Manuscript acp-2018-1191

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

Dear Editor,

We would like to thank the anonymous reviewers for their valuable comments, which have led to significant improvements in the quality and clarity of this manuscript. We have carefully considered all of the comments and prepared detailed, item-by-item responses in the following **“Responses to RC1” and “Responses to RC2”**. We have also highlighted the revisions in red font in the revised manuscript.

Should you have any questions, please feel free to contact me via email (njumazw@163.com).

Best regards,
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Manuscript acp-2018-1191

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

Responses to RC1

Overall comment:

This is an interesting paper putting forward a historical perspective on PM2.5 surface concentrations in China. The authors propose a statistical method that relates satellite observed aerosol optical depth (AOD) over China to measurements of PM2.5 at the surface. The authors use the years 2013 and later when both satellite and surface measurements were available to train their method. Prior to 2013 there was no ground based network to speak of in China.

Then the method, essentially a multivariate regression of information on the atmospheric state, is applied to infer surface PM2.5 for the entire 2005-2017 period from MODIS AOD. This allows the authors to evaluate the effectiveness of the various Chinese air pollution control policies that have been applied in this period. Based on the satellite-estimated PM2.5 trends, the authors claim a “periodic victory” for Chinese policies to clean up the air.

I think the paper addresses a relevant topic that is appropriate for publication in ACP, but I have concerns about the method, which is not well described in this manuscript. Also for non-Chinese readers, it would be necessary to clarify what the various Chinese policies consisted of. We read very little about what measures were actually implemented, and how they may have had an effect. This is important information to share with an eye on other countries going through a rapid development phase, and wishing to limit the effects of air pollution. The authors owe it to the world, so to speak.

Response: We would like to thank the reviewer for his valuable comments. We have added descriptions of the method. We also incorporated descriptions of major air pollution control measures in the main text. Please see the following responses for details.

(1) The abstract is not very clear. There are many abbreviations referring to policies applicable in certain periods only that will not be immediately clear or well-known to the wide readership of ACP. The authors should rewrite their abstract with a focus on storytelling how Chinese PM2.5

changes over time between 2005 and 2017, and why. The results summarized should be presented in quantitative fashion.

Response: The abstract has been revised according to this comment and the comment from another referee. We simply explained how these policies can impact the PM2.5 pollution. The trends analysis was revised and presented in a quantitative way. A brief description of the model has been added. Please see Abstract in P2.

(2) The method to infer PM2.5 from MODIS AOD is explained only very briefly with repeated reference to a previous paper by the same authors. For this paper to standalone, the authors should provide much more detail on how their statistical "two-stage" method works, and how robust the method is. The authors should briefly explain what drives the relationship between PM2.5 and AOD. Which parameters explain most of the variance and why.

Specifically:

Provide the equation establishing the relationship between AOD and surface PM2.5

Explain how the fit parameters have been derived, and discuss the orthogonality of the various explanatory terms (humidity, boundary layer height, T, : : :)

Discuss the temporal resolution of the relationship ("each year's model")

Discuss the differences and agreement with the model-scaling approach

Since the method relies on the quality of the MODIS and surface PM2.5 data, these aspects should be discussed as well.

Response: According to the comments, we have made corresponding revisions as follows:

1) We added details about the equations of the two-stage model, please see P8-P9;
2) In original manuscript, we have discussed the model performance for each year, see Lines 9-21, P10 in Section 4.1. In revised manuscript, we added the provincial fixed effects, model fitting, and CV results of the first-stage LME model for each year in Tables S2-S5 (Supplementary Materials). And we have discussed it in Line 22, P10~Line 5, P11.
3) A brief description of scaling method was added (Line 25, P3~Line 1, P4). We compared the model performance with previous scaling method studies, see Lines 11-17, P11.
4) Lines 23-25, P7 shows the quality of MODIS AOD data. Lines 17-21, P7 added the issues of PM2.5 data quality.

(3) Related to the lack of information on the method, are the terms “random intercepts” and “random slopes” mentioned on page 7. Without reading the previous paper by the authors in a different journal, it is entirely unclear what these terms mean. It shows that this manuscript cannot be read on its own, which is not the standard for a paper in ACP.

Response: We added details about the equations of the two-stage model, please see P8-P9.

(4) Related to the trends, it is unclear how the trends were determined. Did they use a linear model of the form y = a + b t, how did they deal with seasonality, weighing of sparsely sampled months, etc.? They need to provide more detail and also include figures showing the temporal evolution of the PM2.5 estimates, along with the satellite data, and ground-based observations for one or a few particular locations.

Response: We added details about the method for trend analysis in Lines 14-24, P9. For seasonality, we have described how we dealt with it in our original manuscript. See Lines 10-12, P9. We deseasonalized the monthly PM2.5 time series by calculating the monthly PM2.5 anomaly time series for each grid cell to remove the seasonal effect.

(5) Section 2 on the policies is too technocratic. We read about the official titles of the policies, but the authors should make clear not just in (the valuable but too long) Table 1 but also in the main text what the policies consisted of. I realize they cannot be exhaustive all the time, but they should provide an assessment of what they think were the most effective measures taken under a certain policy, and the evidence to back this up. This is important to make a convincing case, and allows others to learn from the policies taken. One suggestion is to come up with a figure showing a timeline of the various measures and their anticipated effect on Chinese PM2.5 levels. Such a figure could then later be confronted with the observed PM2.5 evolution, and tell the story whether measures have been effective.

Response: Revisions have been made according to the comments. First, we described major air pollution control measures, corresponding achievements, and how these policies were associated with PM2.5 pollutions in the main text. Such as Lines 4-13, P13; Lines 22-27, P13; Lines 14-21, P14; Line 23, P14~Line 3, P15; Line 23, P15~Line 22, P16. Second, a new figure (Figure 6) to show the overall national and regional trends for different periods and corresponding air pollution control policies. And we moved a table from supplementary materials to the main manuscript (see Table 2), which corresponds to Figure 6.

(6) P2, L3: polices-> policies

Response: We have corrected this mistake. See Line 3, P2.

(7) P3, L13-14: the citations are quite China-centric. Consider citing studies on SO2 and NO2 trends over China from non-Chinese groups, e.g. Itahashi et al. [2012], Krotkov et al. [2016], Miyazaki et al. [2017].

Suggested references:

Krotkov, N. A., McLinden, C. A., Li, C., Lamsal, L. N., Celarier, E. A., Marchenko, S. V., Swartz, W. H., Bucsela, E. J., Joiner, J., Duncan, B. N., Boersma, K. F., Veefkind, J. P., Levelt, P. F., Fioletov, V. E., Dickerson, R. R., He, H., Lu, Z., and Streets, D. G.: Aura OMI observations of regional SO2 and NO2 pollution changes from 2005 to 2015, Atmos. Chem. Phys., 16, 4605-4629, doi:10.5194/acp-16-4605-2016, 2016.

Miyazaki, K., Eskes, H., Sudo, K., Boersma, K. F., Bowman, K., and Kanaya, Y.: Decadal changes in global surface NOx emissions from multi-constituent satellite data assimilation, Atmos. Chem. Phys., 17, 807-837, https://doi.org/10.5194/acp-17-807-2017, 2017.

Itahashi, S., Uno, I., Yumimoto, K., Irie, H., Osada, K., Ogata, K., Fukushima, H.,Wang, Z., and Ohara, T.: Interannual variation in the fine-mode MODIS aerosol optical depth and its relationship to the changes in sulfur dioxide emissions in China between 2000 and 2010, Atmos. Chem. Phys., 12, 2631-2640, https://doi.org/10.5194/acp-12-2631-2012, 2012.

Response: Thanks for the recommendation. These studies show that satellite remote sensing provides a powerful tool to assess the spatiotemporal trends of air pollutions for both global and regional scales. The references have been added in Lines 19-21, P3.

(8) P4, L11: pollution(s)

Response: This revision has been made (Line 15, P4).

(9) P4, L26: policy, not policies

Response: This revision has been made (Line 5, P5).

(10) P5, L21: unclear what R2 refers to

Response: It is coefficient of determination. We have added the description after R2 (L26, P5).

(11) P5, L25: “Validation results indicated…” be more specific. Validation done where, when?

Response: Two ways were used to validate the accuracy of historical estimates. First, we compared the historical estimates monitoring data from Hong Kong and Taiwan before 2013. Second, we estimated $PM_{2.5}$ concentrations in the first half of 2014 using the 2013 model and compared them with the ground measurements to evaluate the accuracy of $PM_{2.5}$ estimates beyond the model year, which can represent the accuracy of historical estimates. This description has been added (Lines 4-8, P6).

(12) P6, L12: suggest to remove referring to Ma et al. [2016]. This paper should describe the method briefly itself.

Response: We added details about the equations of the two-stage model, please see P8-P9.

(13) P6, L20-21: please discuss the representativeness of the PM2.5 stations for the size of a MODIS pixel, or vice versa?

Response: We pointed out the uneven spatial distribution of ground $PM_{2.5}$ monitors. Please see Lines 6-12, P11.

(14) P9, L25: grammar

Response: This sentence has been deleted in our revision process.

(15) P10, L9-10: “strengthened the ECER measures” -> explain how

Response: Major air pollution control measures and corresponding achievements were added. See Lines 4-13, P13.

(16) P10, L11-12: explain qualitatively how this would have worked

Response: The main reasons were added. See Lines 22-27, P13.

(17) P10, L18-19: explain why further reduction emissions had no beneficial effect anymore

Response: The main reasons were added. See Lines 13-21, P14.

(18) P10, L21-22: rephrase... I don't think bottleneck is the term you should use.

Response: We have rephrase "bottleneck" to "limitation". See Line 13, P14.

(19) P10, L25: "After that" -> be more specific what the policy consisted of then

Response: Major measures included were added in Line 23, P14~Line 12, P15.

(20) P11, section 4.4: it would be useful to include here already how the findings relate to Chinese and WHO air quality standards.

Response: We thought that adding a comparison in Section 4.5 would be better. We added a sentence in Lines 10-12, P17. We want to show that although China has achieved great success in $PM_{2.5}$ pollution control, PM2.5 levels are still much higher than Chinese and WHO air quality standards.

(21) P11, L6-7: how? we remain in the dark what was actually done and how that helped

Response: Major air pollution control measures and corresponding achievements were added. See Line 23, P15~Line 23, P16.

(22) P11, L11: what explains the regional differences?

Response: We discussed the regional differences in Lines 22-26, P19.

(23) P11, L21: close(d)

Response: This revision has been made. See Line 10, P17.

(24) P11, L25: what are the "official results"?

Response: They are the "official results" of "APPC-AP performance assessment (Table 4)". This revision has been made accordingly. See Line 13, P17,

(25) P12, L20: “the overall decrease” -> be quantitative

Response: Done. See Lines 23-24, P18; Lines 2, 7-8, P19.

(26) P13, L2: “All these policies” -> it should be made clear what was the essence of this

Response: Since we have added the essence in the main text, we did not add it here again. We refer it to Sections 4.4 and 4.5. See Lines 6-7, P19.

(27) P13, L4: MEE -> ?

Response: the Ministry of Ecology and Environment (MEE), see Line 3, P17.

(28) P13, L9: “air pollution control in China has achieved a periodic victory”-> this is awkward, do the authors mean that the measures taken so far have resulted in a temporary solution, or, more precisely, have succeeded to mitigate the worst aspects of PM2.5 pollution?

Response: What we want to say here is that air pollution control in China has achieved great success in PM2.5 pollution reduction. Sorry for the awkward phrase. We have revised this sentence to “Currently, China has achieved great success in $PM_{2.5}$ pollution control.” See Line 1, P20.

(29) Figure 2: unclear what difference is between upper and lower rows.

Response: They are model fitting (upper row) and cross validation (CV, lower row) results. We have revised the caption accordingly. We have revised the caption of Figure 2. And we added a brief description of CV in Line 25, P8~L3, P9.

Manuscript acp-2018-1191

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

Responses to RC2

General comment:

The paper provides a useful overview of recent air quality control policies in China, while using an independent source of data to assess their efficacy. A statistical method is used to correlate satellite retrievals of Aerosol Optical Depth (AOD) to ground level PM2.5 in China, by correlating AOD with meteorological data, fire spots and forest cover. It uses the large network of Chinese measurement stations to verify the model. The 2013 model, which was developed in another paper (Ma et al 2016) is used to project the concentration of PM2.5 backwards to 2005, while a separate model is developed each year for 2014 - 2017. This gives a 13-year PM2.5 dataset with complete spatial and temporal coverage for 2005 – 2017, which is then used to assess the success of China's air quality control policy that underwent significant changes during this period. Linear trends are calculated for the periods corresponding to specific policies (e.g. Five Year Plans). Calculated PM2.5 concentrations are also compared with official government data, to verify that targets were met. While this retrospective analysis of the success of China's control of PM2.5 pollution is very useful, the authors need to ensure that they acknowledge the role that inter-annual variation in meteorology may play in these trends.

Response: We would like to thank the reviewer for his valuable comments. We have revised the manuscript according to the comments, please see the following responses. For the impact of meteorological conditions, we have discussed this in Lines 11-14, 20-21, P19.

(1) Abstract The majority of the abstract summarizes the discussion section. A brief description of the two stage statistical model, including its predictors could be added.

Response: A brief description of the two stage statistical model and its predictors have been added in abstract. See Lines 8-11, P2.

(2) Intro P3, L23: It may be worth adding a sentence that briefly explains what the ‘scaling method’ is. There is a citation to Liu 2014 to back up the statement that, “Compared to the scaling method, statistical models have greater prediction accuracy but require large amount ground-measured PM2.5 data to develop the statistical models (Liu, 2014)”. However, there is not a reference that corresponds to the “Liu, 2014” citation. Since the justification of method choice relies on this reference, it should be added before the paper is reviewed again.

Response: Done. See Line 25, P3~Line 1, P4.

(3) Overview of air pollution control policies in China from 2005 to 2017 This section is a very broad summary of the actions within Five Year Plans and other major government directives that are relevant to air pollution control. The specific policies (e.g. ‘Implement desulphurization and denitration facilities for coal-fired power sector and major industrial sectors’) are summarised in Table 1, along with the metrics by which the policies’ success will be judged. It may be useful to, where possible, cite government press releases/reports or literature that assess the success of these policies. However, the text in this section does not make any mention of the policies listen in Table 1. It would be useful for the reader for some information from Table 1 to be synthesised into this section, along with citations to previous studies that have attempted to assess the success of these policies (e.g. Schreifels et al, 2012)

Reference: Schreifels, Jeremy J., Yale Fu, and Elizabeth J. Wilson. "Sulfur dioxide control in China: policy evolution during the 10th and 11th Five-year Plans and lessons for the future." Energy Policy48 (2012): 779-789.

Response: This comment is helpful. After careful consideration, we added major air pollution control measures, corresponding achievements, and how these policies were associated with PM2.5 pollutions in the main text and cited relevant references, including reference of Schreifels et al, 2012. See Lines 4-13, P13; Lines 22-27, P13; Lines 13-21, P14; Line 23, P14~Line 3, P15; Line 23, P15~Line 22, P16.

(4) P5, L13. It may be worth defining what China's 'new air quality standard' here, where it is first mentioned. It may be useful to provide the old air quality standard, and the name of the standard (GB 3095-2012). Currently the actual threshold number of China's air quality standard is first referenced of P13, L10 in the conclusion.

Response: Done. We briefly described the new air quality standard in Lines 4-11, P15.

(5) Data and Method P6, L19: Paper uses PM2.5 data from the CNEMC. Other papers, (e.g. Rohde and Muller (2015); Liu et al (2016)) have noted quality issues with this data. Were any quality control procedures applied to this data?

References: Liu, Jianzheng, Weifeng Li, and Jie Li. "Quality screening for air quality monitoring data in China." Environmental pollution216 (2016): 720-723.

Rohde, Robert A., and Richard A. Muller. "Air pollution in China: mapping of concentrations and sources." PloS one10.8 (2015): e0135749.

Response: Yes, we performed the data screening procedure before model fitting. Abnormal values (extreme high or extreme low values for a site compared with its neighboring sites, repeated values for continuous hours, etc.) were deleted before model fitting. We required at least 20 hourly records to calculate the daily average $PM_{2.5}$ concentrations. Please see Lines 17-21, P7.

(6) Since the ground monitoring stations are typically within urban areas, could this bias the statistical model so that the PM2.5 predictions for non-urban areas is inaccurate? Why use the updated data to create separate statistical models for 2014, 2015, 2016 and 2017, yet only use the 2013 model to project back the PM2.5? Why should the 2013 model be more appropriate than the other years? Why not combine all the years where measurements are available? How is it justified to fit the model separately to the data in each province? Isn't using province boundaries somewhat arbitrary?

Response: Yes, we acknowledge this is a problem in statistical modeling of satellite PM2.5. We have discussed this in Lines 6-12, P11.

There are two reasons that we only use the 2013 model to project back the PM2.5. First, the historical data were derived from our previous study, which only used the 2013 model. This dataset has been shown high accuracy and has been widely used in environmental epidemiological (Liu et al., 2016;Wang et al., 2018a), health impact (Liu et al., 2017;Wang et al., 2018b), and social economic impact (Chen and Jin, 2019;Yang and Zhang, 2018) studies in China. Second, a recent study has shown that the historical hindcast ability of the annual model decreased when hindcast year was long before the model year (Xiao et al., 2018). Therefore, we did not use the models of 2014 to 2017 to estimate the hindcast $PM_{2.5}$.

For provincial models, we added the description how we fit the provincial model in Line 13-16, P8. We added the provincial results in Table S2-S4 (Supplementary Materials). And described the results in Line 23, P10~Line 5, P11. Results showed that the performance of first-stage LME model would greatly decreased if we fit the model for entire China.

(7) Many other studies of trends in atmospheric concentrations use a non-parametric trend estimator such as the Thiel-Sen slope estimator. The authors should justify their choice of the least squares regression to estimate the slope of the trend.

Response: In fact, the method we used in this study has been successfully applied to trend analyses of monthly mean $PM_{2.5}$ and AOD anomaly time-series data (Hsu et al., 2012;Boys et al., 2014;Zhang and Reid, 2010;Xue et al., 2019). Therefore, we thought that the method we used is appropriate. See Lines 22-24, P9. Besides, we added a description of the method. Please see Lines 14-22, P9.

(8) In the results section, and Figures 6 & 7, a p threshold of 0.1 is mentioned, but you do not mention in the methods which statistical test you used to check the significance of your trends.

Response: The method of *t* test was used to obtain the statistical significance of the trends. See Lines 21-22, P9.

(9) Some of these questions about the methodology can be answered by reading the author's previous Ma et al 2016 paper, which is published in Environmental Health Perspectives. I recommend the authors reduce their reliance on referring to this previous paper, so that the methods section in the current paper can be understood without referring to another paper which the reader will not necessarily have access to.

Response: We added details about the equations of the two-stage model, please see P8-P9.

(10) P5, L26: Is it useful to the reader to list 9 studies that have referenced your previous paper? This list includes studies that this paper's co-authors are also co-authors on.

Response: These papers were the follow up studies using the $PM_{2.5}$ dataset from 2004 to 2013 we developed in our previous study. Although some of them are the follow up studies by co-authors of this study, the publications of these studies show that the $PM_{2.5}$ dataset has been widely recognized and used in academic field. And these references can support the rationality that we directly use this $PM_{2.5}$ dataset from 2004 to 2013 in current study.

According to this comment, we have removed 3 references here (see Lines 13-15, P6) to simplify this paragraph.

(11) Results and Discussions Is it really useful to compare the PM2.5 trend with the corresponding FYP policies? This suggests that policies have immediate effects, and that they are the main contributor to the trends in PM2.5. There are other important confounding factors such as interannual variation in meteorology, China's economic output etc. May be best to avoid statements on the effectiveness of certain policies, or mention the above caveats in the conclusion.

Response: We added discussions about the impacts of meteorology and economic. See Lines 11-21, P19.

(12) I suggest the authors add a comparison of their results with other research that quantifies the trend in PM2.5 derived AOD in China, such as Lin et al., 2017. It may be interesting to perform a non-linear trend analysis on this dataset in certain key regions (e.g. Jing-Jin-Ji or PRD). Reference: Lin, C. Q., Liu, G., Lau, A. K. H., Li, Y., Li, C. C., Fung, J. C. H., & Lao, X. Q. (2018). High-resolution satellite remote sensing of provincial PM2. 5 trends in China from 2001 to 2015. Atmospheric Environment, 180, 110-116.

Response: The revision has been made. We compared our results with two recent studies. See Lines 3-13, P18.

(13) As you break down the trend into multiple overlapping periods of different lengths, it is difficult to get an overall impression of the rises and falls in the trend in different regions. Alternatively, a figure could be added with the yearly or monthly deseasonalised PM2.5 (averaged by different regions)

Response: We have added a new figure (Figure 6, P27) according to the comment. And we moved a table from supplementary materials to the main manuscript (see Table 2), which corresponds to Figure 6.

(14) I suggest the authors also mention the possibility of contribution of natural sources of aerosol to the trends. At P10, L16, the authors mention that the majority of the trend in PM2.5 during 2010-2013 are driven by decreases in Xinjiang and Central Inner Mongolia, which are both desert regions where the PM2.5 likely has a high dust component. This can be seen in your results. For example in panel (e) of Figure 7, where the western half of the Taklamakan desert has a strong positive trend, despite it being unlikely that there are large changes in emissions in this unpopulated region.

Response: The possible impact of dust in this region has been added. See Lines 6-9, P14.

(15) P3, L8: “However, the Chinese government did not realize the PM2.5 issues until 2012.” This sentence seems disingenuous and qualitative so should be removed or rephrased.

Response: We have changed “realize” to “focus on”. See Line 8, P3.

(16) P4, L6: Remove or replace the word ‘preliminary’.

Response: We changed it to “preliminarily”. Line 11, P4.

(17) P5 L14. “These policies indicated that the air pollution control in China began to focus on air quality improvement.” This sentence could be rephrased, as it is currently seems tautological.

Response: We changed it to “These policies indicated that the focus of air pollution control in China began to focus on $PM_{2.5}$ concentrations reductions”. See Lines 19-20, P5.

(18) P10, L22: The sentence “As the further development of social economic, the ECER policy had shown its bottleneck for PM2.5 reductions.” does not make sense. Bottleneck may be the wrong word to describe this.

Response: We have rephrase “bottleneck” to “limitation”. See Line 13, P14.

(19) P12, L25. Change ‘to addressed’ to “to address.”

Response: Done. See Line 3, P19.

(20) P13, L6. ‘Temporal’ is not the right word here. Should be temporary?

Response: Done. See Line 13, P16.

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

Hsu, N. C., Gautam, R., Sayer, A. M., Bettenhausen, C., Li, C., Jeong, M. J., Tsay, S. C., and Holben, B. N.: Global and regional trends of aerosol optical depth over land and ocean using SeaWiFS measurements from 1997 to 2010, Atmos. Chem. Phys., 12, 8037-8053, 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, 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, 2017.

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 PM2. 5 related chronic mortality risk in China based on multi-model exposure data, Environ. Int., 110, 105-112, 2018b.

Xiao, Q., Chang, H. H., Geng, G., and Liu, Y.: An ensemble machine-learning model to predict historical PM2. 5 concentrations in China from satellite data, Environ. Sci. Technol., 52, 13260-13269, 2018.

Xue, T., Zheng, Y., Tong, D., Zheng, B., Li, X., Zhu, T., and Zhang, Q.: Spatiotemporal continuous estimates of PM2. 5 concentrations in China, 2000–2016: A machine learning method with inputs from satellites, chemical transport model, and ground observations, Environ. Int., 123, 345-357, 2019.

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.

Zhang, J., and Reid, J. S.: A decadal regional and global trend analysis of the aerosol optical depth using a data-assimilation grade over-water MODIS and Level 2 MISR aerosol products, Atmos. Chem. Phys., 10, 10949-10963, 2010.

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

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ABSTRACT

Understanding the effectiveness of air pollution control policies is important for future policy making. China implemented strict air pollution control policies 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 11th 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 using the Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6 aerosol optical depth (AOD), assimilated meteorology, and land use data. The first-stage is a day-specific linear mixed effect (LME) model and second-stage is generalized additive model (GAM). 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 $PM_{2.5}$ pollution (1.88 and 3.14 μg/m^3/year for entire China and Jingjinji Region in 2004-2007, $p<0.005$) was suppressed after 2007. The overall $PM_{2.5}$ trend for entire China was -0.56 μg/m^3/year with marginal significance ($p=0.053$) and $PM_{2.5}$ concentrations in Pearl River Delta Region had a big drop (-4.81 μg/m^3/year, $p<0.001$) in 2007-2010. The ECER policy during 12th FYP period were basically the extension of 11th FYP policy. $PM_{2.5}$ is a kind of composite pollutant which comprises primary particles and secondary particles such as sulfate, nitrate, ammonium, organic carbon, elemental carbon, etc. Since ECER policy focused on single-pollutant control, it had shown great limitation for $PM_{2.5}$ reductions since. The $PM_{2.5}$ concentrations did not decrease from 2010 to 2013 in polluted areas (p values of the trends were greater than 0.05). Therefore, 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) and measures for multi-pollutant control were proposed. These policies had led to dramatic decrease in $PM_{2.5}$ after 2013 (-4.27 μg/m^3/year for entire China in 2013-2017, $p<0.001$).

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., 2017a). However, the Chinese government did not focus on 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, many studies have shown that satellite remote sensing provides a powerful tool to assess the spatiotemporal trends of air pollutions for both global and regional scales (Miyazaki et al., 2017;Itahashi et al., 2012;Krotkov et al., 2016). Estimating ground $PM_{2.5}$ using satellite aerosol optical depth (AOD) data was also 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, i.e, the scaling method and statistical approach (Liu, 2014). The scaling method uses atmospheric chemistry models to simulate the association between AOD and $PM_{2.5}$, and then calculate the satellite-derived $PM_{2.5}$ using the equation: $Satellite\text{-}derived\ PM_{2.5} = \frac{Simulated\ PM_{2.5}}{Simulated\ AOD} \times Satellite\ \ AOD$ (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 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 studies (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 preliminarily 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 $PM_{2.5}$ pollution. 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 dataset 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 policy. 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 in China was emission control oriented, that is, the indicators for local governments' environmental performance assessment were emission reduction rates, not the environmental quality. 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. These policies indicated that the focus of air pollution control in China began to focus on $PM_{2.5}$ concentrations reductions.

3 Data and method

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

We estimated the monthly satellite-based $PM_{2.5}$ data from 2004 to 2013 at 0.1° resolution in our previous work (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 (coefficient of determination) 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. Two ways were used to validate the accuracy of historical estimates. First, we compared the historical estimates monitoring data from Hong Kong and Taiwan before 2013. Second, we estimated $PM_{2.5}$ concentrations in the first half of 2014 using the 2013 model and compared them with the ground measurements to evaluate the accuracy of $PM_{2.5}$ estimates beyond the model year, which can represent the accuracy of historical estimates. 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).

For $PM_{2.5}$ concentrations from 2004 to 2013, we directly used above-mentioned satellite-based $PM_{2.5}$ dataset, which was estimated using the model developed in 2013. First, this dataset has been shown high accuracy and has been widely used in environmental epidemiological (Liu et al., 2016a;Wang et al., 2018a), health impact (Liu et al., 2017b;Wang et al., 2018b), and social economic impact (Chen and Jin, 2019;Yang and Zhang, 2018) studies in China. Second, a recent study has shown that the historical hindcast ability of the annual model decreased when hindcast year was long before the model year (Xiao et al., 2018). Therefore, we did not use the models of 2014 to 2017 to estimate the hindcast $PM_{2.5}$.

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.

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/, accessed on Mar 29, 2019). Meteorological data were extracted from Goddard Earth Observing System Data Assimilation System GEOS-5 Forward Processing (GEOS 5-FP) meteorological data (ftp://rain.ucis.dal.ca, accessed on Mar 29, 2019). MODIS fire spots were from the NASA Fire Information for Resource Management System (https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms, accessed on Mar 29, 2019). 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, accessed on Mar 29, 2019).

Previous studies have shown the data quality issue of ground $PM_{2.5}$ measurements from CEMC network (Liu et al., 2016b;Rohde and Muller, 2015). We performed the data screening procedure before model fitting. Abnormal values (extreme high or extreme low values for a site compared with its neighboring sites, repeated values for continuous hours, etc.) were deleted before model fitting. We required at least 20 hourly records to calculate the daily average $PM_{2.5}$ concentrations. DT and DB AOD were combined using inverse variance weighting method to improve the spatial coverage of AOD data (Ma et al., 2016). This combined AOD data has been shown good consistency (R^2=0.8, mean bias=0.07) with ground AOD measurements from Aerosol Robotic Network (AERONET) (Ma et al., 2016). All data were assigned to a predefined 0.1° grid. Then all of the variables were matched by grid cell and day-of-year (DOY) 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 model structure of first-stage model was shown as follows:

$$PM_{2.5,st} = (\mu + \mu') + (\beta_1 + \beta_1')AOD_{st} + (\beta_2 + \beta_2')WS_{st} + (\beta_3 + \beta_3')PBLH_{st} + (\beta_4 + \beta_4')PS_{st} + (\beta_5 + \beta_5')RH\_PBLH_{st} + \beta_6 Precip\_Lag1_{st} + \beta_7 Fire\_spots_{st} + \varepsilon_{1,st}(\mu'\beta_1') \sim \mathrm{N}[(0,0), \Psi_1] + \varepsilon_{2,sj}(\beta_2'\beta_3'\beta_4'\beta_5') \sim \mathrm{N}[(0,0,0,0), \Psi_2] \tag{1}$$

where $PM_{2.5,st}$ is ground $PM_{2.5}$ measurements at grid cell s on DOY t; AOD_{st} is DT-DB merged AOD; WS_{st}, $PBLH_{st}$, PS_{st}, RH_PBLH_{st}, $Precip\_Lag1_{st}$ are meteorological variables; $Fire\_spots_{st}$ is the fire count; μ and μ' are the fixed and day-specific random intercepts, respectively; β_1-β_7 are fixed slopes; β_1' is the day-specific random slope for AOD; β_2'-β_5' are the season-specific random slopes for meteorological variables; $\varepsilon_{1,st}$ is the error term at grid cell s on DOY t; $\varepsilon_{2,sj}$ is the error term at grid cell s in season j; Ψ_1 and Ψ_2 are the variance-covariance matrices for the day- and season-specific random effects, respectively. The first-stage model was fitted for each province separately. We created a buffer zone for each province to include data with at least 3,000 data records and at least 300 days. We averaged overlapped predictions from neighboring provinces to generate a smooth national $PM_{2.5}$ concentration surface.

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.

$$PM_{2.5}\_resid_{st} = \mu_0 + s(X, Y)_s + s(ForestCover)_s + s(UrbanCover)_s + \varepsilon_{st} \tag{2}$$

where $PM_{2.5}\_resid_{st}$ is the residual of first-stage model at grid cell s on DOY t; μ_0 is the intercept; $s(X, Y)_s$ is the smooth term of the coordinates of the centroid of grid cell s; $s(ForestCover)_s$ and $s(UrbanCover)_s$ are the smooth functions of forest cover and urban area for grid cell s; and ε_{st} is the error term.

10-fold cross validation (CV) was used to evaluate the model over-fitting, that is, the model could have better prediction performance in the model fitting dataset than the data which are not included model fitting. In 10-fold CV, all samples in the model dataset are randomly and equally divided into ten subsets. One subset was used as testing samples and the rest subsets are used to fit the model. This process was repeated for 10 rounds until each subset was used for testing for once. 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 CV to assess model performance and over-fitting.

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):

$$(\mathrm{PM}_{2.5})_{anomaly,\,s,\,m} = (\mathrm{PM}_{2.5})_{s,\,m} - \overline{(\mathrm{PM}_{2.5})_{s,\,j}} \qquad m = 1, 2, 3, \ldots, M \qquad j = 1, 2, 3, \ldots, 12 \tag{3}$$

$$(\mathrm{PM}_{2.5})_{anomaly,\,s,\,m} = \mu + \beta \times m + \varepsilon, \qquad m = 1, 2, 3, \ldots, M \tag{4}$$

where $(\mathrm{PM}_{2.5})_{anomaly,\,s,\,m}$ is the $PM_{2.5}$ anomaly at grid cell *s* for month *m* during the calculating period; $(\mathrm{PM}_{2.5})_{s,\,m}$ is the estimated $PM_{2.5}$ concentration at grid cell *s* for month *m*; *m* is the month index and *M* is the total number of months during the calculating period (2004-2017, *M*=168); $\overline{(\mathrm{PM}_{2.5})_{s,\,j}}$ is the 14-year average $PM_{2.5}$ concentration of the month to which month *m* belongs (*j* = 1 for January, *j* = 2 for February, ···, etc.); μ is the intercept; β is the slope, which is also the trend of $PM_{2.5}$ (μg/m^3/month); ε is the error term. The annual $PM_{2.5}$ trend (μg/m^3/year) = 12×β. The method of *t* test was used to obtain the statistical significance of the trends. This method has been successfully applied to trend analyses of monthly mean $PM_{2.5}$ and AOD anomaly time-series data (Hsu et al., 2012;Boys et al., 2014;Zhang and Reid, 2010;Xue et al., 2019).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.

The fixed effects, model fitting, and CV results of the first-stage LME model for each province are shown in Tables S2-S5 (SM). AOD is the only variable that was statistically significant in all provincial models for all years ($p < 0.05$). Wind speed, relative humidity, precipitation, and fire spots were significant in most provincial models. The CV R^2 varies for different province and different year. The CV R^2 values range from 0.61 in Xinjiang to 0.77 in Heilongjiang for 2014, from 0.34 in Xinjiang to 0.76 in Hebei for 2015, from 0.44 in Tibet to 0.77 in Jiangsu for 2016, and from 0.38 in Xinjiang to 0.79 in Sichuang for 2017. We also fitted a first-stage LME model for entire China. Results show that the overall CV R^2 values for first-stage LME model dropped to 0.57, 0.52, 0.56, and 0.54, for 2014, 2015, 2016, and 2017, respectively. Therefore, fitting the first-stage model for each province separately can greatly improve the prediction accuracy.

A potential source of uncertainties of statistical models is the uneven spatial distribution of ground $PM_{2.5}$ monitors. The CEMC air quality network mainly covers large urban centers with very limited sites coverage in rural areas, especially in western part of the country. Since it requires large amount ground-measured $PM_{2.5}$ data to develop satellite-based statistical model, this bias cannot be avoided. Despite this limitation, high model performances have been achieved in this study and previous similar studies (Zheng et al., 2016;Huang et al., 2018;Xue et al., 2019), which are much better than the scaling method. For example, Geng et al. (2015) estimated long-term $PM_{2.5}$ concentrations in China using scaling method and found the validation R^2 of $PM_{2.5}$ predictions was 0.72 compared to the five-month averaged ground $PM_{2.5}$ concentrations for Jan-May, 2013. A global study of $PM_{2.5}$ estimates combing scaling and statistical methods shows that their validation R^2 of long-term average $PM_{2.5}$ was 0.67 for their first-stage scaling method (van Donkelaar et al., 2016).

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

Figure 4 shows that 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 ($p<0.05$). Figure 6 and Table 2 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 7).

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 7(a)) but the trends were insignificant (Figure 7(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 7(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 2). The trends of YRD and PRD Regions are insignificant. During the 10th YFP period, China missed the emission control goals. The emission of sulfur dioxide increased by ~28% (Xue et al., 2014;Schreifels et al., 2012). The 11th FYP for National Economic and Social Development of China released in 2006 proposed the ECER goals. However, China did not achieve the annual goal in 2006. These could explain the increasing trend of $PM_{2.5}$ during 2004-2007.

After that, China released the Comprehensive Working Plan on ECER (http://www.gov.cn/zwgk/2007-06/03/content_634545.htm, accessed on Mar 29, 2019) in 2007 to strengthen the ECER measures. Major control measures included (Schreifels et al., 2012): implementing flue gas desulphurization for coal-fired power plant, closing inefficient and backward production capacity, implementing energy conservation projects, increasing pollution levy for SO_2 emission, recommending baghouse dust filter for industrial soot and dust emission control etc. As a result, great achievements had been made at the end of 11th FYP (Schreifels et al., 2012;Zhou et al., 2015): total emission of SO_2 decreased by ~14% compared to the level of 1995; approximate 86% of the power plant were installed with desulphurization facilities in 2010 compared to 14% in 2005; nearly 80 GW of small coal-fired power units were closed during 2006-2010; soot emission of coal-fired power plants in 2010 was reduced by 55.6% compared with that in 2005, etc.

Due to these control measures, the increasing trend of $PM_{2.5}$ pollution was suppressed after 2007. $PM_{2.5}$ concentrations of Central and South China decreased significantly, with highest trend of around -9 μg/m^3/year (Figure 7(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 7(f), $p>0.05$). Table 2 shows that the overall $PM_{2.5}$ trend for entire China was -0.56 μg/m^3/year with marginal significance ($p=0.053$). Overall trends of 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, $p<0.001$). Results show that although air pollution control policies of 11th FYP were not designed for $PM_{2.5}$ prevention and control, they still had co-benefits on $PM_{2.5}$ pollution control. There were two main reasons. First, SO_2 is the precursor gas of sulfate. Previous studies have shown that sulfate was the major component of $PM_{2.5}$ during 11th FYP period(Li et al., 2009;Li et al., 2010;Pathak et al., 2009). The reduction of SO_2 could therefore contribute to the suppression of increasing $PM_{2.5}$ pollution. Second, the control of industrial dust and soot, which include a portion of primary $PM_{2.5}$ (Yao et al., 2009), also contributed to the $PM_{2.5}$ pollution reduction.

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

Figure 8(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 2), the decreasing trend mainly happened in Xinjiang and Central Inner Mongolia. The deserts in Xinjiang and Inner Mongolia are the major sources of dust pollution in China. A recent study showed that dust is the largest contributor to $PM_{2.5}$ over this region (Philip et al., 2014). The change in natural dust in desert areas may be the major contributor to the decreasing trend of $PM_{2.5}$ during 2010-2013. Most of the polluted area in China did not had obvious change (Figure 8(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 limitation for $PM_{2.5}$ reductions. $PM_{2.5}$ is a kind of composite pollutant and its constituents includes primary particles and secondary particles such as sulfate, nitrate, ammonium, organic carbon, elemental carbon, etc. With the deepening of SO_2 and industrial dust/soot emission reduction, their contributions to $PM_{2.5}$ pollution control would reduce. Although 12th FYP on Environmental Protection also proposed 10% reduction of NO_x from 2010 to 2015. However, along with economic growth in China, the benefits of emission control for single-pollutant could be offset by increased energy usage. Considering the complicated $PM_{2.5}$ compositions, comprehensive and coordinated control measures for multiple pollutants were urgently needed.

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. APPC-KR proposed a series of key projects which included 477 SO_2 treatment projects, 755 NO_x treatment projects, 10 073 industrial soot and dust treatment projects, 1 311 VOCs treatment projects in key industrial sectors, 281 vapor recovery projects for oil and gas. 188 yellow-sticker vehicle elimination projects, 192 fugitive dust comprehensive treatment projects, and 122 capacity building projects. An English translation version of APPC-KR and its key projects has been prepared by Clean Air Alliance of China (CAAC) and can be found elsewhere (http://www.cleanairchina.org/product/6347.html, accessed on Mar 29, 2019) (CAAC, 2013a, b).

In addition, in 2012, China issued a new air quality standard, i.e., the *National Ambient Air Quality Standard of China* (NAAQS) (GB 3095-2012). Compared with the former NAAQS (GB 3095-1996) issued in 1996, this new standard incorporated $PM_{2.5}$ as a major control pollutant. According to GB 3095-2012, the Level 1 annual mean standard of $PM_{2.5}$ is 15 $\mu g/m^3$, which is assigned for protecting the air quality of natural reserves and scenic areas and is equivalent to the World Health Organization (WHO) Air Quality Interim Target-3 (IT-3) Level. The Level 2 standard of 35 $\mu g/m^3$ is designated for residential, cultural, industrial, and commercial areas, which is equivalent to WHO Air Quality Interim Target-1 (IT-1) Level. Meanwhile, a comprehensive real-time air quality monitoring network covering 74 major Chinese cities was established in late 2012.

The implementation of APPC-KR, together with the implementation of APPC-AP starting from 2013 (shown in the following section), had led to dramatic drops in $PM_{2.5}$ concentrations in China after 2013. Table 3 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 air pollution control measures included ten categories:

- Increase effort for comprehensive pollution control, reduce emissions of multi-pollutants;
- Optimize industrial structure, promote industrial restructuring;

- Accelerate technology transformation, improve innovation capability;
- Adjust energy structure, increase clean energy supply;
- Strengthen environmental thresholds, optimize industrial layout;
- Promote the role of market mechanism, improve environmental economic policies;
- Improve law and regulation system, carry on supervision and management based on law;
- Establish regional coordination mechanism and integrated regional environmental management;
- Establish monitoring and warning system, cope with heavy pollution episodes;
- Clarify responsibilities of government, enterprise and society, mobilize public participation

Detailed measures in the APPC-AP can be found in its English translation version (http://www.cleanairchina.org/product/6349.html, accessed on Mar 29, 2019) (CAAC, 2013c). To ensure that APPC-AP goals could be accomplished, China adopted a temporary 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, accessed on Mar 29, 2019). There had been great achievements at the end of 2017. For examples (Zheng et al., 2018): 71% of the power plants met the ultralow emission levels; average efficiency of coal fired power units reduced from 321 gce/kWh in 2013 to 309 gce/kWh in 2017; Non-methane volatile organic compounds (NMVOC) emissions were cut down by 30% through the implementation of leak detection and repair (LDAR) program for petrochemical industry; all coal boilers smaller than 7MW in urban areas were shut down; all “yellow label” vehicles (referring to which gasoline and diesel vehicles that fail to meet Euro 1 and Euro 3 standards, respectively) were eliminated by the end of 2017, etc.

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 8(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 $\mu g/m^3$/year (all $p<0.05$), respectively (Table 2). Table 4 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, accessed on Mar 29, 2019). 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 close to the goal. However, the pollution level was still higher than WHO Air Quality IT-1 level and NAAQS (GB 3095-2012) Level 2 annual $PM_{2.5}$ standard (both 35 μg/m^3).

According to the official results of APPC-AP performance assessment (Table 4), $PM_{2.5}$ 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 satellite $PM_{2.5}$, the populations weighted average results (Table 4) 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 $PM_{2.5}$ pollution. The population weighted average satellite $PM_{2.5}$ can better represent the health impact of $PM_{2.5}$ pollution. 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

Xue et al. (2019) developed a machine learning method to estimate $PM_{2.5}$ concentrations in China from 2000–2016. They reported that overall trends of $PM_{2.5}$ in China were 2.097 μg/m^3/year (p<0.001), 0.299 μg/m^3/year (p>0.05), −4.511 μg/m^3/year (p<0.001) in 2000-2007, 2008-2013, and 2013-2016, respectively. Lin et al. (2018) estimated high-revolution $PM_{2.5}$ in annual scale in China from 2001 to 2015, and found nation-scale trends of 0.04 μg/m^3/year, -0.65 μg/m^3/year, -2.33 μg/m^3/year in 2001-2005, 2005-2010, and 2011-2015, respectively. Overall, our satellite-based $PM_{2.5}$ trends are consistent with these two recent studies, except that we found no significant trend from 2005 to 2010 (0.41 μg/m^3/year but p>0.05), which is different from the study of Lin et al. (2018). The main reason could be that they did not include western China in their study area. And statistical significance levels were not reported in their study, which could not allow us to know whether the trend was significant or not.

Although there have been several studies have studied the historical trends of $PM_{2.5}$ in China, few has study the relations between the trends and air pollution control policies. This paper reviewed the air pollution control policies from 2005 to 2017. And 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 (see Table 1 and Section 4.3) had co-benefits on $PM_{2.5}$ pollution control. The overall $PM_{2.5}$ pollution had certain decrease (-0.56 μg/m^3/year for entire China, p=0.053) 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 shown its limitation. The $PM_{2.5}$ concentrations of polluted areas did not decrease from 2010 to 2013 (e.g., -0.45 μg/m^3/year for Jingjinji Region, p=0.783).

To address 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 (GB 3095-2012). All these polices (details can be found in Table 1 and Sections 4.4 and 4.5) had led to dramatic decreases of $PM_{2.5}$ after 2013 (-4.27 μg/m^3/year for entire China, p<0.001). 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.

It should be noted that inter-annual variation in meteorology has also contributed to the changes in $PM_{2.5}$. A recent study shows that meteorological conditions contributed approximately 20% of the $PM_{2.5}$ reduction in Beijing from 2013 to 2017, while the control of anthropogenic emissions contributed 80% (Chen et al., 2019). In addition, the slowdown of economic development after financial crisis in 2008 might contribute to the $PM_{2.5}$ emissions reduction. According to China Statistical Yearbook (NBS, 2018), the gross domestic products (GDP) growth rate decreased from 14.2% in 2007 to 6.9% in 2017. However, the GDP growth rates are still relatively high at current stage (6%~7%). Contrarily, the $PM_{2.5}$ concentrations have decreased dramatically. Without effective air pollution control policies, the $PM_{2.5}$ pollution level would not decrease rapidly. Therefore, effective air pollution control policy was the main reason for $PM_{2.5}$ pollution reduction after 2013. Meteorological conditions also contributed a small portion of $PM_{2.5}$ reductions.

The trends in $PM_{2.5}$ concentrations in China also showed spatial heterogeneity. Multiple reasons may explain the regional differences, e.g., the pollution levels of base year, the regional differences of industrial structures, the spatial heterogeneity of anthropogenic and natural emissions, economic and industry development differences, variations of regional policies, and variations of meteorological conditions, etc.

Currently, China has achieved great success in $PM_{2.5}$ pollution control. 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 GB 3095-2012, which is corresponding to WHO Air Quality IT-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.

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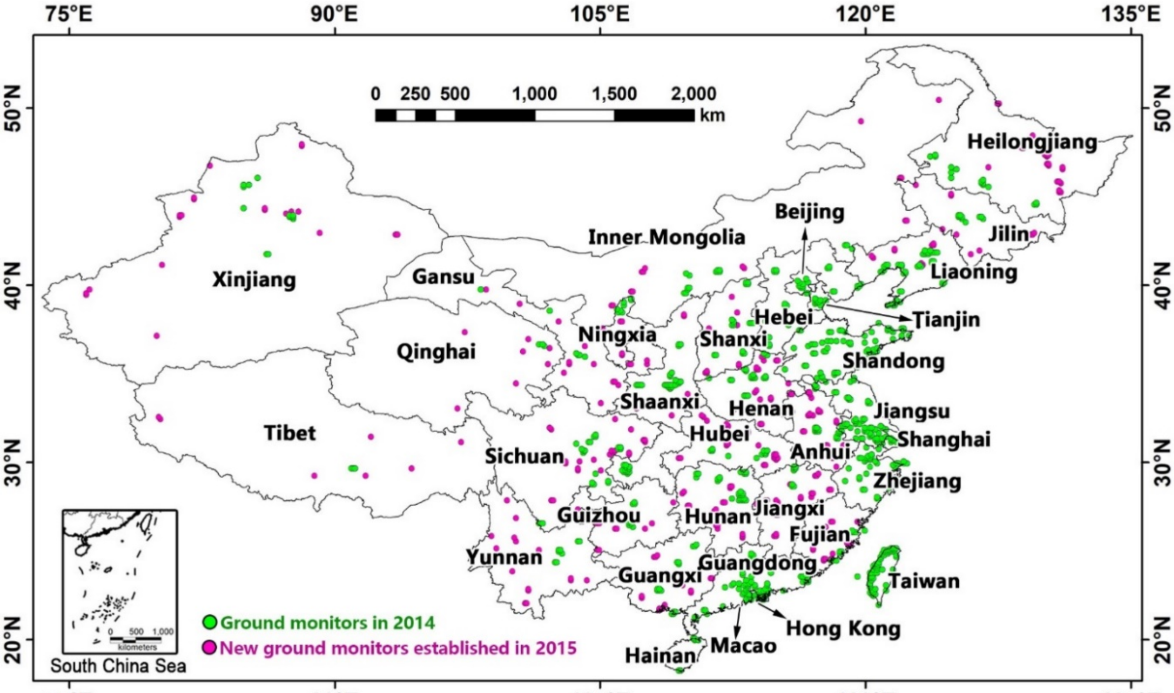

Figure 1. Spatial distributions of ground $PM_{2.5}$ monitors involved in model fitting and validation. Red circles denote the ground monitor in 2014. Pink circles denote new ground monitors established in 2015.

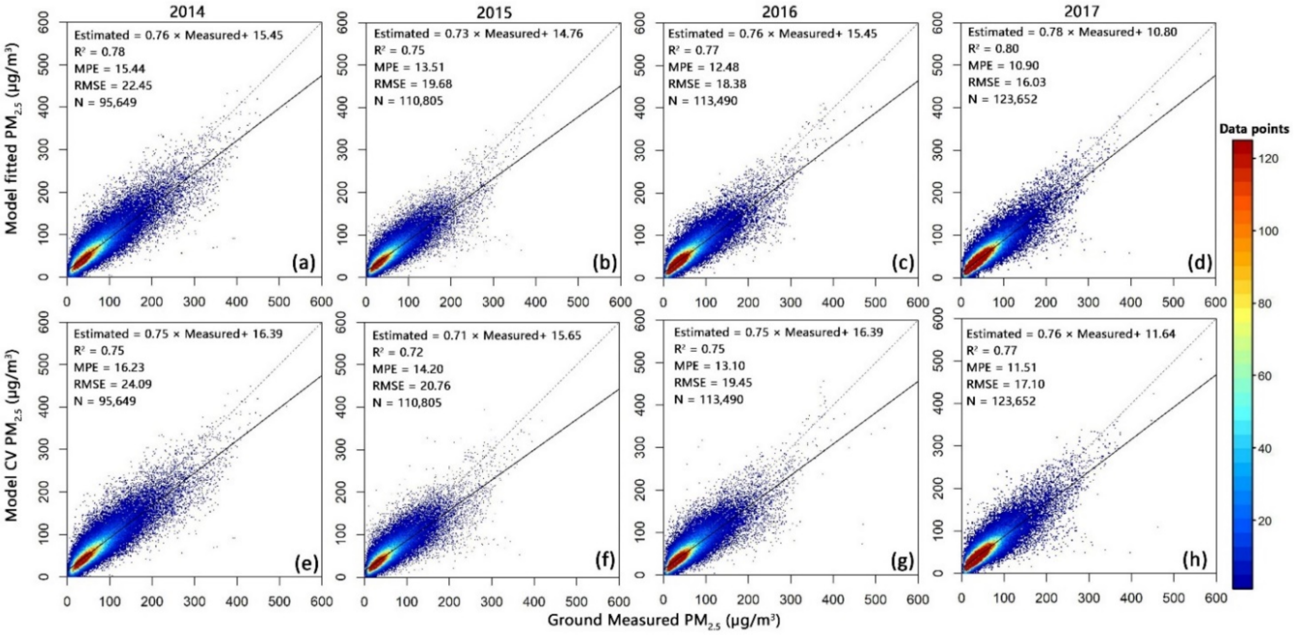

Figure 2. Model fitting (upper row) and cross validation (CV, lower row) results for satellite $PM_{2.5}$ prediction models from 2014 to 2017.

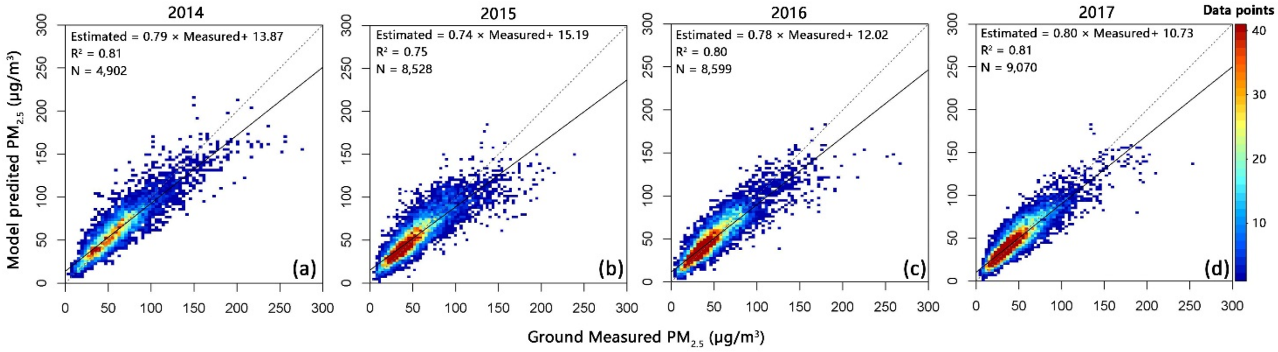

Figure 3. Validation of monthly mean $PM_{2.5}$ predictions from 2014 to 2017.

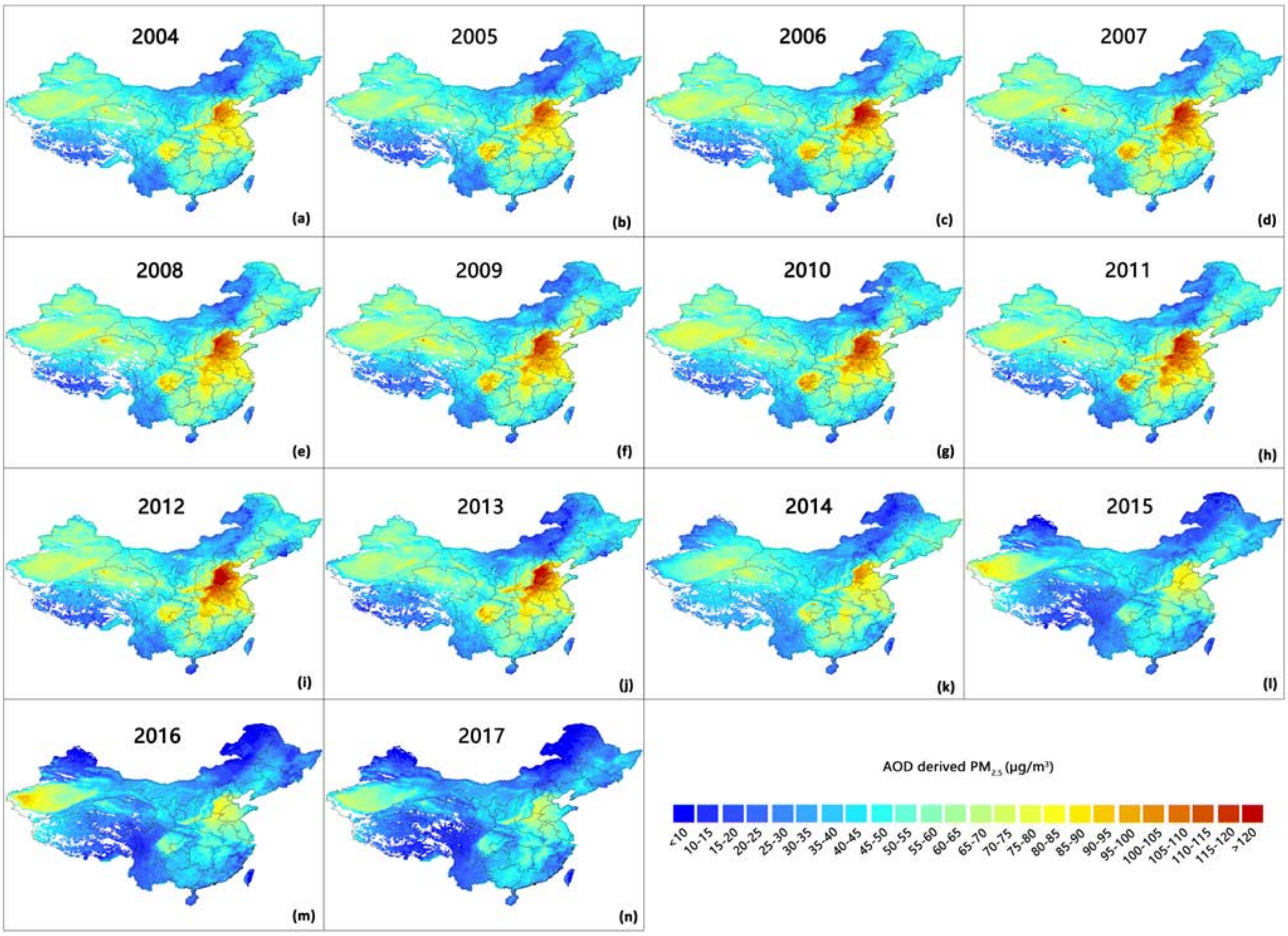

Figure 4. Spatial distributions of annual mean satellite-derived PM$_{2.5}$ concentrations from 2004 to 2017.

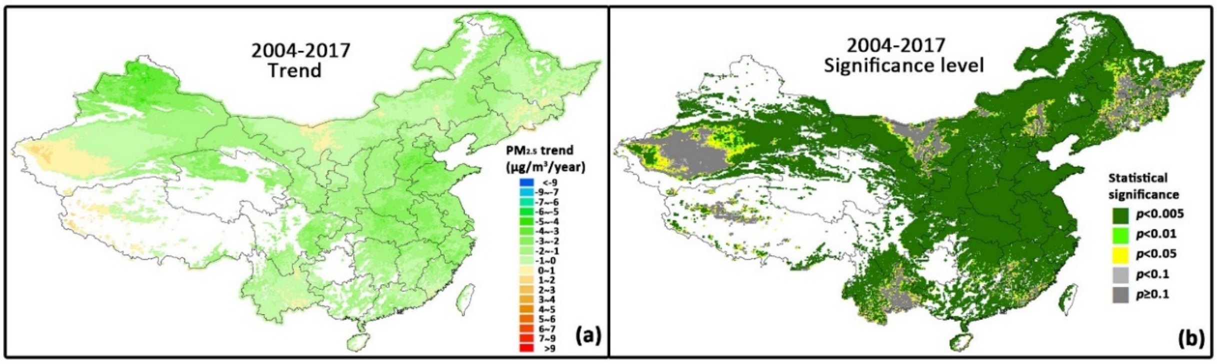

Figure 5. Spatial distributions of PM$_{2.5}$ trends and significance levels in China from 2004 to 2017.

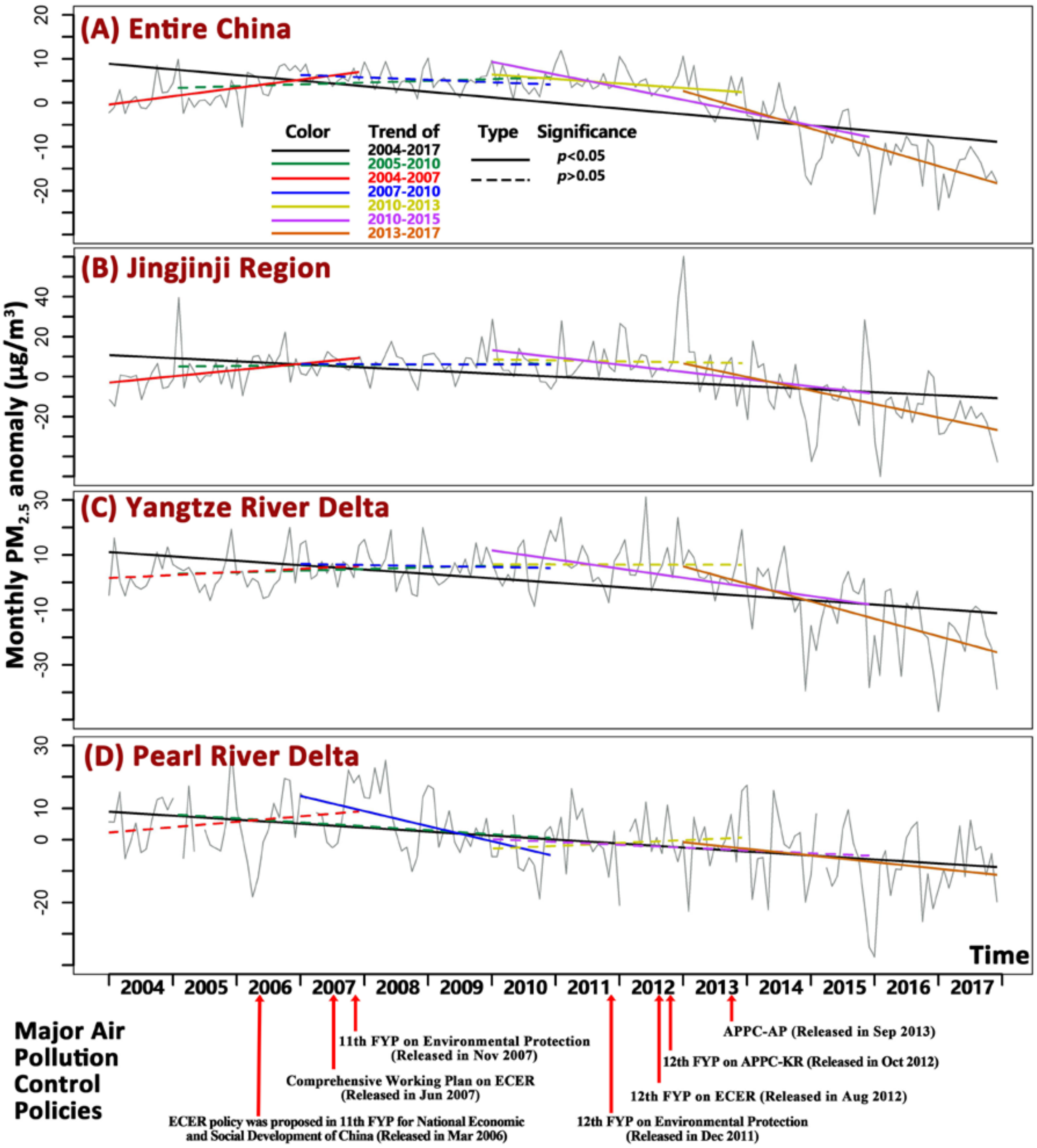

Figure 6. PM$_{2.5}$ trends of entire China, Jingjinji, Yangtze River Delta (YRD), and Pearl River Delta (PRD) Regions from 2004 to 2017, and corresponding air pollution control policies

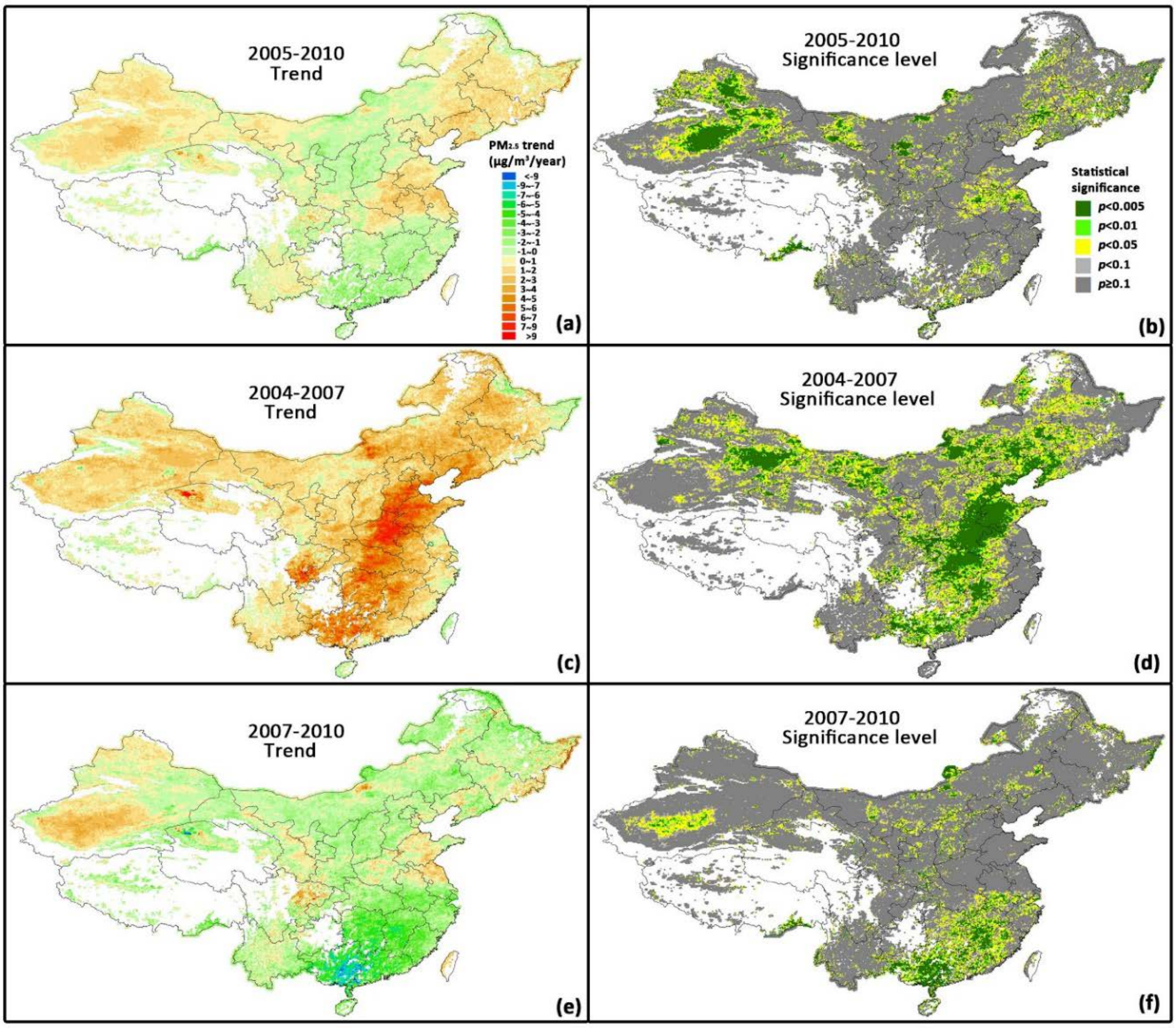

Figure 7. Spatial distributions of $PM_{2.5}$ trends and significance levels in China from 2005 to 2010.

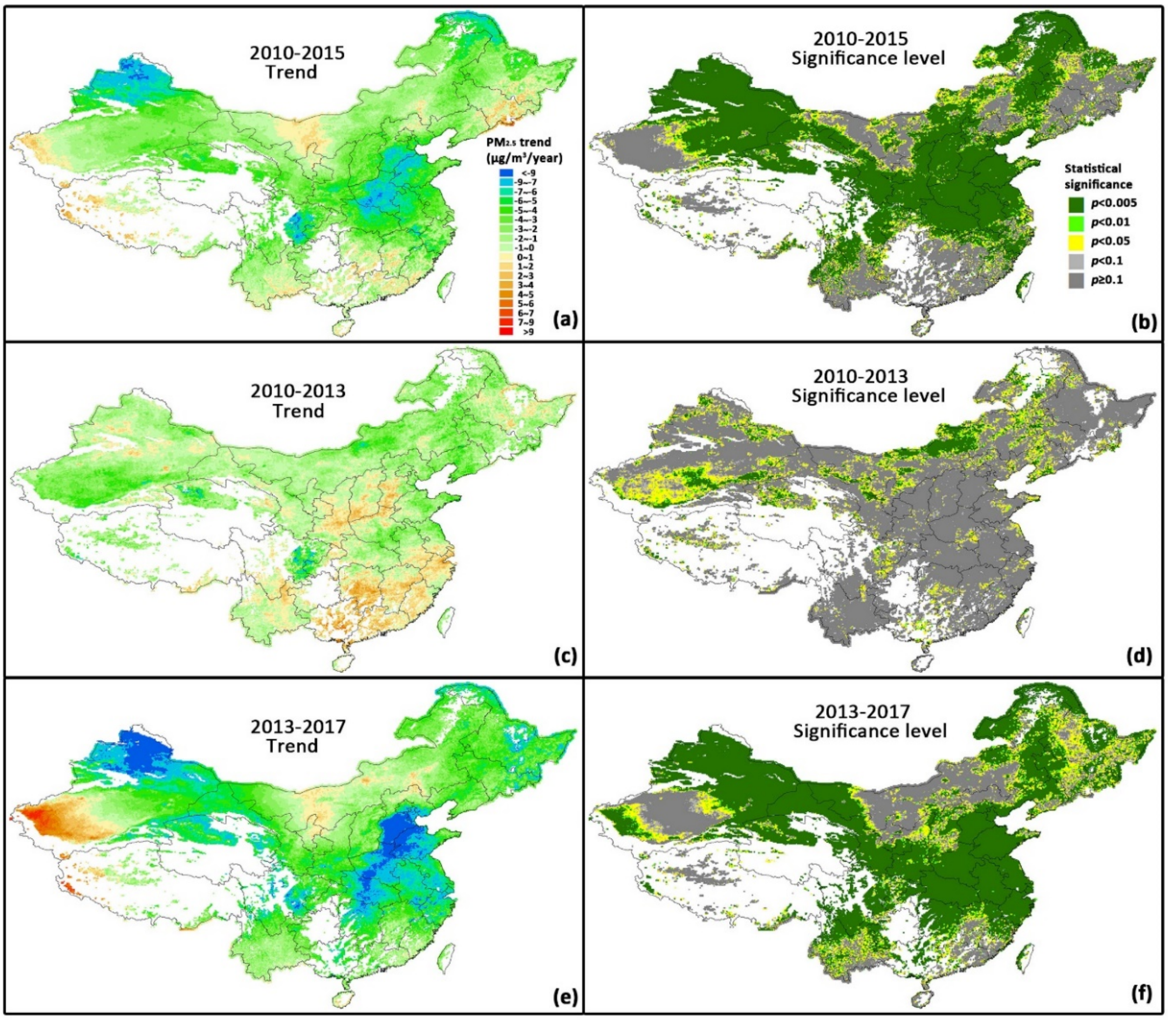

Figure 8. Spatial distributions of $PM_{2.5}$ trends and significance levels in China from 2010 to 2017.

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	2012	2013-2017	• $PM_{2.5}$ concentrations of Jingjinji, Yangtze River Delta, and Pearl River Delta regions should reduce by 25%, 20%, and 15% respectively • $PM_{2.5}$ concentrations of Beijing should be controlled at around 60 $\mu g/m^3$	• 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. Trends and 95% confidence intervals (CI) of PM$_{2.5}$ concentrations for entire China, Jingjinji, Yangtze River Delta, and Pearl River Delta Regions from 2004 to 2017

Period	Trend	Entire China	Jingjinji Region	Yangtze River Delta	Pearl River Delta
2004-2017	Trend (µg/m^3/year)	**-1.27**	**-1.55**	**-1.60**	**-1.27**
	95% CI (µg/m^3/year)	**(-1.50, -1.04)**	**(-2.06, -1.03)**	**(-2.02, -1.18)**	**(-1.66, -0.88)**
	Significance	**$p<0.001$**	**$p<0.001$**	**$p<0.001$**	**$p<0.001$**
2005-2010	Trend (µg/m^3/year)	0.41	0.26	0.61	-1.26
	95% CI (µg/m^3/year)	(-0.01, 0.82)	(-0.83, 1.36)	(-0.31, 1.54)	(-2.73, 0.21)
	Significance	$p=0.055$	$p=0.633$	$p=0.191$	$p=0.091$
2004-2007	Trend (µg/m^3/year)	**1.88**	**3.14**	1.12	1.72
	95% CI (µg/m^3/year)	**(1.12, 2.64)**	**(1.07, 5.22)**	(-0.51, 2.74)	(-0.79, 4.23)
	Significance	**$p<0.001$**	**$p<0.005$**	$p=0.174$	$p=0.174$
2007-2010	Trend (µg/m^3/year)	-0.56	-0.08	-0.37	**-4.81**
	95% CI (µg/m^3/year)	(-1.12, 0.01)	(-1.80, 1.64)	(-2.10, 1.35)	**(-7.06, -2.55)**
	Significance	$p=.053$	$p=0.927$	$p=0.664$	**$p<0.001$**
2010-2013	Trend (µg/m^3/year)	**-1.03**	-0.45	-0.04	0.89
	95% CI (µg/m^3/year)	**(-1.84, -0.21)**	(-3.73, 2.83)	(-2.16, 2.08)	(-1.34, 3.13)
	Significance	**$p<0.05$**	$p=0.783$	$p=0.970$	$p=0.425$
2010-2015	Trend (µg/m^3/year)	**-2.89**	**-3.63**	**-3.33**	-0.90
	95% CI (µg/m^3/year)	**(-3.50, -2.28)**	**(-5.59, -1.68)**	**(-4.76, -1.89)**	(-2.34, 0.54)
	Significance	**$p<0.001$**	**$p<0.001$**	**$p<0.001$**	$p=0.219$
2013-2017	Trend (µg/m^3/year)	**-4.27**	**-6.77**	**-6.36**	**-2.11**
	95% CI (µg/m^3/year)	**(-5.20, -3.34)**	**(-9.46, -4.07)**	**(-8.38, -4.34)**	**(-4.14, -0.09)**
	Significance	**$p<0.001$**	**$p<0.001$**	**$p<0.001$**	**$p<0.05$**

Table 3. 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 ($\mu g/m^3$)	2015 ($\mu g/m^3$)	Decreased by	2010 ($\mu g/m^3$)	2015 ($\mu g/m^3$)	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%

Table 4. 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 ($\mu g/m^3$)	2017 ($\mu g/m^3$)	Decreased by	2013 ($\mu g/m^3$)	2017 ($\mu g/m^3$)	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 $\mu g/m^3$	58 $\mu g/m^3$	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, accessed on Mar 29, 2019

Supplemental Material

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

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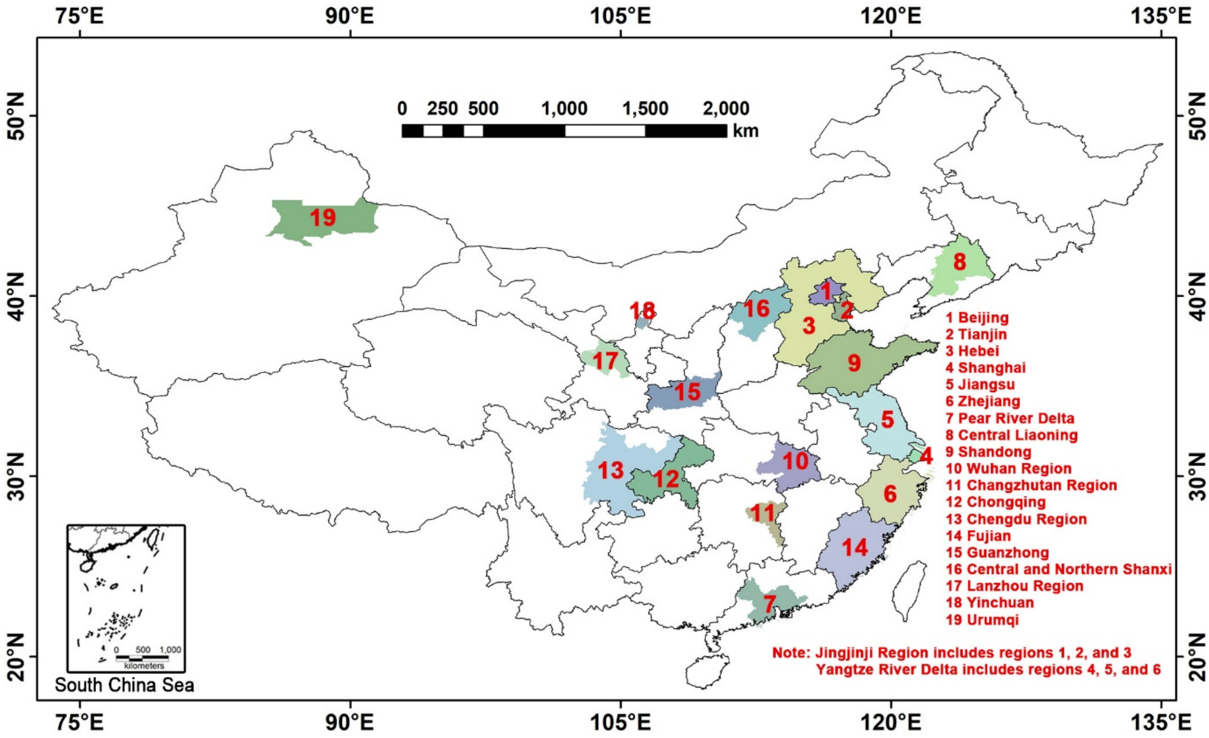

Figure S1. Key regions in 12th Five Year Plan on Air Pollution Prevention and Control in Key Regions

Table S1 Summary statistics of variables for the modeling dataset from 2014 to 2017

Year	Variables [a]	Min	Max	Median	Mean	S.D.
2014 (N=95,649)	$PM_{2.5}$ (μg/m^3)	0.50	517.00	53.45	65.66	47.84
	AOD (unitless)	-0.01	4.51	0.50	0.67	0.61
	WS (m/s)	0.02	18.72	3.82	4.25	2.35
	PBLH (100m)	0.61	52.93	16.22	17.07	5.86
	PS (hPa)	589.22	1037.16	1001.92	980.71	55.83
	RH_PBLH (%)	7.93	96.46	49.05	49.93	18.22
	Precip_Lag1 (mm)	0.00	200.72	0.01	1.29	5.69
	Fire_spots (counts)	0.00	462.00	0.00	2.97	10.64
	ForestCover (%)	0.00	92.52	3.75	13.10	18.74
	UrbanCover (%)	0.00	100.00	22.17	27.48	22.68
2015 (N=110,805)	$PM_{2.5}$ (μg/m^3)	0.50	417.99	43.64	54.02	39.32
	AOD (unitless)	-0.05	4.16	0.44	0.58	0.54
	WS (m/s)	0.03	18.45	3.53	3.97	2.28
	PBLH (100m)	0.63	49.78	15.26	16.05	6.30
	PS (hPa)	558.24	1038.16	996.03	964.45	72.78
	RH_PBLH (%)	5.30	98.81	51.37	51.75	17.74
	Precip_Lag1 (mm)	0.00	283.99	0.02	1.71	6.83
	Fire_spots (counts)	0.00	688.00	0.00	2.58	11.29
	ForestCover (%)	0.00	97.60	4.55	14.23	19.61
	UrbanCover (%)	0.00	100.00	19.19	24.23	21.10
2016 (N=113,490)	$PM_{2.5}$ (μg/m^3)	1.00	520.61	40.00	50.65	38.55
	AOD (unitless)	-0.03	4.25	0.40	0.53	0.48
	WS (m/s)	0.04	15.25	3.43	3.81	2.11
	PBLH (100m)	0.71	52.44	14.13	15.04	6.45
	PS (hPa)	558.16	1042.00	995.34	964.64	72.06
	RH_PBLH (%)	4.86	96.48	52.39	52.56	17.13
	Precip_Lag1 (mm)	0.00	277.79	0.02	2.15	8.69
	Fire_spots (counts)	0.00	330.00	0.00	2.08	7.06
	ForestCover (%)	0.00	97.60	4.58	14.37	19.72
	UrbanCover (%)	0.00	100.00	19.20	24.36	21.24
2017 (N=123,652)	$PM_{2.5}$ (μg/m^3)	2.00	632.00	39.25	48.32	35.68
	AOD (unitless)	-0.03	3.99	0.38	0.50	0.46
	WS (m/s)	0.03	18.22	3.57	3.94	2.18
	PBLH (100m)	0.71	51.45	14.69	15.68	6.85
	PS (hPa)	555.44	1038.19	997.61	968.18	69.90
	RH_PBLH (%)	7.06	97.09	48.70	49.54	16.64
	Precip_Lag1 (mm)	0.00	240.04	0.00	1.48	6.68
	Fire_spots (counts)	0.00	288.00	0.00	2.32	8.98
	ForestCover (%)	0.00	97.60	4.58	14.45	19.81
	UrbanCover (%)	0.00	100.00	19.45	24.66	21.32

[a] Abbreviations used for the meteorological variables: WS: wind speed at 10 m above ground; PBLH: planetary boundary layer height; PS: surface pressure; RH_PBLH: mean relative humidity in planetary boundary layer; Precip_Lag1: cumulative precipitation of the previous day.

Table S2 Fixed effect, model fitting and CV results of the first-stage LME model for each province for 2014 model

Province	N	Intercept [a]	Slope [a]							Fitting R^2	CV R^2
			AOD	WS [f]	PBLH	PS	RH_PBLH	Precip_Lag1	Fire_spots		
Anhui	13373	65.11	28.33				-57.44		0.15	0.71	0.69
Chongqing	6965	72.09	30.10			0.06		-0.13		0.80	0.76
Fujian [b]	7483	41.06	14.43	-1.52		0.09	-24.98		1.17	0.69	0.66
Gansu	5873	59.91	39.87	-1.39	-0.33	-0.07	-9.55		0.38	0.80	0.76
Guangdong [c]	7612	50.59	20.81	-1.13			-28.76		0.62	0.76	0.73
Guangxi	3227	51.84	25.49	-2.77			-19.51	-0.19	0.63	0.74	0.68
Guizhou	3490	67.78	29.12			0.12			0.09	0.81	0.73
Hebei [d]	13477	69.55	48.36	-2.41	-1.11	0.20	-73.09	-0.27	0.17	0.79	0.77
Heilongjiang	5604	53.86	46.13	-2.03					0.25	0.81	0.77
Henan	6676	73.15	30.26				-39.01		0.16	0.74	0.69
Hubei	8263	72.34	38.37				-58.79	-0.23		0.76	0.72
Hunan	6829	77.31	32.53				-64.27	-0.26		0.76	0.72
Inner Mongolia	28179	67.48	50.19	-3.17	-0.63	0.02	-53.29		0.36	0.69	0.67
Jiangsu [e]	13190	118.58	27.79	-2.22		-1.40	-44.89		0.15	0.75	0.72
Jiangxi	7108	56.69	31.44			0.37	-45.50	-0.21	0.24	0.73	0.68
Jilin	7190	56.37	43.94	-1.84			-42.23	-0.26	0.28	0.77	0.74
Liaoning	19667	58.75	36.14	-2.32			-59.05	-0.18	0.43	0.71	0.69
Ningxia	11263	60.50	40.06	-1.73		-0.05	-8.33		0.18	0.70	0.66
Qinghai	8465	66.60	36.28		-0.66		-18.73	-0.22	0.32	0.71	0.63
Shaanxi	5929	75.53	25.71			0.17			0.30	0.81	0.76
Shandong	14021	75.53	29.44	-2.39		-0.23	-48.91		0.16	0.74	0.72
Shanxi	13274	76.15	35.35			0.20	-22.82		0.14	0.73	0.70
Sichuang	12455	64.61	32.88		-0.56		-25.26	-0.20		0.71	0.68
Tibet	2976	67.43	35.61	-2.64	-0.97		-64.88	-0.31		0.81	0.73
Xinjiang	12807	60.79	43.02	-1.12	-0.39	-0.03	-18.96	-0.25		0.66	0.61
Yunnan	21163	58.04	34.61	-1.71		-0.03	-45.61	-0.15	0.20	0.67	0.64
Zhejiang	11901	62.03	31.99				-48.97		0.29	0.77	0.74

[a] Only statistically significant (p<0.05) intercepts and slopes are shown. [b] Including Taiwan. [c] Including Hong Kong, Macao, and Hainan. [d] Including Beijing and Tianjin. [e] Including Shanghai. [f] Abbreviations used for the meteorological variables: WS: wind speed at 10 m above ground; PBLH: planetary boundary layer height; PS: surface pressure; RH_PBLH: mean relative humidity in planetary boundary layer; Precip_Lag1: cumulative precipitation of the previous day.

Table S3 Fixed effect, model fitting and CV results of the first-stage LME model for each province for 2015 model

Province	N	Intercept [a]	Slope [a]							Fitting R^2	CV R^2
			AOD	WS [f]	PBLH	PS	RH_PBLH	Precip_Lag1	Fire_spots		
Anhui	13635	47.62	24.29			0.23	-45.81	-0.10	0.07	0.69	0.66
Chongqing	7024	55.05	19.47	-1.01		0.13	-8.95	-0.19	0.24	0.75	0.70
Fujian [b]	7719	34.16	10.07	-1.50	-0.27	0.04	-25.53	-0.08	0.53	0.70	0.65
Gansu	32540	59.03	32.04			0.06	-20.57	-0.27	0.05	0.62	0.60
Guangdong [c]	5853	36.64	12.24	-0.80	-0.93				0.29	0.77	0.73
Guangxi	3992	43.76	14.64	-1.92	-0.87			-0.07	0.15	0.72	0.65
Guizhou	12853	51.40	16.15	-1.49		0.09	-10.60	-0.20		0.72	0.69
Hebei [d]	9771	54.44	40.71	-2.26		0.16	-37.12			0.79	0.76
Heilongjiang	8641	41.10	28.66				-25.68		0.16	0.73	0.69
Henan	9895	61.21	29.23			0.08	-52.16	-0.21	0.08	0.69	0.65
Hubei	12826	54.70	25.27			0.14	-21.69	-0.18		0.70	0.67
Hunan	9419	55.28	22.17	-1.12		0.07	-32.24	-0.15		0.71	0.67
Inner Mongolia	31502	56.35	40.51	-1.59			-28.54	-0.10	0.21	0.62	0.60
Jiangsu [e]	12027	86.43	24.78			-0.53	-52.36		0.09	0.75	0.73
Jiangxi	17732	42.81	22.67	-2.16		0.21	-41.73	-0.07		0.66	0.63
Jilin	3755	45.83	30.60						0.19	0.79	0.71
Liaoning	9400	48.82	18.21				-17.36		0.30	0.76	0.73
Ningxia	4241	56.86	30.46							0.64	0.56
Qinghai	15971	54.07	27.86		-0.47		-9.16	-0.29		0.57	0.52
Shaanxi	5315	50.59	25.05					-0.15		0.77	0.72
Shandong	10429	75.81	31.05	-2.01		-0.33	-50.63		0.25	0.77	0.74
Shanxi	11357	62.95	29.52			0.16	-32.53	-0.19		0.74	0.71
Sichuang	8914	54.04	24.73	-1.03	-0.50	0.05	-16.26	-0.25		0.66	0.61
Tibet	7799	66.10	43.62			0.05	-60.75	-0.43		0.53	0.43
Xinjiang	7190	60.29	64.37				-34.22	-0.52		0.44	0.34
Yunnan	10510	48.94	16.79	-1.63		0.07	-11.22	-0.26	0.14	0.70	0.65
Zhejiang	10584	39.99	23.17	-1.30		0.32	-31.92	-0.07	0.00	0.78	0.75

[a] Only statistically significant ($p<0.05$) intercepts and slopes are shown. [b] Including Taiwan. [c] Including Hong Kong, Macao, and Hainan. [d] Including Beijing and Tianjin. [e] Including Shanghai. [f] Abbreviations used for the meteorological variables: WS: wind speed at 10 m above ground; PBLH: planetary boundary layer height; PS: surface pressure; RH_PBLH: mean relative humidity in planetary boundary layer; Precip_Lag1: cumulative precipitation of the previous day.

Table S4 Fixed effect, model fitting and CV results of the first-stage LME model for each province for 2016 model

Province	N	Intercept [a]	Slope [a]							Fitting R^2	CV R^2
			AOD	WS [f]	PBLH	PS	RH_PBLH	Precip_Lag1	Fire_spots		
Anhui	14914	44.80	24.24			0.16	-42.67	-0.10		0.76	0.73
Chongqing	9190	54.67	25.94			0.10	-39.43	-0.04	0.11	0.74	0.70
Fujian [b]	7168	31.80	10.22	-1.72		0.11	-31.00	-0.03	0.40	0.66	0.61
Gansu	9467	54.31	38.43	-1.14			-26.24	-0.18		0.74	0.70
Guangdong [c]	8286	39.28	15.12	-1.37				-0.07	0.40	0.65	0.61
Guangxi	4083	41.75	15.11	-1.64		0.05	-18.97			0.73	0.67
Guizhou	14281	48.26	20.43	-1.73		0.08	-15.63	-0.08	0.20	0.69	0.66
Hebei [d]	10642	50.53	43.07	-1.72	-0.78	0.11	-36.68	-0.13		0.79	0.77
Heilongjiang	9647	34.59	22.03			0.21	-26.11		0.09	0.70	0.65
Henan	11188	54.77	31.47			-0.03	-57.98		0.12	0.79	0.76
Hubei	15131	54.38	29.60	-0.99			-36.59	-0.10	0.12	0.73	0.71
Hunan	13082	47.55	21.75	-0.83		0.05	-18.74	-0.11	0.15	0.70	0.66
Inner Mongolia	33307	50.79	41.73	-1.79			-33.24	-0.12	0.10	0.63	0.61
Jiangsu [e]	13355	74.35	24.50			-0.42	-53.70	-0.06		0.79	0.77
Jiangxi	15457	39.13	20.02	-0.91		0.21	-23.39	-0.09	0.32	0.68	0.66
Jilin	8300	34.74	21.92		-0.51	0.22			0.08	0.74	0.69
Liaoning	19799	44.26	31.22	-2.06			-35.91		0.15	0.69	0.67
Ningxia	12035	53.18	42.44	-1.27			-31.71	-0.12		0.71	0.68
Qinghai	2993	56.11	32.53	-1.94						0.61	0.45
Shaanxi	8809	56.45	35.21			0.11	-25.20	-0.12		0.77	0.72
Shandong	11375	68.09	27.67	-2.47		-0.31			0.23	0.78	0.76
Shanxi	16385	57.44	36.74	-1.89	-0.44	0.09	-23.85	-0.09		0.75	0.73
Sichuang	4920	51.91	15.04			0.10		-0.05		0.77	0.73
Tibet	15310	59.53	40.02			0.06	-53.59	-0.07		0.52	0.44
Xinjiang	7087	53.79	59.94				-46.31	-0.37		0.59	0.45
Yunnan	11281	46.89	19.54	-1.63		0.07	-20.59	-0.07	0.16	0.67	0.63
Zhejiang	14726	31.11	19.40	-2.02		0.37	-27.66	-0.04	0.18	0.75	0.73

[a] Only statistically significant (*p*<0.05) intercepts and slopes are shown. [b] Including Taiwan. [c] Including Hong Kong, Macao, and Hainan. [d] Including Beijing and Tianjin. [e] Including Shanghai. [f] Abbreviations used for the meteorological variables: WS: wind speed at 10 m above ground; PBLH: planetary boundary layer height; PS: surface pressure; RH_PBLH: mean relative humidity in planetary boundary layer; Precip_Lag1: cumulative precipitation of the previous day.

Table S5 Fixed effect, model fitting and CV results of the first-stage LME model for each province for 2017 model

Province	N	Intercept [a]	Slope [a]							Fitting R^2	CV R^2
			AOD	WS [f]	PBLH	PS	RH_PBLH	Precip_Lag1	Fire_spots		
Anhui	10643	33.34	24.43			0.43	-28.16			0.78	0.76
Chongqing	2954	40.28	12.39				14.44			0.85	0.77
Fujian [b]	8428	33.50	8.66	-1.50		0.10	-35.31	-0.12		0.65	0.61
Gansu	9362	52.93	43.23				-17.89	-0.39		0.79	0.76
Guangdong [c]	8309	37.25	15.70	-1.46				-0.07	0.36	0.71	0.67
Guangxi	4518	39.88	20.87	-2.43		0.04			0.64	0.77	0.69
Guizhou	9340	43.05	15.72	-1.53		0.05		-0.11	0.25	0.75	0.71
Hebei [d]	11179	46.71	45.70	-1.45		0.08	-46.86		0.08	0.82	0.79
Heilongjiang	6849	30.83	23.82						0.18	0.73	0.69
Henan	12266	57.19	33.39				-52.46	-0.11	0.16	0.78	0.75
Hubei	13316	52.16	29.69	-0.62				-0.13	0.22	0.76	0.73
Hunan	9302	46.88	21.65			0.09		-0.11	0.12	0.79	0.76
Inner Mongolia	35210	47.03	38.35	-1.72	-0.40		-29.59		0.24	0.65	0.63
Jiangsu [e]	12634	74.10	21.35	-1.40					0.14	0.81	0.79
Jiangxi	10413	37.41	17.66			0.32	-9.71	-0.08	0.20	0.76	0.72
Jilin	4419	30.17	22.24		-0.84				0.25	0.73	0.66
Liaoning	11202	39.08	19.20				-23.87		0.37	0.74	0.71
Ningxia	12247	53.82	47.68				-21.65	-0.46		0.78	0.75
Qinghai	16382	52.46	33.20			0.05	-20.85	-0.33		0.70	0.66
Shaanxi	7989	56.31	44.65			0.12	-30.19	-0.31		0.82	0.79
Shandong	12010	54.14	27.18	-2.29			-39.52		0.16	0.77	0.74
Shanxi	11897	60.05	38.03	-2.14	-0.47	0.03		-0.27		0.77	0.74
Sichuang	5963	48.93	11.73			0.10		-0.11		0.82	0.79
Tibet	7907	63.19	42.87			0.08	-54.34	-0.22		0.67	0.56
Xinjiang	7407	52.28	57.15				-23.09	-0.43		0.54	0.38
Yunnan	8039	45.24	19.31	-0.99		0.06	-15.24	-0.14	0.17	0.74	0.70
Zhejiang	12987	33.98	20.92	-1.48		0.26			0.24	0.77	0.75

[a] Only statistically significant ($p<0.05$) intercepts and slopes are shown. [b] Including Taiwan. [c] Including Hong Kong, Macao, and Hainan. [d] Including Beijing and Tianjin. [e] Including Shanghai. [f] Abbreviations used for the meteorological variables: WS: wind speed at 10 m above ground; PBLH: planetary boundary layer height; PS: surface pressure; RH_PBLH: mean relative humidity in planetary boundary layer; Precip_Lag1: cumulative precipitation of the previous day.

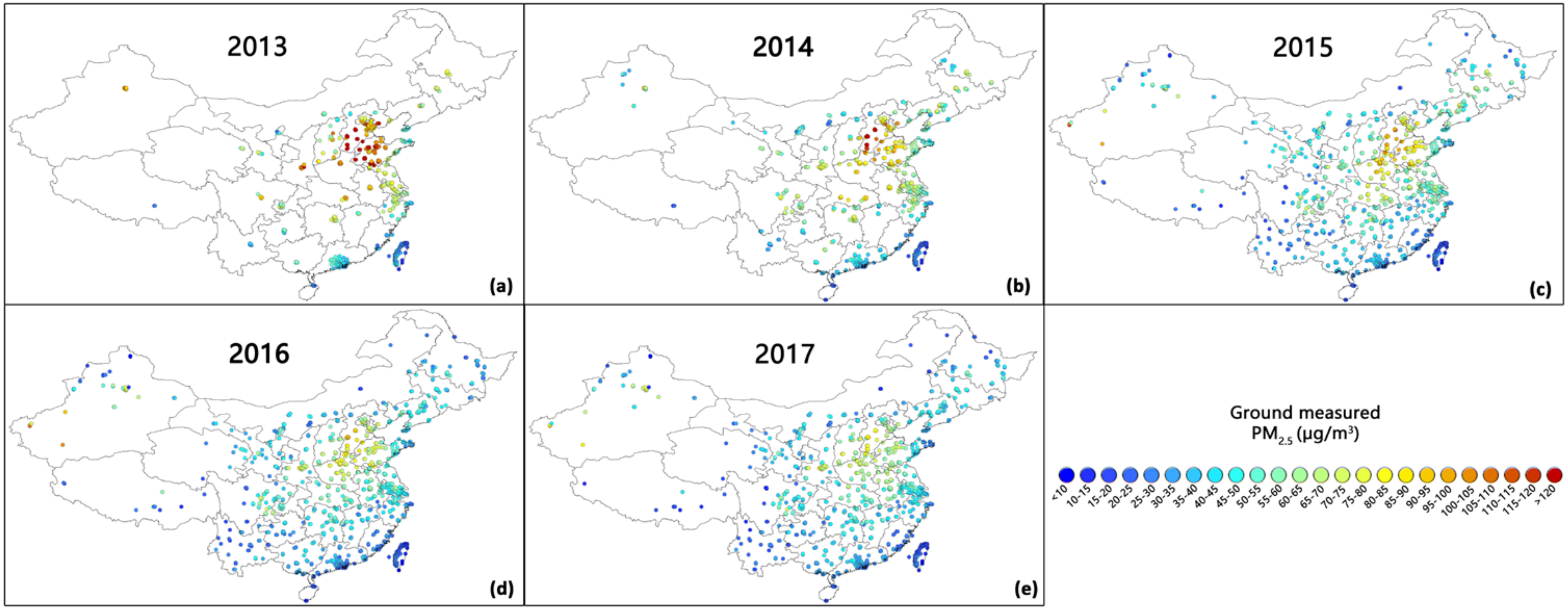

Figure S2. Spatial distributions of annual mean ground measured $PM_{2.5}$ concentrations in China from 2013 to 2017

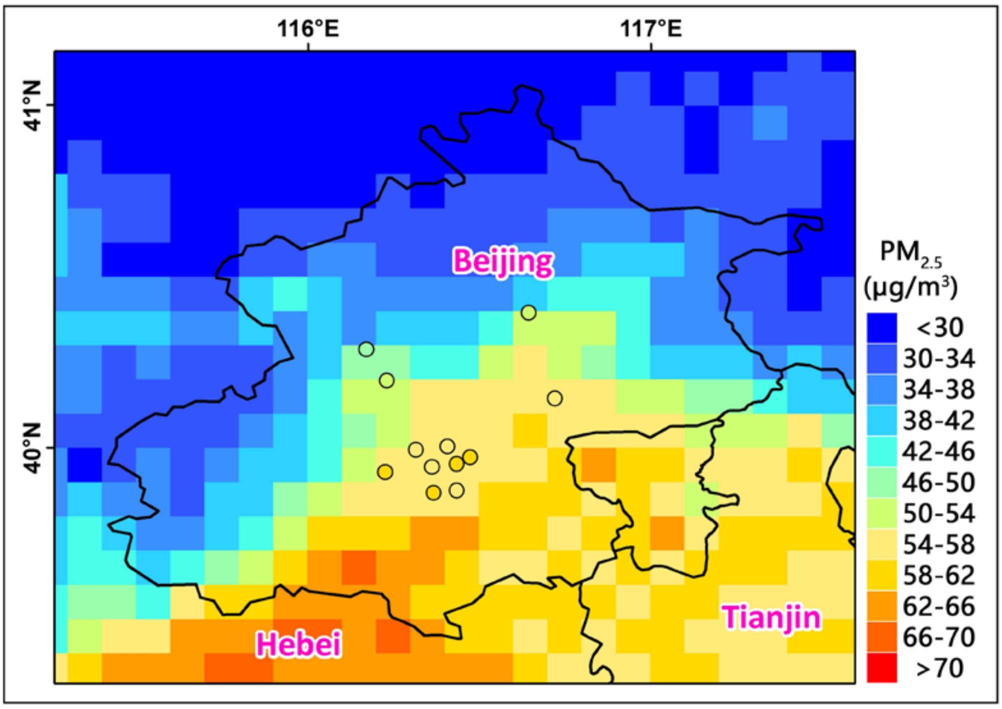

Figure S3 Spatial distribution of satellite and ground $PM_{2.5}$ concentrations of 2017 in Beijing. The circles denote the ground monitoring stations. 5