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Dominant role of emission reduction in $PM_{2.5}$ air quality improvement in Beijing during 2013-2017: a model-based decomposition analysis

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Abstract.

In 2013, China's government published the Air Pollution Prevention and Control Action Plan (APPCAP) with a specific target for Beijing, which aims to reduce annual mean $PM_{2.5}$ concentrations in Beijing to 60 μg m^{-3} in 2017. During 2013-2017, the air quality in Beijing was significantly improved following the implementation of various emission control measures locally and regionally, with the annual mean $PM_{2.5}$ concentration decreasing from 89.5 μg m^{-3} in 2013 to 58 μg m^{-3} in 2017. As meteorological conditions were more favourable to the reduction of air pollution in 2017 than in 2013 and 2016, the "real" effectiveness of emission control measures on the improvement of air quality in Beijing has frequently been questioned.

In this work, by combining a detailed bottom-up emission inventory over Beijing, the MEIC regional emission inventory, and the WRF-CMAQ model, we attribute the improvement in Beijing's $PM_{2.5}$ air quality in 2017 (compared to 2013 and 2016) to the following factors: changes in meteorological conditions, reduction of emissions from surrounding regions, and seven specific categories of local emission control measures in Beijing. We collect and summarize data related to 32 detailed control measures implemented during 2013-2017, quantify the emission reductions associated with each measure using the bottom-up local emission inventory in 2013, aggregate the measures into seven categories, and conduct a series of CMAQ simulations to quantify the contribution of different factors to the $PM_{2.5}$ changes.

We found that, although changes in meteorological conditions partly explain the improved $PM_{2.5}$ air quality in Beijing in 2017 compared to 2013 (3.8 μg m^{-3}, 12.1% of total), the rapid decrease in $PM_{2.5}$ concentrations in Beijing during 2013-2017 was dominated by local (20.6 μg m^{-3}, 65.4%) and regional (7.1 μg m^{-3}, 22.5%) emission reductions. The seven categories of emission control measures, i.e., *Coal-fired boiler control*, *Clean fuels in the residential sector*, *Optimized industrial structure*, *Fugitive dust control*, *Vehicle emission control*, *Improved end-of-pipe control*, and *Integrated treatment of VOCs*, reduced the $PM_{2.5}$ concentrations in Beijing by 5.9, 5.3, 3.2, 2.3, 1.9, 1.8, and 0.2 μg m^{-3}, respectively, during 2013-2017. We also found that, changes in meteorological conditions could explain roughly 30% of total reduction in $PM_{2.5}$ concentration during 2016-2017 with more prominent contribution in winter months (November and December). If the meteorological conditions in 2017 had remained the same as those in 2016, the annual mean $PM_{2.5}$ concentrations would have increased from 58 μg m^{-3} to 63 μg m^{-3}, exceeding the target established in the APPCAP. Despite the remarkable impacts from meteorological condition changes, local and regional emission reductions still played major roles in the $PM_{2.5}$ decrease in Beijing during 2016-2017, and *Clean fuels in the residential sector*, *Coal-fired boiler control*, and *Optimized industrial structure* were the three most effective local measures (contributing reductions of 2.1, 1.9 and 1.5 μg m^{-3}, respectively). Our study confirms the effectiveness of clean air actions in Beijing and its surrounding regions and reveals that a new generation of control measures and strengthened regional joint emission control measures should be implemented for continued air quality improvement in Beijing because the major emitting sources have changed since the implementation of the clean air actions.

1 Introduction

Most countries inevitably undergo and tackle severe air pollution in the development process. In recent years, severe $PM_{2.5}$ pollution, in China has gradually become an urgent challenge to the government (Wang et al., 2012; Li et al., 2017). It not only poses a threat to human health but has also badly influenced the social economy and ecological environment (Menon et al., 2002; Chan et al., 2006; Ming et al., 2009; Zheng et al., 2015; Zhu et al., 2015). Beijing, as the capital of China, has suffered especially severe air quality problems. In 2013, the annual average $PM_{2.5}$ concentrations in Beijing reached 90 μg m^{-3}, which was nearly three times higher than China's National Ambient Air Quality Standard (NAAQS) of 35 μg m^{-3} (MEP, 2012). In addition to the high annual average $PM_{2.5}$ concentrations, several frequent and severe heavy haze episodes in January 2013 made the situation even worse and caused great public concern (Zhang et al., 2014; Zheng et al., 2016).

To address the increasingly serious $PM_{2.5}$ pollution, the Chinese government released the Air Pollution Prevention and Control Action Plan (APPCAP) in September 2013, which aimed to mitigate severe PM pollution across China, especially in some typical regions. In particular, the average $PM_{2.5}$ concentrations of Beijing should be reduced to less than 60 μg m^{-3} by 2017. Based on the ambition and guidance of the APPCAP, Beijing has made further efforts and formulated the *Beijing 2013-2017 Clean Air Action Plan (*referred to as the *Beijing Action Plan)* to mitigate air pollutions. The *Beijing Action Plan* represents the most important and systematic set of local air pollution control and management policies in the past five years. After implementing a series of air pollution control policies and measures, the annual mean $PM_{2.5}$ concentrations in Beijing decreased to 58 μg m^{-3} in 2017 (BMEP, 2018), 35.6% lower than that in 2013 and surpassing the air quality goals of the APPCAP. Meanwhile, the surrounding regions of Beijing, such as Tianjin, Hebei, Shandong, Shanxi and Henan province, also implemented the APPCAP, and the air quality of the whole region has attained marked improvements, which have also been confirmed by satellite-based and ground-based observations (Liu et al., 2016; Cai et al., 2017; Zhao et al., 2017; Wang et al., 2017; Zheng et al., 2018).

The $PM_{2.5}$ concentrations in the atmosphere are affected by several factors, while pollutant emissions, regional transport and meteorological conditions play dominant roles (He et al., 2001; Chen et al., 2018). In general, local pollutant emissions contribute most to the air pollution for a given city, and the control of emissions is always one of the most effective ways to mitigate air pollution. Regarding the influence of regional transport, considering that Beijing is embraced on three sides by mountains except for the south and southeast direction, the transport of air pollutants from the south and southeast can easily affect the $PM_{2.5}$ concentrations in Beijing (Sun et al., 2015; Wang et al., 2015; Chen et al., 2017). However, regional cities in these two directions, such as Baoding, Changzhou, Hengshui, Shijiazhuang, Tangshan, and Tianjin, suffer even worse air pollution (Li et al., 2017). A combination of $PM_{2.5}$ formation and transport results in regionally complex air pollution characteristics in Beijing (Lang et al., 2013; Chen et al., 2016; Zhang et al., 2018; Zhong et al., 2018). In addition to the impact of pollutant emissions and transport, $PM_{2.5}$ concentrations are also highly influenced by some other factors, including atmospheric advection, atmospheric diffusion and secondary aerosol formulation. (Sun et al., 2015; Yin et al., 2016; Zhang et al., 2016). Several studies have also reported that frequent stable meteorological conditions play an important role in severe pollution episodes (Elser et al., 2016; Ma et al., 2017; Zhang et al., 2018). Based on emission inventories and air quality models, existing studies have established a mature sensitivity decomposition framework to assess the contributions of emission control to air quality improvements (Zhao et al., 2013; Cai et al., 2017). However, some studies have investigated the effects of meteorological conditions on air quality by controlling the meteorological inputs of chemical transport models (Zhang et al., 2018).

The mitigation of $PM_{2.5}$ pollution in Beijing was significant during 2013-2017, especially during 2016-2017. This impact resulted from the integrated effects of various factors, including the local emission control through the *Beijing Action Plan*, the surrounding emission reductions through the APPCAP, and the impacts of meteorological condition changes. Several studies have researched the roles of meteorology, regional and local emissions in Beijing's $PM_{2.5}$ pollution; however, most of these studies analysed a single factor or focused on heavy pollution episodes (Wang et al., 2013; Zeng et al., 2014; Zhang et al., 2015; Zheng et al., 2016; Liu et al., 2017; Ma et al., 2017; Wang et al., 2017). There has been no systematic and decomposed attribution analysis of Beijing's air quality improvements at an annual scale, especially during the periods of 2013-2017 and 2016-2017, during which the $PM_{2.5}$ concentrations in Beijing decreased significantly. To better understand the great progress in air cleaning of Beijing in recent years, a more comprehensive analysis covering the periods of 2013-2017 and 2016-2017 is urgently needed. In this study, based on several sensitivity simulations, we established a decomposition analysis framework to evaluate the impacts of local control policies, surrounding emission reductions and the meteorological changes on $PM_{2.5}$ abatement in Beijing during 2013-2017 and 2016-2017. First, the emission reductions of Beijing and its surroundings were estimated based on the quantification of air pollution control measures; meanwhile, a new multiple-pollutant emission inventory of Beijing and its surroundings, covering the periods of 2013-2017, was updated and developed. Second, based on a "zero-out" method, we designed a set of sensitivity experiments under different local and regional emission control measures and different meteorological conditions. Third, we used the Weather Research and Forecasting Model (WRF) and Community Multiscale Air Quality Model (CMAQ) to reproduce and simulate the air quality under different meteorological conditions and emission scenarios. Finally, an integrated and decomposed attribution analysis of $PM_{2.5}$ abatements in Beijing was developed to quantify the impacts of local pollution control, surrounding emission reductions, and meteorological changes.

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The study also identified the key point of next steps for air pollution control, which would be beneficial for future policy-making.

2 Methodology and Data

A model-based decomposition attribution analysis of $PM_{2.5}$ abatements in Beijing during 2013-2017 was developed under the framework shown in Figure 1. First, we used the observation data from 12 national observation stations in Beijing to review the air quality during 2013-2017, especially the monthly $PM_{2.5}$ concentrations in this period. The contributions of total $PM_{2.5}$ abatements in Beijing in 2017 were decomposed into three basic parts, including meteorology change, surrounding emission control and local emission control. Then, we use the WRF-CMAQ modelling system and observed $PM_{2.5}$ concentrations to quantify the contributions of these three factors. To further evaluate the effect of local control policies, we divided the *Beijing Action Plan* into seven specific policy types, estimated the corresponding emission reductions and updated the emission inventory during 2013-2017 under the framework of the MEIC model (Zhang et al., 2007; http://www.meicmodel.org/). The contributions from local emission control to the $PM_{2.5}$ air quality improvements in Beijing were also decomposed into specific measures with the WRF-CMAQ model and measure-related sensitivity experiments.

2.1 Surface air quality data

The study first reviewed the air quality in Beijing from 2013 to 2017 with both ground observation data and satellite observation data. Since 2012, Beijing has maintained an automated air quality monitoring network with 35 stations spatially distributed in the 16 administrative districts and counties (the specific locations of the air quality monitors are shown in the supporting information (SI), Figure S1). Since 2013, hourly concentrations of SO_2, NO_2, CO, $PM_{2.5}$, PM_{10}, and O_3 have been continuously measured and recorded by Beijing's Environment Protection Bureau (EPB). In this study, we reviewed the changes in SO_2, NO_2, CO, O_3, $PM_{2.5}$ and PM_{10} in Beijing annually during 2013-2017 and analysed the monthly $PM_{2.5}$ concentrations during this period. The hourly observation data we used were from the 12 national observation stations in Beijing, which are included among the above 35 stations (SI, Figure S1).

2.2 Estimates of local emission reduction from specific control measures

In this study, the base year (2013) air pollutant emission inventory of Beijing was provided by the Beijing Municipal Environmental Monitoring Center. This local emission inventory basically had the same source classification as the MEIC model. In addition, the power and heating sectors and most industrial sectors were treated as point sources, and the emission of fugitive dust was added. Therefore, the spatial distribution of emission sources and the activity rates of this local emission inventory were more accurate than those of the MEIC model, thereby reducing the uncertainty in the emission reduction estimation and air quality simulation to some degree.

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Beijing started the air quality protection process in 1998 and has focused most on the control of SO_2 and NO_x (Wang et al., 2012; Zhang et al., 2016). The Chinese government released the APPCAP nationwide in 2013 and committed to reducing $PM_{2.5}$ pollution for the first time ever (Zheng et al., 2018). The APPCAP aims to reduce the annual $PM_{2.5}$ concentrations of the Beijing-Tianjin-Hebei region by 25% compared with 2013, and particularly, the $PM_{2.5}$ concentrations of Beijing should be controlled to less than 60 μg m^{-3}. To fulfil the air quality targets, Beijing released its own *2013-2017 Clean Air Action Plan* under the framework of the *Nation Action Plan*, which contains much more ambitious and stricter control measures than ever before. We summarized and classified all measures in the *Beijing Action Plan* into seven types, including *Coal-fired boiler control, Clean fuels in the residential sector, Optimized economic structure, Improved end-of-pipe control, Vehicle emission control, Integrated treatment of VOCs* and *Fugitive dust control*. All the quantifiable control measures are listed in Table 1. Following several previous studies (Jiang et al 2015), air pollution control policies and measures could be quantified by adjusting the emission calculation parameters; then, the emissions in Beijing for 2016 and 2017 were estimated based on these updated parameters. The emission reduction associated with a single policy can then be estimated from the emission difference between before and after the implementation of this specific policy.

2.3 Regional emission inventory data

The air pollutant emission inventory of Beijing's surrounding regions (including Tianjin, Hebei, Henan, Shandong, Shanxi, Inner Mongolia) for the period of 2013-2017 was obtained using the MEIC model. The methodologies and data on which the MEIC is based have been introduced in our previous studies (Zhang et al 2007; Lei et al., 2011; Shen et al., 2014; Hong et al., 2017; Qi et al., 2017; Zheng et al., 2017). For the updated emission inventory and emission reductions of the surrounding area, we collected and analysed the results of our previous work (Zheng et al., 2018). The emission inventories for other parts of entire Mainland China were provided by the MEIC model, which has been updated to 2017 based on Zheng's work (Zheng et al., 2018).

2.4 WRF-CMAQ model

2.4.1 Model configuration

In this work, WRFv3.8 and CMAQ 5.1 were used to build up the air quality modelling system. WRF model provided the meteorological conditions, while CMAQ model simulated the air quality and main pollutant concentrations. For the WRF model configuration, we chose the Kain-Fritsch cloud parameterization (version 2, Kain, 2004), the ACM2 PBL parameterization scheme (Pleim, 2007), the RRTM radiation scheme, and the Pleim-Xiu land-surface model (Xiu and Pleim, 2000). For the CMAQ model configuration, we applied the CB05 as gas-phase chemical mechanism and AERO6 as particulate matter chemical mechanisms. For each modelling scenario, we chose a ten-days spin-up period to mitigate the initial condition impacts.

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Three nested simulation domains for the CMAQ model were developed in this study (SI, Figure S2). The first domain covered the entire China area and some parts of south and east Asia, with a horizontal resolution of 36 km × 36 km. The second domain covered the majority of eastern and northern China. The third domain was 4 km × 4 km and focused on Beijing and its surrounding regions, including the municipality of Tianjin and the provinces of Hebei, Henan, Shandong, and Shanxi. The initial and boundary conditions were derived from the final analysis data (FNL) of the U.S. National Centers for Environmental Prediction (NCEP, http://rda.ucar.edu/datasets/), which was further used to drive the CMAQ. The chemical fields simulated by CMAQ had 14 vertical layers from the surface to an altitude of approximately 10 km above the ground, and the thickness of the first layer was approximately 50 m. To make the analysis and evaluation more comprehensive, we simulated all emission scenarios for the whole year in cases where the severe pollution period was missing.

For the emission inputs of the model system, the anthropogenic emission inventory for Beijing was provided by the Beijing Municipal Environmental Monitoring Center, the inventories for other regions in China were provided by the MEIC model, and the inventories for other Asian countries were derived from the MIX emission inventory (Li et al., 2017). The natural source emission was adopted from the Model of Emission of Gases and Aerosols from Nature (MEGAN).

2.4.2 Model validation

To evaluate the meteorology results simulated by the WRF model, we collected the hourly observed meteorology data from the Computational and Information Systems Laboratory at the National Center for Atmospheric Research in Boulder (NCAR, https://rda.ucar.edu/) and calculated the mean bias (MB), mean error (ME), correlation coefficient (Corr), root mean square error (RMSE), normalized mean bias (NMB), and normalized mean error (NME). The evaluation results showed that the simulation basically reproduced the meteorological conditions in 2013 and 2017, and the temperature simulation especially featured a high accuracy. The monthly evaluation results of the simulated temperature, relative humidity, wind speed and wind direction for Beijing in 2013, 2016 and 2017 are shown in the SI (Table S1).

To evaluate the pollutant concentration results simulated by the CMAQ model, we collected the hourly observed major pollutant concentration data (including SO_2, NO_2, $PM_{2.5}$, PM_{10}, CO, and O_3) from the Beijing Municipal Environmental Protection Bureau. We compared the time series of $PM_{2.5}$ from observations and CMAQ simulation results (SIM_{E13M13}, SIM_{E16M16}, and SIM_{E17M17}) for Beijing in 2013, 2016 and 2017 (Figure 2). The MB, ME, Corr, RMSE, NMB, and NME of the hourly observed and simulated results for the six major pollutants were also calculated and listed in the SI (Table S2). The time series and evaluation results indicated that the CMAQ model and simulation results in this work can relatively well reproduce the temporal and spatial distribution of air pollutants in Beijing and its surroundings. As for the simulated $PM_{2.5}$ of 2017, the monthly Corr of $PM_{2.5}$ concentrations varied from 0.53 (in May) to 0.89 (in October), and the NMB and NME of monthly $PM_{2.5}$ simulations were within ±45% and ±55%, respectively. According to the observation data, the annual average $PM_{2.5}$ concentrations in Beijing decreased by 31.5 μg m^{-3} from 2013 to 2017, while the simulated $PM_{2.5}$ decreased by 32.8 μg m^{-3} (Table 2). Compared with 2016, the observed and simulated $PM_{2.5}$ decreased by 14.9 and 16.6 μg m^{-3}, respectively (Table

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2). The evaluation results suggested that the modelling system in this work can be used to quantify and analyse the attribution of $PM_{2.5}$ mitigations in Beijing.

2.5 Scenario design and decomposition analysis

To decompose the attribution of $PM_{2.5}$ abatements in Beijing from 2013-2017 and 2016-2017, we set up 18 sensitivity simulations to quantify the contributions of meteorology changes, emission reductions in surrounding areas and seven types of local emission control policies using the variable-controlling and switch methods. The description and details of all scenarios are listed in Table 2, and the direct simulation results are listed in column *Simulated* $PM_{2.5}$ (μg m^{-3}).

SIM_{E13M13}, SIM_{E16M16}, and SIM_{E17M17} were three base cases and were driven by the actual emission inventories and meteorology of 2013, 2016 and 2017, respectively, to reproduce the air quality of the corresponding year. SIM_{E17M13} and SIM_{E17M16} were designed to investigate the impact of meteorology. These two cases were driven by varying meteorological conditions (those of 2013 and 2016, respectively) and the same emission inventory (for the year 2017). $SIM_{E17S13M17}$ and $SIM_{E17S13M17}$ were designed to quantify the impact of surrounding emission reduction during 2013-2017 and 2016-2017. In both of these cases, the emission inventory of Beijing was set to the 2017 level, while that of the surroundings was set to the 2013 and 2016 levels, respectively. Fourteen simulations corresponding to the seven types of control policy in the two periods (2013-2017 and 2016-2017), $SIM_{E17LijM17}$ (*i* and *j* represent the number and the first applied year of each policy), were designed to quantify the air quality improvements contributed by each local control policy. The meteorological conditions of all 14 cases were set to those of 2017; for each simulation, emission reduction introduced by the corresponding control policy was added to the 2017 baseline, and then the derived emission inventory was applied to drive the corresponding air quality modelling.

A linear additive relationship was assumed among all contributors to perform a decomposition analysis, and simulated contributions of all sensitivity experiments were then normalized by the difference in observed $PM_{2.5}$ concentrations between 2013 (or 2016) and 2017, which were calculated by the following equations:

$$\mathrm{sCon}_i = \mathrm{sPM}_{2.5i} - \mathrm{sPM}_{2.5SIME17M17} \quad (1)$$

$$\mathrm{nCon}_{i(13)} = \mathrm{sCon}_{i(13)} \times (\mathrm{PM}_{2.5OBS2013} - \mathrm{PM}_{2.5OBS2017}) / \sum_{i=1}^{9} \mathrm{sCon}_{i(13)} \quad (2)$$

$$\mathrm{nCon}_{i(16)} = \mathrm{sCon}_{i(16)} \times (\mathrm{PM}_{2.5OBS2016} - \mathrm{PM}_{2.5OBS2017}) / \sum_{i=1}^{9} \mathrm{sCon}_{i(16)} \quad (3)$$

where i represents the case number of each sensitivity experiment; $\mathrm{sPM}_{2.5i}$ represents the simulated $PM_{2.5}$ (μg m^{-3}) of each case; $\mathrm{sCon}_{i(13)}$ and $\mathrm{sCon}_{i(16)}$ represent the simulated air quality improvements by each contributor from 2013-2017 and 2016-2017, respectively; and $\mathrm{nCon}_{i(13)}$ and $\mathrm{nCon}_{i(16)}$ represent the normalized results.

3 Results

3.1 Observed changes in surface air quality in Beijing during 2013-2017

In 2013, air pollution was the major environmental problem in Beijing and its surrounding regions (Zhang et al., 2016). In addition to the severe and persistent haze events, the annual mean $PM_{2.5}$concentration was 89.5 μg m^{-3} in Beijing. Furthermore, the concentrations of other major air pollutants were also at fairly high levels, with 56.0 μg m^{-3} for NO_2,26.5 μg m^{-3} for SO_2, 183.4 μg m^{-3} for O_3, and 3.4 mg m^{-3} for CO.

During 2013-2017, the annual average concentrations of SO_2, NO_2, $PM_{2.5}$ and PM_{10} decreased steadily in Beijing (SI, Figure S3(a)). SO_2 had the most significant decrease of -69.8% (SI, Figure S3(b)), indicating the great effectiveness of the clean air actions on SO_2 emission control. $PM_{2.5}$ had the second greatest decrease of 35.2%, and the annual concentration of $PM_{2.5}$ in 2017 was 58 μg m^{-3}, achieving the air quality targets in the *APPCAP* as scheduled.

Although the annual average $PM_{2.5}$ concentrations decreased remarkably during 2013-2017, the monthly concentration varied substantially in different years, as shown in Figure 3. Compared with the 2013 level, the average $PM_{2.5}$ concentrations of each month in 2017 all had a notable decline and presented a similar trend from Jul to Dec. However, compared with the 2016 level, the $PM_{2.5}$ pollution levels in Jan and Feb were more severe than those in 2017, while the pollution levels improved after Oct and decreased by nearly 66.3% in Dec (from 130.7 μg m^{-3} in 2016 to 44.0 μg m^{-3} in 2017). The monthly $PM_{2.5}$ concentrations in Nov and Dec in 2016 were also much higher than those in 2013. A heavy $PM_{2.5}$ pollution episode occurred in the autumn of 2016 and the winter of 2016-2017. However, the $PM_{2.5}$ concentrations decreased notably after Sep in 2017 compared with both 2013 and 2016. The observed $PM_{2.5}$ trends indicate that the emission trend and intensity are major factors in the variation in $PM_{2.5}$ concentrations, while the meteorology changes also play an important role. The quantification of the contributions of emission control and meteorology changes will benefit numerous future applications.

3.2 Attribution of the 2013-2017 emission reduction in Beijing to specific measures

Based on the MEIC model and the detailed local bottom-up emission inventory, Beijing's atmospheric emissions were updated by year and source sector, as shown in Figure 4. Furthermore, the attribution of emission reductions in Beijing to specific control measures during 2013-2017 and 2016-2017 is displayed in Figure 5.

The major air pollutant emissions in Beijing in 2013 are estimated as follows: 95 kt of SO_2, 218 kt of NO_x, 273 kt of volatile organic compounds (VOCs) and 81 kt of $PM_{2.5}$. The power and heating sector and the residential sector were the major sources of SO_2 emissions, accounting for 45.1% and 40.6%, respectively. NO_x emissions mainly came from mobile sources, which contributed 67.2%. Solvent use, mobile sources and industry made notable contributions to VOC emissions, accounting for 32.0%, 23.8% and 23.7%, respectively. Fugitive dust and the residential sector were the major emitters of $PM_{2.5}$, with proportions of 48.7% and 26.2%. However, the implementation of the *Beijing Action Plan* had a significant impact in terms of local emission reductions. Compared with 2013, Beijing's anthropogenic emissions in 2017 were estimated to have decreased by 83.6% for SO_2, 42.9% for NO_x, 42.4% for VOCs, and 54.7% for $PM_{2.5}$. Furthermore, the structure of the emission

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proportions also changed. For NO_x emissions, transportation remained the largest emitter of NO_x in 2017 but represented a much higher proportion in 2017 than in 2013. The contributions of other sectors, especially power and heating, decreased. With notable contributions of VOC emission reductions in the residential and industrial sectors, the proportions of these two sectors decreased obviously in 2017, and solvent use and transportation became the major emitters. For $PM_{2.5}$, through the effective measures implemented in the residential, industrial, and power and heating sectors, these sectors emitted less $PM_{2.5}$ in 2017 than in 2013, and almost all of the $PM_{2.5}$ emissions came from fugitive dust.

In general, the power and heating, industrial, and residential sectors exhibited the most notable emission reductions during 2013-2017. The variations in emissions by sector and year are mainly attributable to air pollution control policies and measures. As previously mentioned, seven types of air pollution control measures were simultaneously contributing to the emission reduction process. According to our research, during 2013-2017, *Coal-fired boiler control* and *Clean fuels in the residential sector* had the most notable effects on SO_2 emission reductions and reduced SO_2 emissions by 35 and 28 kt, respectively, accounting for 44.0% and 35.2% of the total (Figure 6 (a); SI, Table S3). Coal combustion was regarded as the major source of SO_2 emissions in Beijing, where coal is primarily used for residential heating and cooking, coal-fired boilers and power plants. The great emission reduction in SO_2 indicated accurate source identification and effective emission control in the past five years. However, end-of-pipe controls on coal combustion in Beijing have been developed and almost finished recently, leaving little room for further emission reduction. Therefore, the adjustment and optimization of the energy structure would be the most effective and dominant pathway for mitigating coal combustion pollution in the future. According to several studies on the source apportionment of $PM_{2.5}$ in Beijing, the transportation sector accounted for a major part of $PM_{2.5}$ pollution in 2013, and its contribution has become much higher since then (Li et al., 2015; Li et al., 2017; Hua et al., 2018; Zhang et al., 2018). *Vehicle emission control*, including both on-road and off-road vehicles, was the biggest contributor to NO_x emission reductions with an estimated total reduction of 44 kt NO_x, accounting for 47% of the total reductions (Figure 6 (a); SI, Table S3). *Improved end-of-pipe control* reduced the NO_x emissions by 10 kt in total and accounted for 10.3% of the total NO_x reductions. In view of the widespread conversion of combustion equipment from coal-based to oil/gas-based equipment, several measures were taken to improve the end-of-pipe control in response to the potential increase in NO_x emissions, including the application of low-nitrogen-burning (LNB) technologies. A large number of gas-fired or oil-fired boilers, equivalent to 34,000 MV, have been renovated, decreasing NO_x emissions by nearly 7.5 kt (SI, Table S3). Benefitting from the advanced planning of VOC pollution control and scientific source apportionment, VOC measures were also as effective as other pollutant measures in Beijing during 2013-2017. *Integrated treatment of VOCs* had the most prominent achievement in reducing VOC emissions, with a reduction of 57 kt and a proportion of 49.3% (Figure 6 (a); SI, Table S3). *Vehicle emission control* and *Optimized industrial structure* also effectively reduced VOC emissions, accounting for 16.1% and 11.4%, respectively (Figure 6 (a); SI, Table S3). For $PM_{2.5}$ emission control, *Clean fuels in the residential sector*, *Fugitive dust control*, *Coal-fired boiler control* and *Optimized industrial structure* all made obvious contributions, which reduced the $PM_{2.5}$ emissions by 13, 11, 10 and 6 kt, respectively, and accounted for 90.3% of the total (Figure 6 (a); SI, Table S3). In recent years, fugitive dust has gradually become the most dominant source of $PM_{2.5}$ emissions, but the relevant control measures are considered less effective than measures focused on coal combustion and the industrial sector. Moreover, as the $PM_{2.5}$ emissions from the industrial sector and coal combustion have gradually decreased and become better managed, fugitive dust, including road dust, construction dust and stock dump dust, has become the most challenging target for future $PM_{2.5}$ control. In general, *Coal-fired boiler control*, *Clean fuels in the residential sector*, *Optimized industrial structure* and *Vehicle emission control* made significant contributions to pollutant emission reductions in Beijing during 2013-2017 overall, while *Integrated treatment of VOCs* and *Fugitive dust control* achieved prominent reductions in VOCs and $PM_{2.5}$ emissions.

To ensure that the national air quality targets of the APPCAP were achieved as scheduled, Beijing implemented a series of stronger and more relevant pollution control policies and measures starting in 2016. For energy structure adjustment, measures associated with *Clean fuels in the residential sector* were enhanced. A total of 92,000 households in urban areas and 369,000 households in rural areas have converted from using coal to clean fuels, close to the total amount of 2013-2016. For industrial structure adjustment, Beijing strengthened the elimination and management of small, cluttered and heavily polluting factories. More than 6,500 factories were eliminated during 2016-2017, approaching one and a half times the total amount during 2013-2016. During 2016-2017, SO_2, NO_x, VOCs and $PM_{2.5}$ were estimated to have decreased by 19.6 kt, 29.0 kt, 42.9 kt and 15.7 kt, respectively (SI, Table S3). *Clean fuels in the residential sector*, *Coal-fired boiler control*, and *Optimized industrial structure* were three of the most effective local measures during this period. In addition, with the enhanced management of non-point air pollution sources, including fugitive dust, heavily polluting vehicles and domestic solvent use, the relevant control measures have generated more remarkable emission reductions in this period than in the previous periods. For instance, *Fugitive dust control* was estimated to have decreased the $PM_{2.5}$ emissions by 4.7 kt during 2016-2017, representing 42.5% of the total $PM_{2.5}$ emission reductions by *Fugitive dust control* during 2013-2017.

3.3 Emission reduction in surrounding regions during 2013-2017

According to our previous research (Zheng et al., 2018), the implementation of national clean air actions has brought conspicuous emission reductions in Beijing's surrounding regions (including Tianjin, Hebei, Henan, Shandong, Shanxi and Inner Mongolia) from 2013-2017. Figure 6 shows the updated emission inventory of Beijing's surrounding regions by year and sector during 2013-2017.

According to Figure 6, SO_2 and $PM_{2.5}$ emissions presented rapid decreasing trends from 2013-2017, while the trend of VOC emissions remained steady with a slight increment. Compared with 2013, SO_2, NO_x and $PM_{2.5}$ emissions were estimated to decrease by 59.5%, 22.9% and 36.6%, respectively, while VOC emissions increased slightly by 0.2%. During 2013-2017, the industrial and the power and heating sectors made the most prominent contributions to SO_2 emission reductions, which decreased SO_2 emissions by 3,021 and 2,000 kt, respectively, indicating that the SO_2 emissions control measures were quite effective. Reductions in the NO_x emissions mainly came from the power and heating sector, with a reduction of 1,541 kt within five years. For $PM_{2.5}$ emission reductions, industrial sectors were the greatest contributors, with reductions of 621 and 528 kt. The VOC emissions in the surrounding regions continued to increase, especially in the solvent use sectors. During the process of implementing national clean air actions, the surrounding regions also carried out several valid measures to control VOC

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emissions, such as the supervision and repair of gasoline stations, oil tankers and oil transfer processes and the integrated treatment and management of petrochemical and refinery industries. The VOC emissions from the residential and transportation sectors in 2017 decreased by 20.7%. However, due to the lack of thorough regulation of chemical industries and the ineffective end-of-pipe control of solvent use sources, the total VOC emissions increased slightly in 2017.

3.4 Decomposition of $PM_{2.5}$ concentration changes in Beijing during 2013-2017

3.4.1 Modelled $PM_{2.5}$ air quality changes in Beijing during 2013-2017

According to the base simulation results, the annual average $PM_{2.5}$ concentrations of Beijing decreased by 32.8 μg m^{-3} from 2013-2017 and by 16.6 μg m^{-3} from 2016-2017, which agree well with the observed decreases (31.5 μg m^{-3} from 2013-2017 and 14.9 μg m^{-3} from 2016-2017). Figure 7 shows the spatial distribution of $PM_{2.5}$ concentrations in Beijing and the surrounding areas in 2013, 2016 and 2017 (panels (a)-(c)), along with the total $PM_{2.5}$ changes and the changes due to major contributing factors from 2013-2017 (panels (d)-(f)) and 2016-2017 (panels (g)-(i)).

In 2013, some typical regions, such as the southern Beijing and most of the cities of Tianjin, Tangshan, Baoding, Shijiazhuang, Handan, and Anyang, suffered intense $PM_{2.5}$ pollution. After implementing the APPCAP and local air pollution control policies, severe pollution was mitigated in most regions, although several heavily polluted spots still existed. However, Beijing had successfully removed itself from the list of heavily polluted areas. According to the base simulation results (Figure 7, panels (a)-(c)), Beijing, especially the southern area, had the most notable $PM_{2.5}$ decrease among all parts of the third nested simulation domain. The municipality of Tianjin and southwestern Hebei Province also achieved prominent improvements in $PM_{2.5}$ pollution levels. Based on the spatial distributions of total $PM_{2.5}$ changes and changes due to major contributing factors in Beijing (Figure 7, panels (d)-(i)), the control of emissions dominated the $PM_{2.5}$ changes in both 2013-2017 and 2016-2017; however, the favourable effects of meteorological changes during 2016-2017 were much more remarkable. We further estimated and quantified the contributions of each factor as follows.

3.4.2 Contribution from changes in meteorological conditions

According to the simulation results of the base cases and emission-fixed sensitivity experiments (Table 2; Table S4), the meteorological conditions in 2017 were found to be more favourable than those in the previous periods, especially 2016. During 2013-2017, changes in meteorological conditions contributed 3.8 μg m^{-3} to the $PM_{2.5}$ air quality improvements, accounting for 12.1% of the total abatements. Under the meteorological conditions of 2013 and the emission level of 2017, the annual average $PM_{2.5}$ concentration of Beijing would have decreased from 90 μg m^{-3} to 62-62.5 μg m^{-3} and would not have achieved the air quality targets established in the APPCAP. During 2016-2017, the favourable effects of meteorology changes became much more striking and contributed 4.4 μg m^{-3}, accounting for 29.5% of the total $PM_{2.5}$ abatement from 2016-2017. Similarly, under the meteorological conditions of 2016, the $PM_{2.5}$ level in Beijing in 2017 would have decreased to 62.5-63.0 μg m^{-3}, still in excess of the APPCAP target.

From the perspective of annual average analysis, changes in meteorology generally had an adverse effect on air pollution mitigation in 2017; however, the impact varies greatly in the monthly analysis. Figure 8 shows the monthly average simulated $PM_{2.5}$ level in the two fixed-emission sensitivity experiments. Compared with the meteorological conditions of 2013 (Figure 8 (a)), the meteorological conditions of 2017 was better in winter, especially in Jan and Feb. Under the anthropogenic emissions of 2017, the meteorological conditions of Jan and Feb 2013 would have increased the $PM_{2.5}$ concentration by 22.5% and 37.7%, respectively. However, the meteorological conditions of 2017 were worse than those of 2013 in spring and summer, especially in Apr, May and Jul. The air quality was good in the first few months of 2016, and the simulation results also indicated that the meteorological conditions during this period in 2017 were much worse than those in 2016, increasing the $PM_{2.5}$ concentrations by 51.6 μg m^{-3} in Jan and 28.6 μg m^{-3} in Feb (Figure 8 (b)). However, the conditions improved in the following months, especially during Oct to Dec. If the meteorological conditions remained the same as those in 2016, the monthly average $PM_{2.5}$ concentrations of Oct, Nov, and Dec would have increased by 25.4%, 58.0% and 92.4%, respectively. It is worth noting that severe $PM_{2.5}$ pollution and haze events always occur in winter in North China; therefore, remarkable improvements in the meteorological conditions in Jan, Feb, Nov and Dec contribute greatly to the mitigation of annual $PM_{2.5}$ concentrations.

3.4.2 Contribution from local and regional emission reduction measures

Although the changes in meteorological conditions were favourable for $PM_{2.5}$-related air quality improvements in Beijing, the control of emissions was still the dominant factor in $PM_{2.5}$ abatement in recent years and contributed reductions of 27.7 μg m^{-3} (accounting for 87.9%) and 10.5 μg m^{-3} (accounting for 70.5%) in 2013-2017 and 2016-2017, respectively.

According to the simulation results of the regional emission-fixed sensitivity experiments (Table 2; Table S4), the contributions of regional emission reductions to the $PM_{2.5}$ abatements in Beijing were 7.1 μg m^{-3} during 2013-2017 and 2.5 μg m^{-3} during 2016-2017, accounting for 22.5% and 16.8%, respectively, in total. The results indicate that by implementing the APPCAP, regional provinces and cities around Beijing achieved notable emission control effects. In particular, emission reductions in the industrial and power sectors have made striking contributions to $PM_{2.5}$-related air quality improvements in regional areas.

In addition to the impacts of meteorology changes and regional emission reductions, the contributions of local emission control to the $PM_{2.5}$ abatement in Beijing were estimated to be 20.6 μg m^{-3} (2013-2017) and 8.0 μg m^{-3} (2016-2017), accounting for 65.4% and 53.7%, respectively. According to the results of the measure-related sensitivity experiments (Table S4), we further decomposed the contributions due to local emission control into each specific measure. As Figure 9 shows, during 2013-2017, *Coal-fired boiler control* made the largest contribution of 5.9 μg m^{-3}, accounting for 18.7% of the total. C*lean fuels in the residential sector* was the second greatest contributor after *Coal-fired boiler control*, decreasing $PM_{2.5}$ concentrations by 5.3 μg m^{-3}. Measures associated with *Optimized industrial structure* also effectively reduced $PM_{2.5}$ concentrations, with a decrease of 3.2 μg/m^3 and a proportion of 10.2%. Measures associated with *Fugitive dust control*, *Vehicle emission control*, *Improved end-of-pipe control*, and *Integrated treatment of VOCs* had relatively minor contributions and reduced the $PM_{2.5}$ concentrations in Beijing by 7.3%, 6.0%, 5.7% and 0.6%, respectively, from 2013-2017 (Figure 9 (a)). During 2016-2017, *Clean fuels in the residential sector*, *Coal-fired boiler control* and *Optimized industrial structure* were the top three contributors to the $PM_{2.5}$ abatement among all local policies, accounting for 14.1%, 12.8% and 10.1% of the total (Figure 9 (b)). These results highlight the great enhancement in the control bulk coal use and the elimination of small, clustered, heavily polluting factories during this period.

In summary, the improvement in the $PM_{2.5}$-related air quality in Beijing was decomposed, and the results are shown in Figure 10. During 2013-2017, meteorology changes, surrounding emission reductions and local emission control contributed 3.8, 7.1 and 20.6 μg m^{-3}, respectively, accounting for 12.1%, 22.5%, and 65.4%. *Coal-fired boiler control*, *Clean fuels in the residential sector* and *Optimized industrial structure* were the top three contributors among all local emission control policies. Emission reduction was the most dominant factor in the air quality improvements in Beijing during this period. For 2016-2017, the contributions of meteorology changes, surrounding emission reductions and local emission control were 4.4, 2.5 and 8.0 μg m^{-3}, respectively. The favourable meteorological conditions during this period had a remarkable effect, accounting for 29.5% of the total pollution reduction. The top three local control measures of this period were the same as those in 2013-2017 but had a different order, i.e., *Clean fuels in the residential sector* and *Optimized industrial structure* made larger contributions.

4 Concluding Remarks

The remarkable decreases in the annual average $PM_{2.5}$ concentrations in Beijing from 2013-2017 and 2016-2017 were the combined results of various factors. In this study, based on a series of numerical simulation experiments and a decomposed attribution analysis, local air pollution control policies, surrounding emission reductions and favourable meteorological conditions were estimated to have contributed 65.4% (20.6 μg m^{-3}), 22.5% (7.1 μg m^{-3}) and 12.1% (3.8 μg m^{-3}), respectively, of the total $PM_{2.5}$ abatement in Beijing (31.5 μg m^{-3}) from 2013-2017 and 53.7% (8.0 μg m^{-3}), 16.8% (2.5 μg m^{-3}) and 29.5% (4.4 μg m^{-3}), respectively, of the total $PM_{2.5}$ abatement (14.9 μg m^{-3}) from 2016-2017. During 2013-2017, air pollution control policies had the most dominant effect on $PM_{2.5}$ abatement, accounting for nearly 88%, but the meteorological impacts have been considerable since 2016, especially in the winter of 2016-2017 and the autumn of 2017.

Under the *Beijing Action Plan*, anthropogenic emissions were reduced by 83.6% for SO_2, 42.9% for NO_x, 42.4% for VOCs, and 54.7% for $PM_{2.5}$ compared with the 2013 level. Under the *APPCAP*, the areas surrounding Beijing also reduced their pollutant emissions by 59.5% for SO_2, 22.9% for NO_x, and 36.6% for $PM_{2.5}$. A measure-by-measure analysis showed that *Coal-fired boiler control*, *Clean fuels in the residential sector* and *Optimized economic structure* were the most effective control measures in general for Beijing during 2013-2017 and 2016-2017, both in terms of emission reductions and $PM_{2.5}$ pollution mitigation.

The results indicated several options for future air pollution control in Beijing. The most notable effect of the *Beijing Action Plan* mainly came from the control of combustion, which suggests that power plants, coal-fired boilers, and residential burning always account for the majority of air pollution sources. Consequently, Beijing should continue to optimize the city's energy structure to achieve a qualitative improvement in energy consumption. However, with the progress on air pollution control in Beijing, the contributions of combustion and industry, of which the sectors and sources are relatively easy to identify and manage, have gradually decreased, and there is less room for improvement. Pollutant emissions from domestic living, such as transportation, restaurant fumes and residential solvent use, have increasingly accounted for larger proportions. Vehicles, VOC emission sources and fugitive dust have gradually become the major and most difficult challenge for Beijing's future air pollution control. On the one hand, the government should further apply stronger and more effective management of non-point pollution sources arising from the demands for city development, such as catering enterprises, vehicles, off-road transportation, construction sites, and the use of solvents and coatings. More resources and investment, more accurate identification and refined management strategies are needed for these diffuse pollution sources. On the other hand, the support and innovation of science and technology should be enhanced further, including not only high-technology strategies of pollutant removal and equipment renovation but also the understanding of pollution mechanisms and the identification of pollution sources. For instance, the scientific source apportionment of atmospheric particulates, the dynamic update of emission inventories, the application of widespread observation systems, the construction of pollution forecasts and warning systems, etc. should be developed further. A support system for air quality analysis, decision making, implementation, assessment and optimization should be established in the future to make qualitative leaps in environmental protection.

Author contributions

Q.Z., J.L. and K.H. conceived the study; J.S., T.C. and F.S. developed bottom-up emission inventory over Beijing; X.L., X.D., and Y.Y. collected pollution control policies over Beijing; D.T. and Y.Z. estimated regional emission reductions; J.C. estimated emission reductions over Beijing and performed CMAQ experiments; J.C. and Q.Z. prepared the manuscript with contributions from all co-authors.

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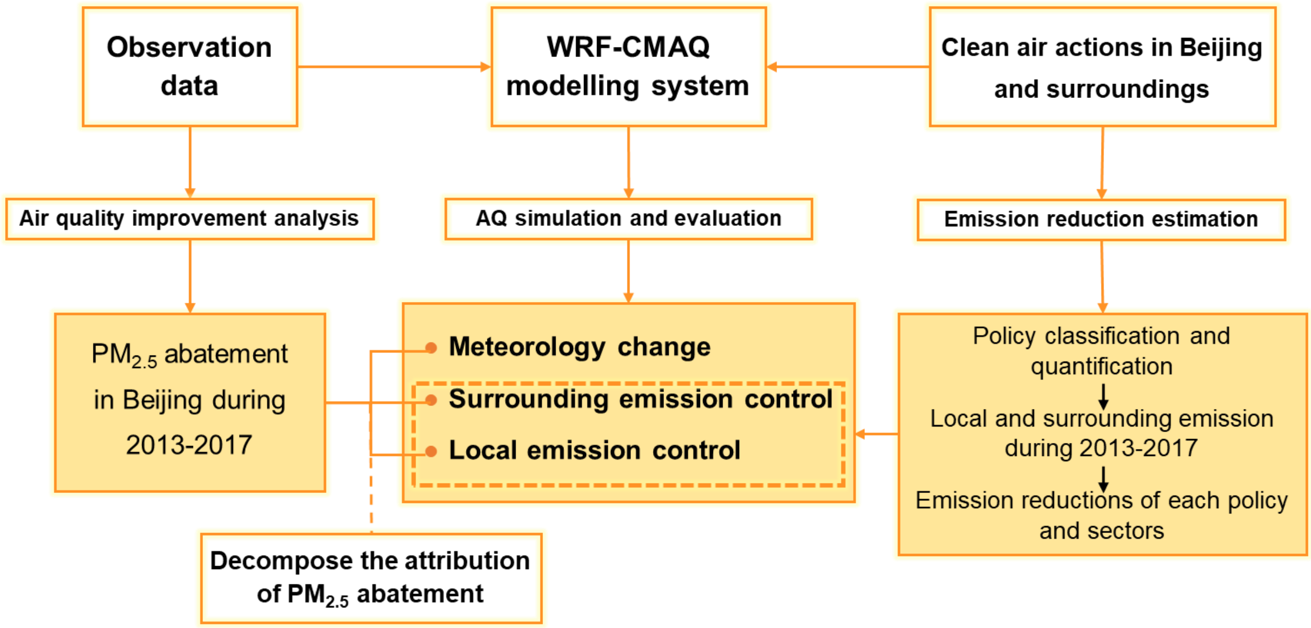

Figure 1: Methodological framework for the decomposition analysis of improved $PM_{2.5}$-related air quality in Beijing during 2013-2017.

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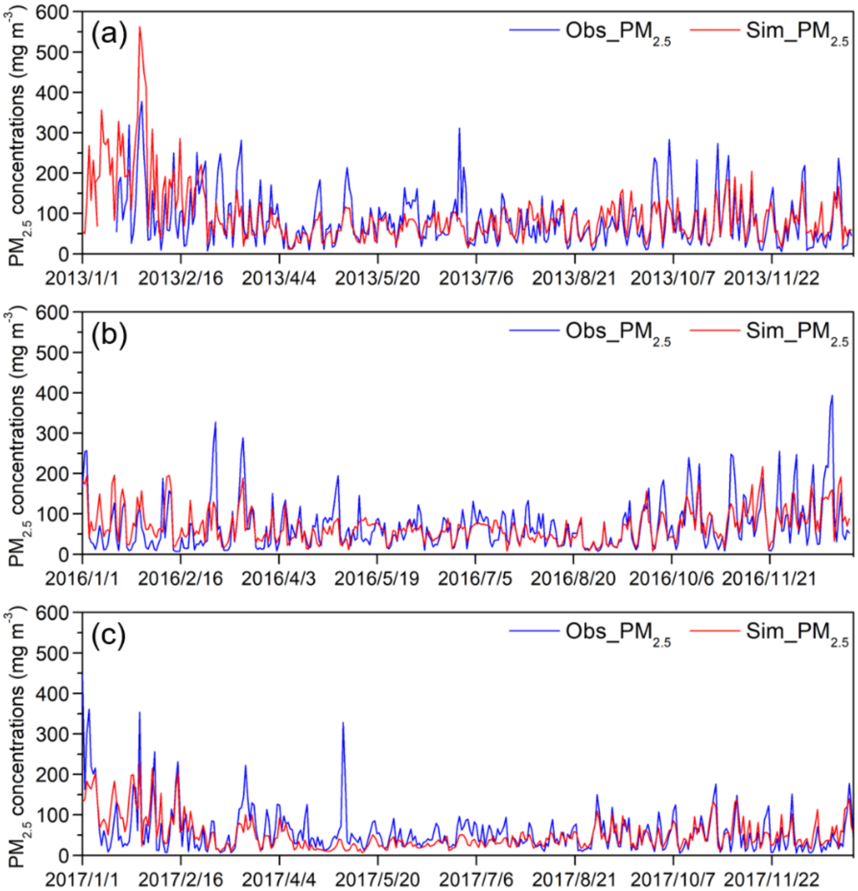

Figure 2: Comparison of observed (blue) and CMAQ-simulated (red) daily mean $PM_{2.5}$ concentrations over Beijing in 2013 (a), 2016 (b) and 2017 (c). Observation data were obtained and averaged from 12 national observation stations in Beijing. Simulated concentrations were sampled from the grids corresponding to the stations locations.

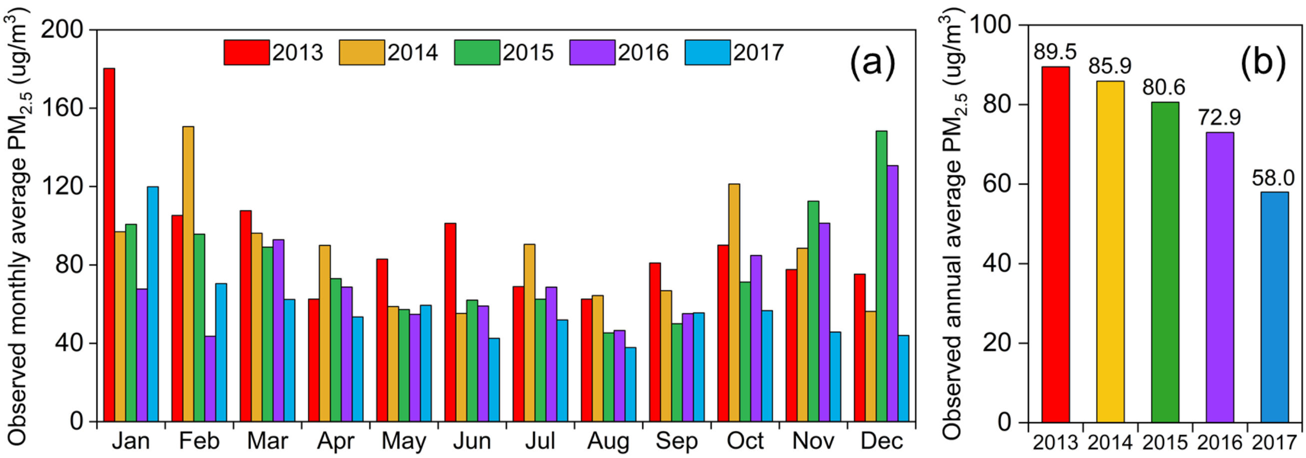

Figure 3: Observed monthly (a) and annual average (b) $PM_{2.5}$ concentrations in Beijing during 2013-2017.

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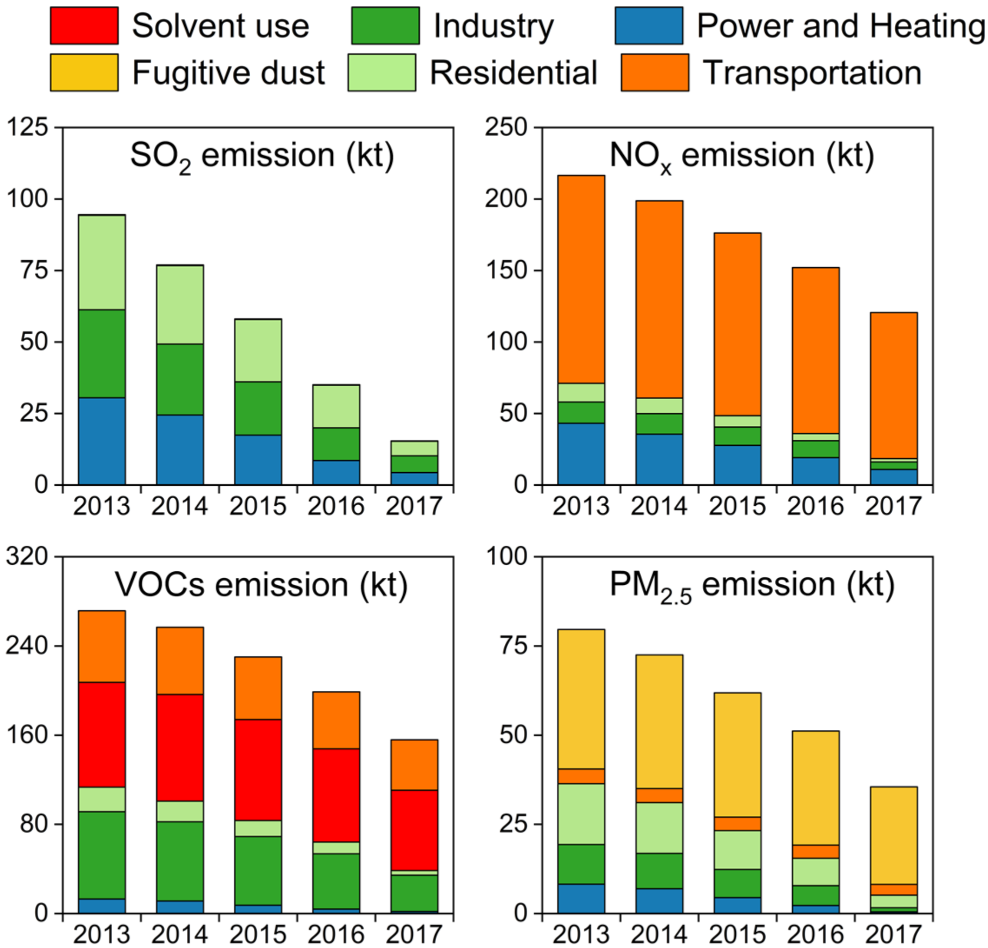

Figure 4: Changes in anthropogenic emissions of SO_2, NO_x, VOCs and primary $PM_{2.5}$ in Beijing during 2013-2017.

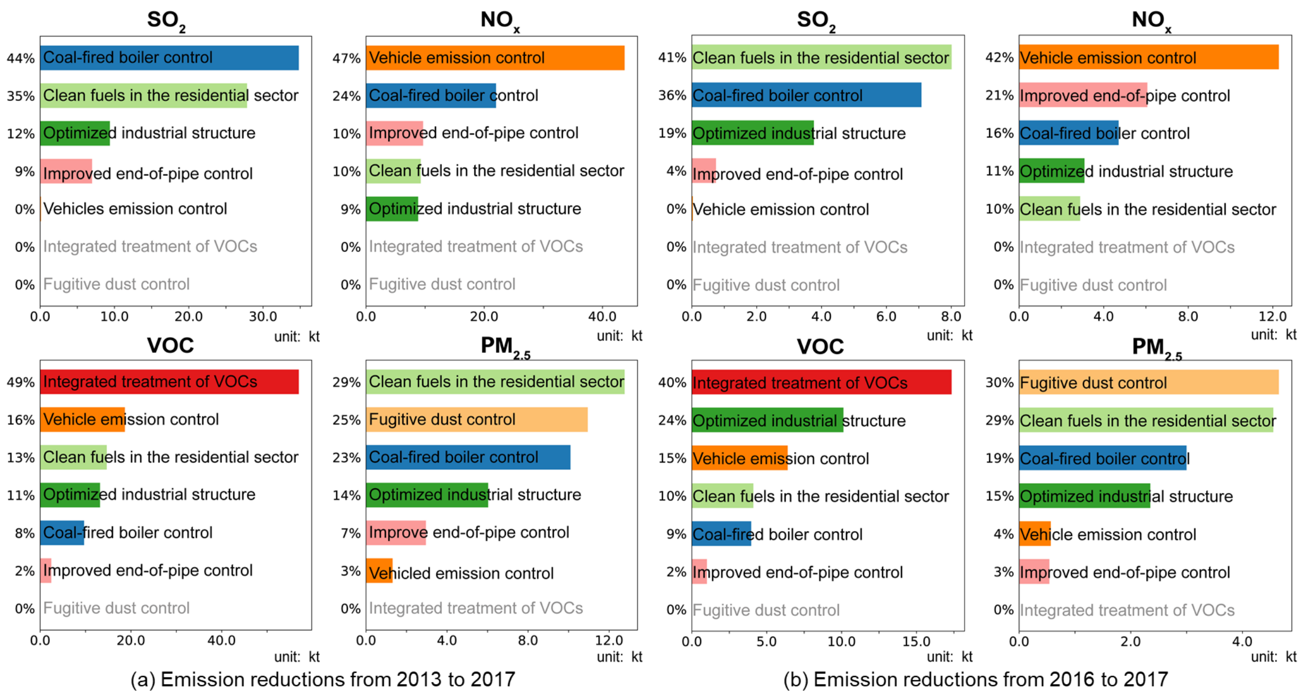

Figure 5: Contribution of the seven categories of control measures to reductions in SO_2, NO_x, VOCs and primary $PM_{2.5}$ emissions in Beijing for the periods of 2013−2017 (a) and 2016−2017 (b). The relative contribution of each measure to total emission reduction is presented on the Y-axis.

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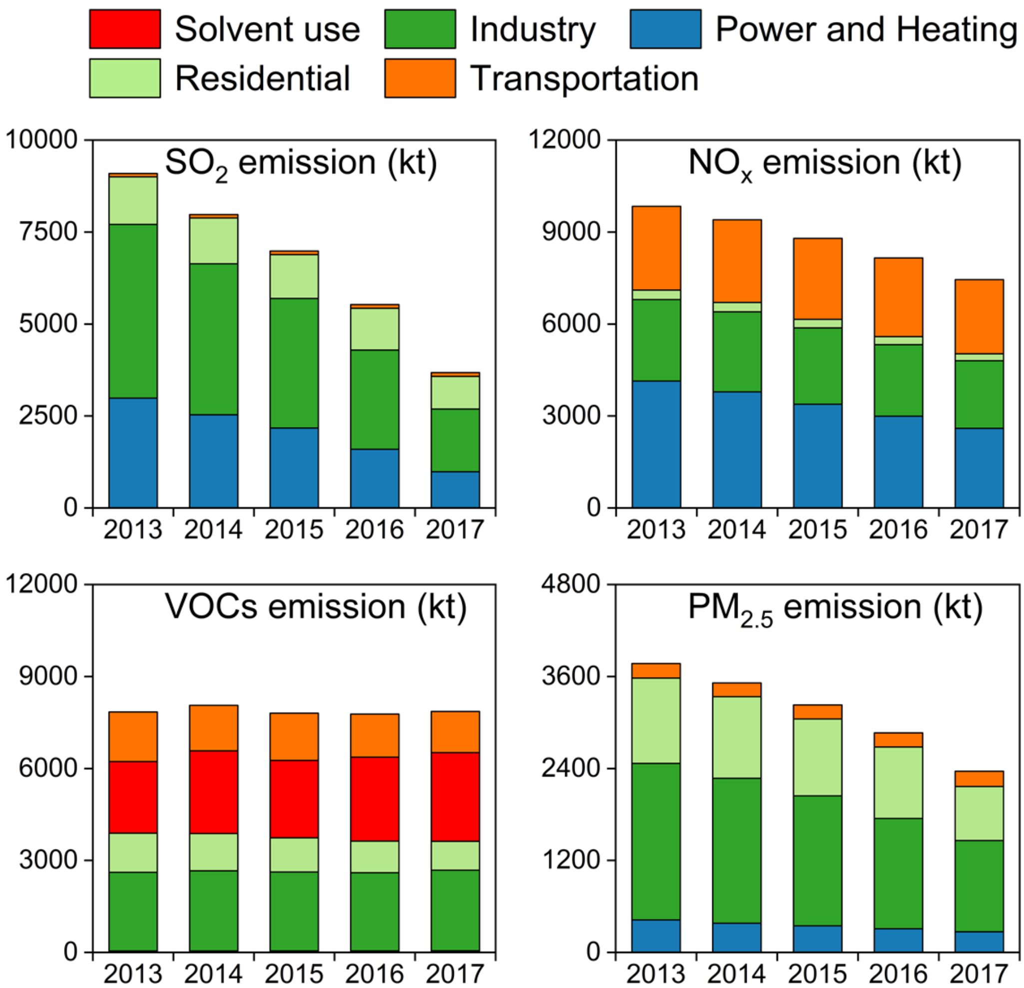

Figure 6: Changes in anthropogenic emissions of SO_2, NO_x, VOCs and primary $PM_{2.5}$ in the areas surrounding Beijing during 2013-2017. The regions include Tianjin, Hebei, Henan, Shandong, Shanxi and Inner Mongolia.

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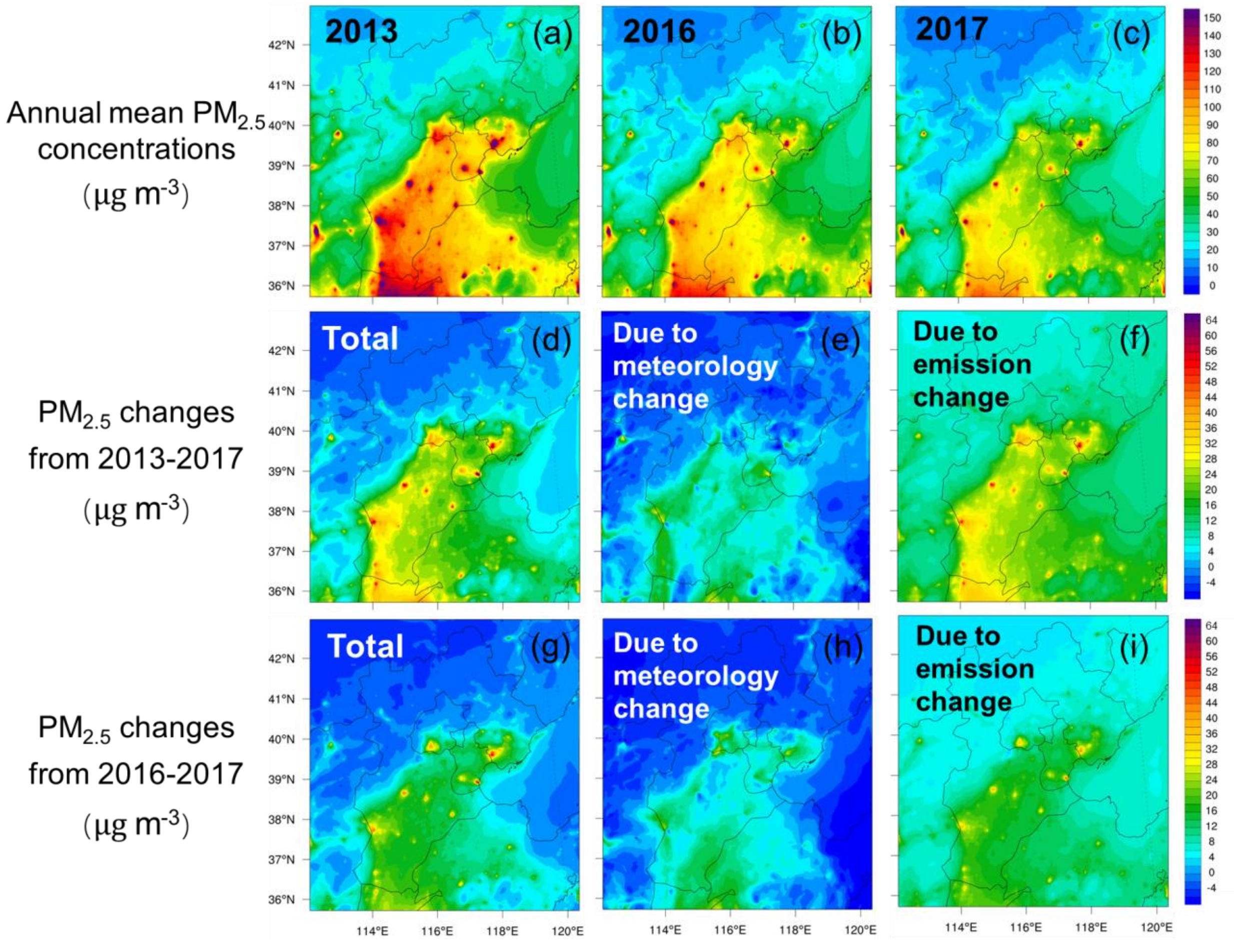

Figure 7: Changes in CMAQ-simulated annual mean $PM_{2.5}$ concentrations. (a)-(c): Base simulations of 2013, 2016, and 2017; (d-f) changes between 2013 and 2017 and contributing factors; (g-i): changes between 2016 and 2017 and contributing factors.

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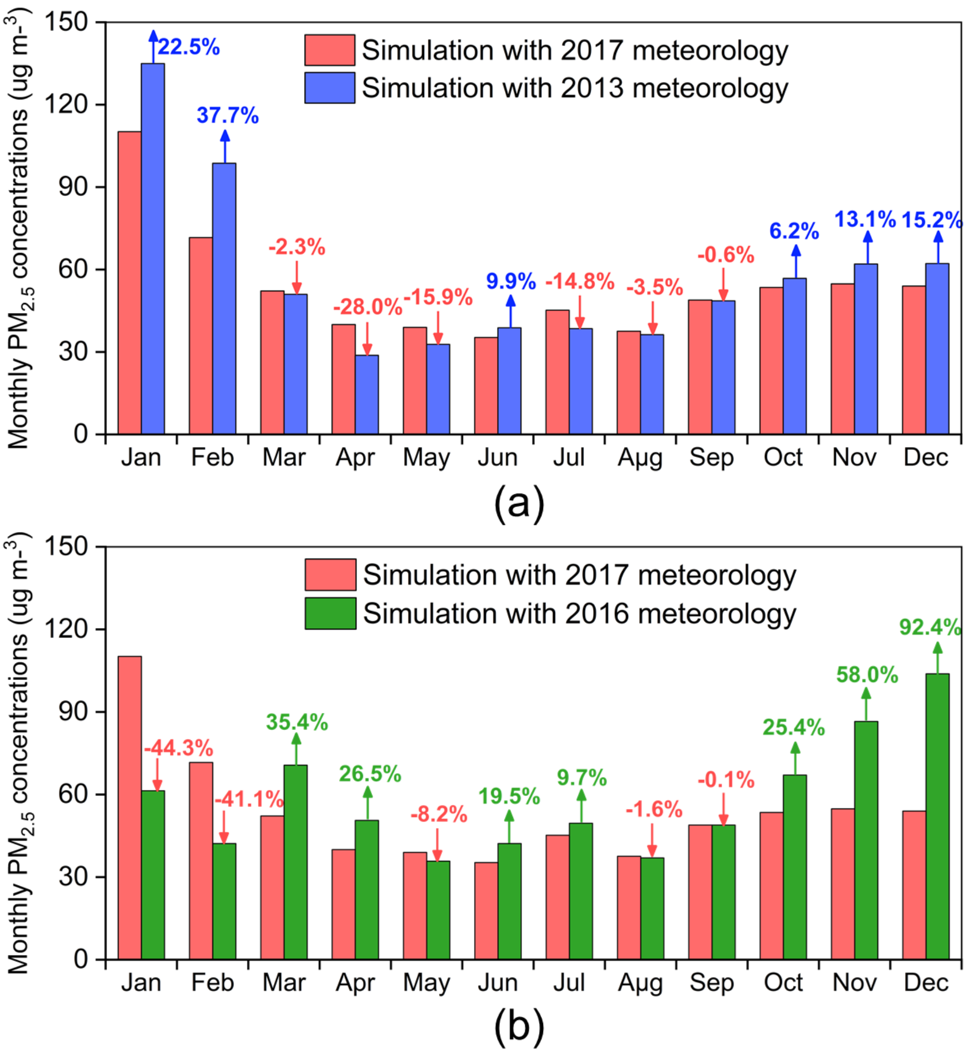

Figure 8: CMAQ-simulated monthly $PM_{2.5}$ concentrations in Beijing under different meteorological conditions. The numbers shown in each panel represent the monthly relative change rates of fixed-emission simulation results compared with the base simulation results.

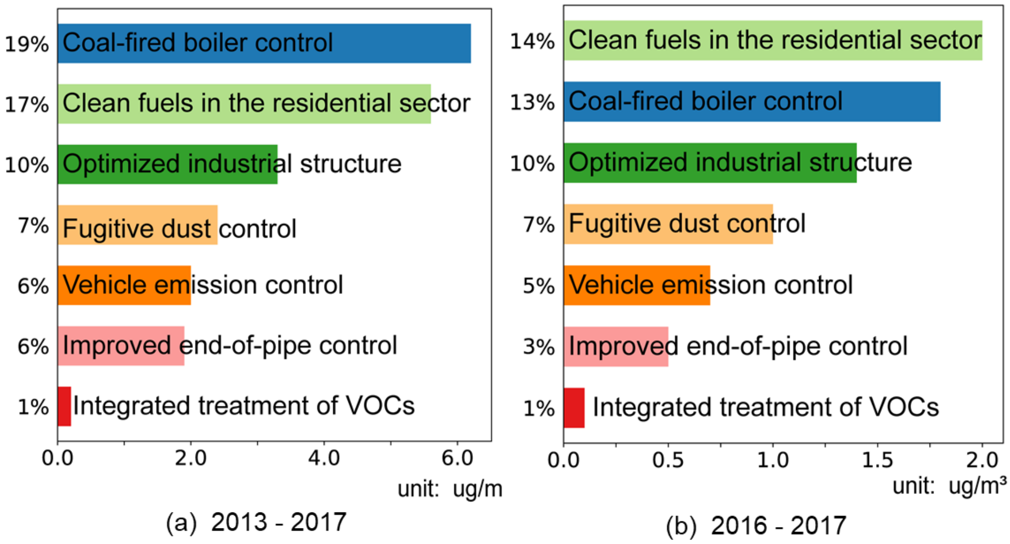

Figure 9: Contribution of the seven categories of control measures to the reductions in the $PM_{2.5}$ concentrations in Beijing for the periods of 2013−2017 (a) and 2016−2017 (b). The relative contribution of each measure to the total $PM_{2.5}$ reductions is presented on the Y-axis.

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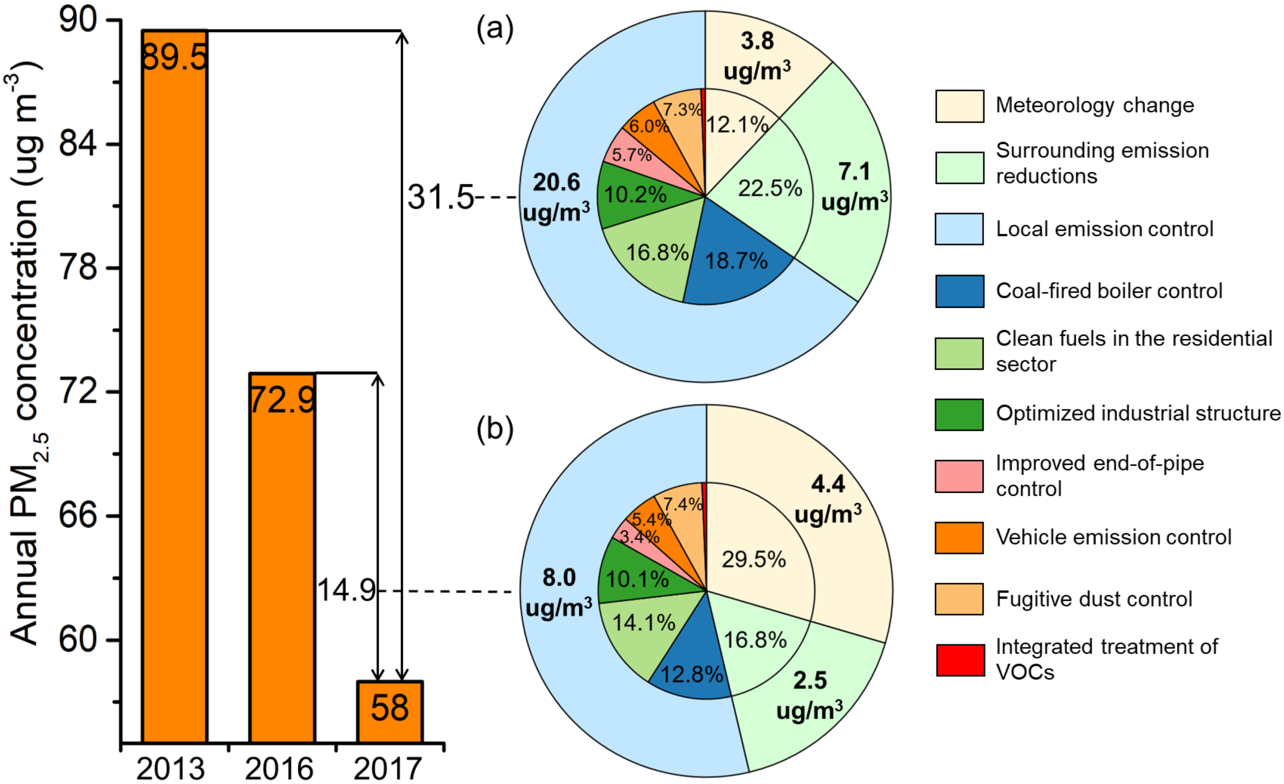

Figure 10: Decomposition of improved $PM_{2.5}$ air quality in Beijing during (a) 2013-2017 and (b) 2016-2017.

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Table 1. Summary of emission control measures implemented in the *Clean Air Action Plan* in Beijing (*2013-2017*).

Policy type	Measure ID	Specific control measures	Sectors
1. Coal-fired boiler control	1-1	By the end of 2017, Beijing had closed the four major coal-fired power plants and constructed four great natural gas thermal-power cogeneration centres instead, which reduced coal use by nearly 8.8 million tons in total.	Power and Heating
	1-2	Beijing made great efforts to renovate the coal-fired facilities with capacities of less than 20 MV in urban districts. A total capacity of 390 thousand MV of coal-fired boilers were eliminated or replaced by clean fuels such as natural gas. Coal use was reduced by more than 8.5 million tons during this process.	Industry
2. Clean fuels in the residential sector	2-1	Through cutting down nonpeak household power prices and establishing new gas heating systems, approximately 900,000 households in Beijing were converted from using coal to using gas or electricity, and coal use was reduced by a total of 2.1 million tons.	Residential
	2-2	The burning of biomass, such as wood and crops, was thoroughly forbidden by the end of 2016.	Residential
3. Optimized industrial structure	3-1	During 2013 to 2017, Beijing phased out a total of 1,992 large high-pollution enterprises in the chemical engineering, furniture manufacturing, printing, and non-mental mineral product industries; furthermore, three-quarters of the cement industry was eliminated.	Industry
	3-2	In the last 5 years, especially since 2016, Beijing has made great efforts to eliminate the small, clustered and polluting factories that cannot meet efficiency, environmental and safety standards, and a total of 11,000 such factories were managed or eliminated.	Industry
4. Improved end-of-pipe control	4-1	Since 2013, a total of 468 projects involving cleaner production and technological upgrades for high-pollution industrial sectors were carried out by the government. During this process, Beijing has gradually retrofitted all cement factories to achieve thorough denitrification and degasing and has enhanced the desulfurization retrofitting of the non-mental mineral product and chemical engineering industries.	Industry
	4-2	Beijing first promoted low-nitrogen-burning (LNB) combustion for all industrial sectors in 2013, and the LNB transformation of nearly 30,000 MV of gas-fired boilers and oil-fired boilers has been completed.	Industry

5. Vehicle emission control	5-1	1) During 2013 to 2017, Beijing retired a total of 2,167,000 old vehicles, and all "yellow-labelled" cars (gasoline and diesel cars that failed to meet Euro Ⅰ and Euro Ⅲ standards) were eliminated completely by 2017. 2) In Mar 2017, Beijing first implemented the latest China Ⅵ emission standards, which are one of the most tightened emission standards in the world. 3) A total of 51,000 taxis completed the replacement of three-way catalytic converters, and 17,000 heavy-duty diesel vehicles were equipped with wall flow particle traps. 4) In Sep 2017, all out-of-city diesel vehicles with lower emission standards than China Ⅲ were forbidden to travel within the sixth ring road.	On-road transportation
	5-2	1) By the end of 2016, all off-road vehicles were required to comply with "*Limits and measurement methods for exhaust pollutants from diesel engines of non-road mobile machinery (China III, IV)*". 2) Since 2017, the use of heavily polluting off-road vehicles has been restricted in the six major urban districts and Tongzhou district.	Off-road transportation
6. Integrated treatment of VOCs	6-1	Beijing started to eliminate organic solvent coatings, bituminous waterproof materials and organic painted furniture manufacturing in 2013. Meanwhile, Beijing promoted the use of high-solids and waterborne paints, which contain much fewer organic chemicals, in machine manufacturing, printing, coating and automobile repair sectors.	Solvent use
	6-2	During 2013 to 2017, the Yanshan company, the only petrochemical industry enterprise in Beijing, completed seven extensive VOC control projects, such as the innovation of sealing and defocusing technology, the detection and repair of leakage points, and the specialized management of refined oil production and storage areas.	Industry
7. Fugitive dust control	7-1	Beijing increased the quality and frequency of the road cleaning process. By the end of 2017, a mechanized cleaning process were adopted in an area of 90,580,000 square metres, accounting for 88% of the total urban road area.	Fugitive dust
	7-2	Beijing shut down a total of 310 concrete mixing plants and updated over 20 thousand cinderblock transporters. Additionally, more than 1,200 construction sites were equipped with video monitoring system at the exits and entrances.	Fugitive dust
	7-3	By the end of 2015, Beijing completed an afforestation project in advance and afforested nearly 700 square kilometres in nearby plain areas.	Fugitive dust

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Table 2. CMAQ simulations conducted in this study for the decomposition analysis. The seven categories of emission control measures include *Coal-fired boiler control* (policy1), *Clean fuels in the residential sector* (policy2), *Optimized industrial structure* (policy3), *Improved end-of-pipe control* (policy4), *Vehicle emission control* (policy5), *Integrated treatment of VOCs* (policy6) and *Fugitive dust control* (policy7), respectively.

Case Number	Year of meteorological data	Year of emission data in Beijing	Year of emission data in surrounding regions	Purpose of the simulation	Simulated $PM_{2.5}$ ($\mu g\ m^{-3}$)
SIM_{E13M13}	2013	2013	2013	reproduce air quality in 2013	86.3 (89.5)
SIM_{E16M16}	2016	2016	2016	reproduce air quality in 2016	70.1 (72.9)
SIM_{E17M17}	2017	2017	2017	reproduce air quality in 2017	53.5 (58.0)
SIM_{E17M13}	2013	2017	2017	quantify the impact of meteorology compared with 2013	57.4
SIM_{E17M16}	2016	2017	2017	quantify the impact of meteorology compared with 2016	57.8
$SIM_{E17S13M17}$	2017	2017	2013	quantify the contribution from the emission reduction of surroundings during 2013-2017	60.9
$SIM_{E17S16M17}$	2017	2017	2016	quantify the contribution from the emission reduction of surroundings during 2016-2017	55.9
$SIM_{E17Li3M17}$ (i=1-7)	2017	2017 (excluding the implementation of each control measure since 2013)	2017	quantify the contribution of each control measures during 2013-2017	(SI)
$SIM_{E17Li6M17}$ (i=1-7)	2017	2017 (excluding the implementation of each control measure since 2016)	2017	quantify the contribution of each control measures during 2016-2017	(SI)