributions of $PM_{2.5}$ trends and significance levels in China from 2004 to 2017.

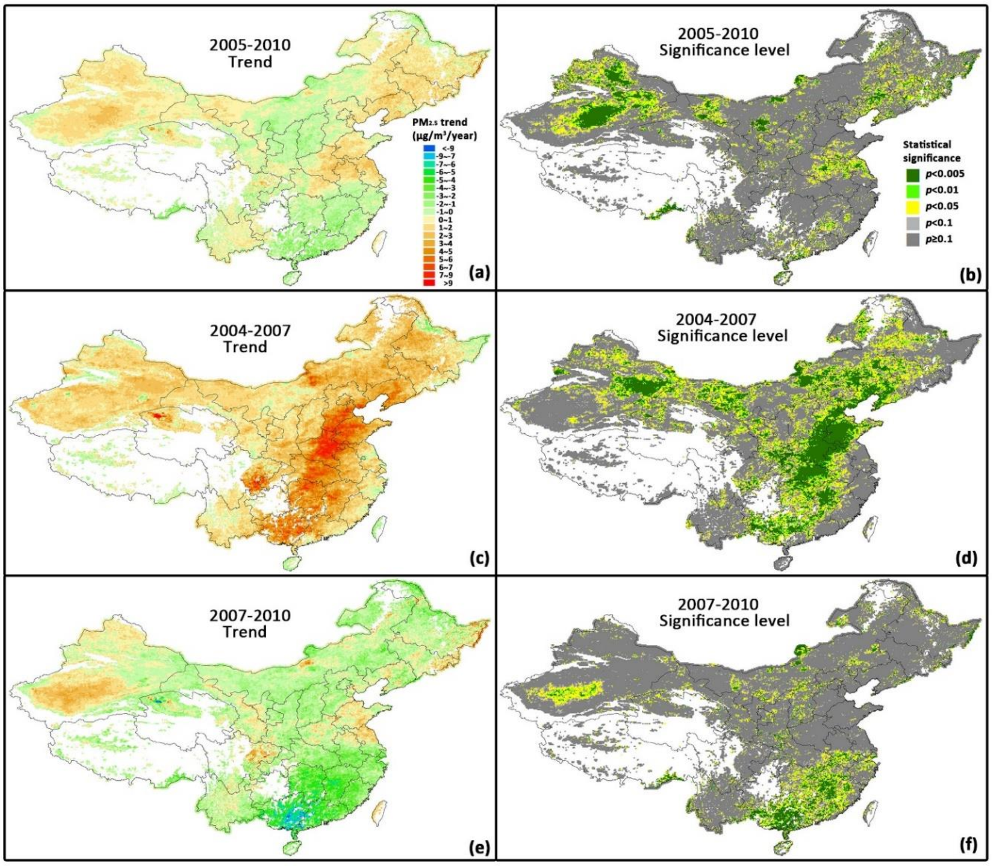

Figure 6. Spatial distributions of $PM_{2.5}$ trends and significance levels in China from 2005 to 2010.

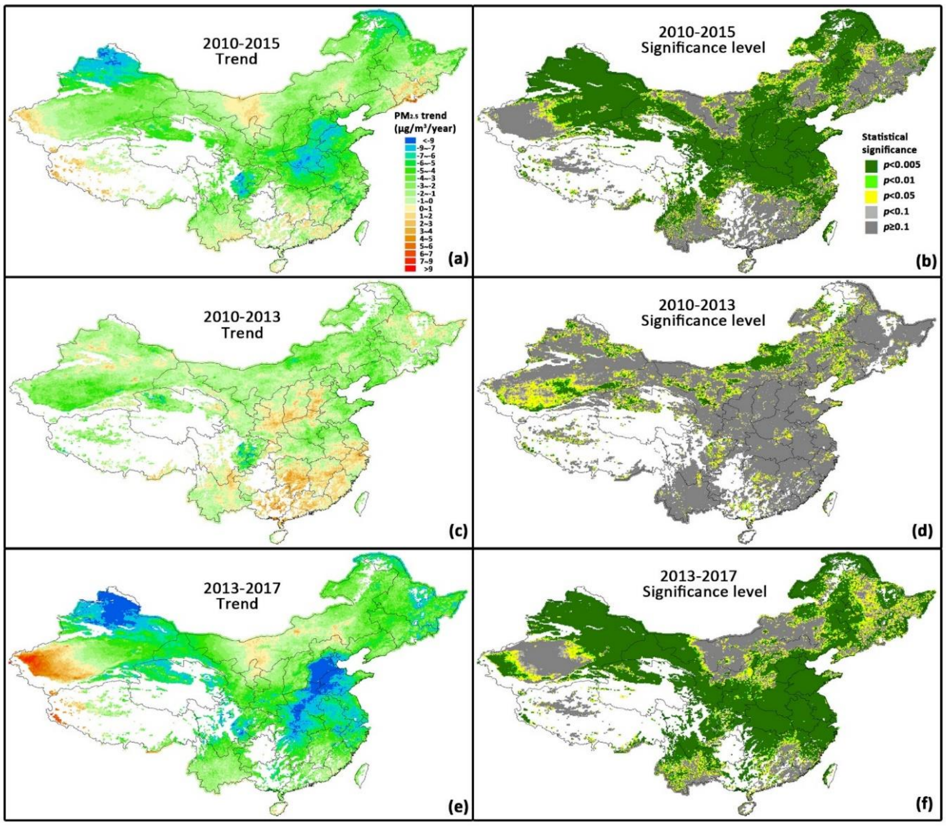

Figure 7. Spatial distributions of $PM_{2.5}$ trends and significance levels in China from 2010 to 2017.

5

Table 1. Overview of major air pollution control policies in China from 2005 to 2017

Policy [a]	Base year	Implementation period	Major goals (Compared to base year)	Major measures
11th FYP on Environmental Protection	2005	2006-2010	• SO$_2$ emission should reduce by 10%	• Implement of desulphurization projects of coal-fired power plants • Prevent and control urban PM$_{10}$ pollution, relocate pollution industrial plants in urban areas, control construction and road dust • Implement total emission control policy for key industrial pollution sources, control emission of sulfur dioxide and soot (dust) • Strengthen vehicle pollution prevention and control, improve quality and efficiency of gasoline
ECER during 11th FYP	2005	2006-2010	• Energy consumption per GDP capita should decrease by20% • SO$_2$ emission should reduce by 10%	• Promote industrial and energy structure adjustment, restrain the development of industries with high energy consumption and pollution, eliminate backward production capacity, promote production capacity with low energy consumption and low pollution • Implement ten major energy conservation projects, implement desulphurization projects of coal-fired power plants
12th FYP on Environmental Protection	2010	2011-2015	• SO$_2$ emission should reduce by 8% • NO$_x$ emission should reduce by 10%	• Implement desulphurization and denitration facilities for coal-fired power sector and major industrial sectors • Control NOx emissions of vehicles and ships • Deepen PM and VOCs pollution control • Promote urban air pollution prevention and control, implement coordinated control of various pollutants in key areas, monitor PM$_{2.5}$ and O$_3$ in Jingjinji, Yangtze River Delta, and Pearl River Delta regions
ECER during 12th FYP	2010	2011-2015	• Energy consumption per GDP capita should decrease by16% • SO$_2$ emission should reduce by 8% • NO$_x$ emission should reduce by 10%	• Adjust and optimize industrial structure, control the development of industries with high energy consumption and pollution, eliminate backward production capacity • Adjust energy consumption structure, strengthen energy conservation for industrial, building, transportation, commercial and civil areas, etc. • Strengthen emissions reduction in key industrial sectors, promote desulphurization and denitration, control emissions of vehicles, promote the control of PM$_{2.5}$
The 12th FYP on APPC-KR [b]	2010	2011-2015	• Emission of the SO$_2$, NOx, and industrial PM should decrease 12%, 13%, and 10%, respectively • The annual average concentration of PM$_{10}$, SO$_2$, NO$_2$ and PM$_{2.5}$ should decrease by 10%, 10%, 7%, and 5%, respectively	• Identify the key regions and implement regional specific management • Strictly control high energy consumption and high pollution projects, control new pollutants emissions, implement strict emission standard, and enhance control requirements of VOCs in key regions • Strengthen elimination of backward production capacity, optimize industrial layout • Optimize energy consumption structure, develop clean energy, control total coal consumption, establish restricted zones for high polluting fuels, eliminate small coal boilers, promote clean and efficient utilization of coal • Comprehensively implement co-control of multiple pollutants (SO$_2$, NO$_x$, PM, VOCs), strengthen vehicle pollution prevention and control • Innovate regional management mechanism, establish joint regional prevention and control coordination mechanism, establish and perfect ground monitoring network
APPC-AP [b]	2012	2013-2017	• PM$_{2.5}$ concentrations of Jingjinji, Yangtze River Delta, and Pearl River Delta regions [c] should reduce by 25%, 20%, and 15% respectively • PM$_{2.5}$ concentrations of Beijing should be controlled at around 60 μg/m^3	• Enhance comprehensive air pollution control on industrial enterprises, deepen non-point source control, strengthen vehicle pollution control • Adjust, optimize, and upgrade industrial structure, strictly control new capacity with high energy consumption and high pollution, accelerate elimination of backward production capacity, reduce excess capacity • Accelerate energy structure adjustment, accelerate utilization of clean energy, control total coal consumption, promote clean utilization of coal, improve energy efficiency • Optimize industrial layout • Utilize the market mechanism, improve the pricing and tax policy, establish regional coordination mechanism • Establish monitoring, early warning, and emergency system for heavy pollution episodes

[a] Abbreviations: FYP: Five Year Plan; ECER: Energy Conservation and Emissions Reduction; APPC-KR: Air Pollution Prevention and Control in Key Regions; APPC-AP: Action Plan of Air Pollution Prevention and Control

[b] The key regions are shown in Figure S1 (Supplemental Materials)

Table 2 Goals accomplishments for key regions of 12th FYP on APPC-KR

Region	Goal (Decreased by)	Average satellite $PM_{2.5}$ concentrations			Population weighted average satellite $PM_{2.5}$ concentrations		
		2010 (μg/m^3)	2015 (μg/m^3)	Decreased by	2010 (μg/m^3)	2015 (μg/m^3)	Decreased by
Beijing	15%	68.75	58.47	14.9%	83.41	70.61	15.3%
Tianjin	6%	97.17	75.17	22.6%	96.13	76.09	20.8%
Hebei	6%	74.72	58.19	22.1%	101.25	75.15	25.8%
Shanghai	6%	66.41	58.83	11.4%	64.30	60.67	5.7%
Jiangsu	7%	81.23	62.24	23.4%	82.18	63.19	23.1%
Zhejiang	5%	52.85	38.73	26.7%	58.68	47.37	19.3%
Pearl River Delta	5%	45.00	37.97	15.6%	50.07	40.99	18.1%
Central Liaoning	6%	58.10	53.00	8.8%	64.97	58.40	10.1%
Shandong	7%	94.57	71.83	24.0%	97.83	73.76	24.6%
Wuhan Region	5%	75.02	55.41	26.1%	79.86	58.62	26.6%
Changzhutan Region	5%	64.81	52.75	18.6%	72.32	60.19	16.8%
Chongqing	6%	65.89	47.48	27.9%	77.36	52.71	31.9%
Chengdu Region	5%	83.55	52.22	37.5%	92.22	57.40	37.8%
Fujian	4%	37.42	28.02	25.1%	34.48	29.22	15.3%
Central and Northern Shanxi	4%	53.76	40.05	25.5%	63.05	46.78	25.8%
Guanzhong	4%	65.91	45.33	31.2%	79.54	53.91	32.2%
Lanzhou Region	4%	55.42	45.31	18.2%	62.47	47.77	23.5%
Yinchuan	5%	42.81	48.14	-12.4%	46.51	51.81	-11.4%
Urumqi Region	4%	60.26	27.83	53.8%	65.80	36.05	45.2%

Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-1191
Manuscript under review for journal Atmos. Chem. Phys.
Discussion started: 23 November 2018

Table 3 Goal accomplishments of APPC-AP (2013-2017)

Region	Goal (Decreased by)	Official assessment results [a]	Average satellite $PM_{2.5}$ concentrations			Population weighted average satellite $PM_{2.5}$ concentrations		
			2013 (μg/m^3)	2017 (μg/m^3)	Decreased by	2013 (μg/m^3)	2017 (μg/m^3)	Decreased by
Jingjinji	25%	39.6%	76.01	47.98	36.9%	100.91	60.97	39.6%
Yangtze River Delta	20%	34.3%	66.60	41.87	37.1%	71.98	46.45	35.5%
Pearl River Delta	15%	27.7%	45.15	38.84	14.0%	49.96	40.37	19.2%
Beijing	Be controlled at around 60 μg/m^3	58 μg/m^3	68.20	44.67	34.5%	82.69	55.07	33.4%

[a] See http://www.mee.gov.cn/gkml/sthjbgw/stbgth/201806/t20180601_442262.htm