Drivers of improved $PM_{2.5}$ air quality in China from 2013 to 2017

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From 2013 to 2017, with the implementation of the toughest-ever clean air policy in China, significant declines in fine particle ($PM_{2.5}$) concentrations occurred nationwide. Here we estimate the drivers of the improved $PM_{2.5}$ air quality and the associated health benefits in China from 2013 to 2017 based on a measure-specific integrated evaluation approach, which combines a bottom-up emission inventory, a chemical transport model, and epidemiological exposure-response functions. The estimated national population–weighted annual mean $PM_{2.5}$ concentrations decreased from 61.8 (95%CI: 53.3–70.0) to 42.0 μg/m^3 (95% CI: 35.7–48.6) in 5 y, with dominant contributions from anthropogenic emission abatements. Although interannual meteorological variations could significantly alter $PM_{2.5}$ concentrations, the corresponding effects on the 5-y trends were relatively small. The measure-by-measure evaluation indicated that strengthening industrial emission standards (power plants and emission-intensive industrial sectors), upgrades on industrial boilers, phasing out outdated industrial capacities, and promoting clean fuels in the residential sector were major effective measures in reducing $PM_{2.5}$ pollution and health burdens. These measures were estimated to contribute to 6.6- (95% CI: 5.9–7.1), 4.4- (95% CI: 3.8–4.9), 2.8- (95% CI: 2.5–3.0), and 2.2- (95% CI: 2.0–2.5) μg/m^3 declines in the national $PM_{2.5}$ concentration in 2017, respectively, and further reduced $PM_{2.5}$-attributable excess deaths by 0.37 million (95% CI: 0.35–0.39), or 92% of the total avoided deaths. Our study confirms the effectiveness of China's recent clean air actions, and the measure-by-measure evaluation provides insights into future clean air policy making in China and in other developing and polluting countries.

clean air actions | $PM_{2.5}$ | emission abatements | air quality improvements | health benefits

Rapid and energy-intensive development in China over the past several decades has led to severe air pollution and negative public health effects, which have become notable environmental and social problems in China (1, 2). At the beginning of 2013, headlines continually reported the severe $PM_{2.5}$ (particulate matter with an aerodynamic diameter of less than 2.5 μm) pollution across the nation. The hourly $PM_{2.5}$ concentration in the capital of China, Beijing, even increased to over 1,000 μg/m^3, which is 40 times higher than the World Health Organization (WHO) standard level for good health (3). $PM_{2.5}$ exposure in 2015 was estimated to result in ∼8.9 million deaths globally, among which over a quarter occurred in China (4).

To address severe air pollution issues and protect public health, the State Council of China promulgated the toughest-ever Air Pollution Prevention and Control Action Plan (Action Plan) in 2013 (5), in which $PM_{2.5}$ concentration reductions of 25%, 20%, and 15% in 2017 compared to the level in 2013 were mandated in 3 key regions (depicted in the *SI Appendix*, Fig. S1): the Beijing-Tianjin-Hebei region (BTH), the Yangtze River Delta region (YRD), and the Pearl River Delta region (PRD), respectively.

In support of the Action Plan, a series of stringent clean air actions was implemented from 2013 to 2017; as summarized in Fig. 1, these actions include strengthening industrial emission

Significance

The high frequency of haze pollution in China has attracted broad attention and triggered, in 2013, the promulgation of the toughest-ever clean air policy in the country. In this study, we quantified the air quality and health benefits from specific clean air actions by combining a chemical transport model with a detailed emission inventory. As tremendous efforts and resources are needed for mitigating emissions from various sources, evaluation of the effectiveness of these measures can provide crucial information for developing air quality policies in China as well as in other developing and highly polluting countries. Based on measure-specific analysis, our results bear out several important implications for designing future clean air policies.

ENVIRONMENTAL SCIENCES

SUSTAINABILITY SCIENCE

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The authors declare no competing interest.

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Data deposition: Gridded monthly emission inventory used in this study and gridded CMAQ model output of monthly mean $PM_{2.5}$ concentrations are available from http://www.meicmodel.org/dataset-appcape.html.

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standards, phasing out small and polluting factories, phasing out outdated industrial capacities, upgrades on industrial boilers, promoting clean fuels in the residential sector, and strengthening vehicle emission standards. Detailed information regarding each measure is documented in the *SI Appendix*, section S1. With the implementation of stringent clean air actions, $PM_{2.5}$ concentration across the country decreased rapidly between 2013 and 2017 (6).

It is expected that the implementation of active clean air policies can achieve remarkable improvements in air quality (7, 8). Recent studies have reported significant $PM_{2.5}$ air quality improvements and associated health benefits from 2013 to 2017 in China (9–13). Meanwhile, the relative contribution of emission control and interannual meteorological variation to reductions in $PM_{2.5}$ concentrations has also been identified (14–16). However, no previous studies have quantified the impacts of different emission control policies on $PM_{2.5}$ air quality across China during the implementation of the Action Plan. Hence, a complete and comprehensive evaluation of the effectiveness of the Action Plan is still missing. Here, we systematically evaluated the drivers of improved $PM_{2.5}$ air quality and the associated health benefits in China from 2013 to 2017, with an emphasis on the impacts of 6 major control measures summarized from the Action Plan (Fig. 1). As the Chinese government has put tremendous effort and resources into controlling emissions from various emitting sources, evaluation of the real effectiveness of these emission control measures can provide crucial information for developing air quality policies in China and shed light on them for other developing and highly polluting countries (17).

The details of our analytic approach are documented in *Materials and Methods*. In summary, the Multi-resolution Emission Inventory for China (MEIC) model was used to provide the baseline emission accounting from 2013 to 2017, and to conduct a measure-by-measure evaluation of emission abatements (18, 19). The Weather Research and Forecasting Model–Community Multiscale Air Quality Model (WRF-CMAQ) (20, 21) was then applied to simulate variations in $PM_{2.5}$ concentrations from 2013 to 2017, separate the contributions of anthropogenic and meteorological factors to $PM_{2.5}$ variations, and quantify measure-specific air quality improvements (*SI Appendix*, section S2 and Table S1). Measure-specific abatements in $PM_{2.5}$-related health burdens were then estimated with a set of epidemiological concentration–response (C-R) functions (i.e., the Global Exposure Mortality Model, or GEMM) (4).

We evaluated the simulated $PM_{2.5}$ concentrations against ground-based observations in 74 cities (536 sites in total; locations are shown in *SI Appendix*, Fig. S1) which had continuous observations between 2013 and 2017. The observational data were obtained from the national monitoring network operated by the China National Environmental Monitoring Center (22). Although publicly available observation data on $PM_{2.5}$ chemical composition was too sparse to support a comprehensive trend evaluation, we compared modeled major $PM_{2.5}$ composition (sulfate, nitrate, ammonium, organic carbon, and black carbon) with observation data collected from a wide variety of sources (60 sites in total; for site information, see *SI Appendix*, Table S2). In general, our model simulations well captured the spatiotemporal variations in $PM_{2.5}$ concentration between 2013 and 2017(*SI Appendix*, Table S3 and Fig. S2), and model performance was in line with other recent regional modeling studies in China (23, 24). The model also shows reasonable performance in $PM_{2.5}$ chemical composition with normalized mean biases (NMBs) ranging from −32.1 to 40.8% for different species. Detailed comparisons between model simulations and observations can be found in *SI Appendix*, section S4 and Figs. S2–S5.

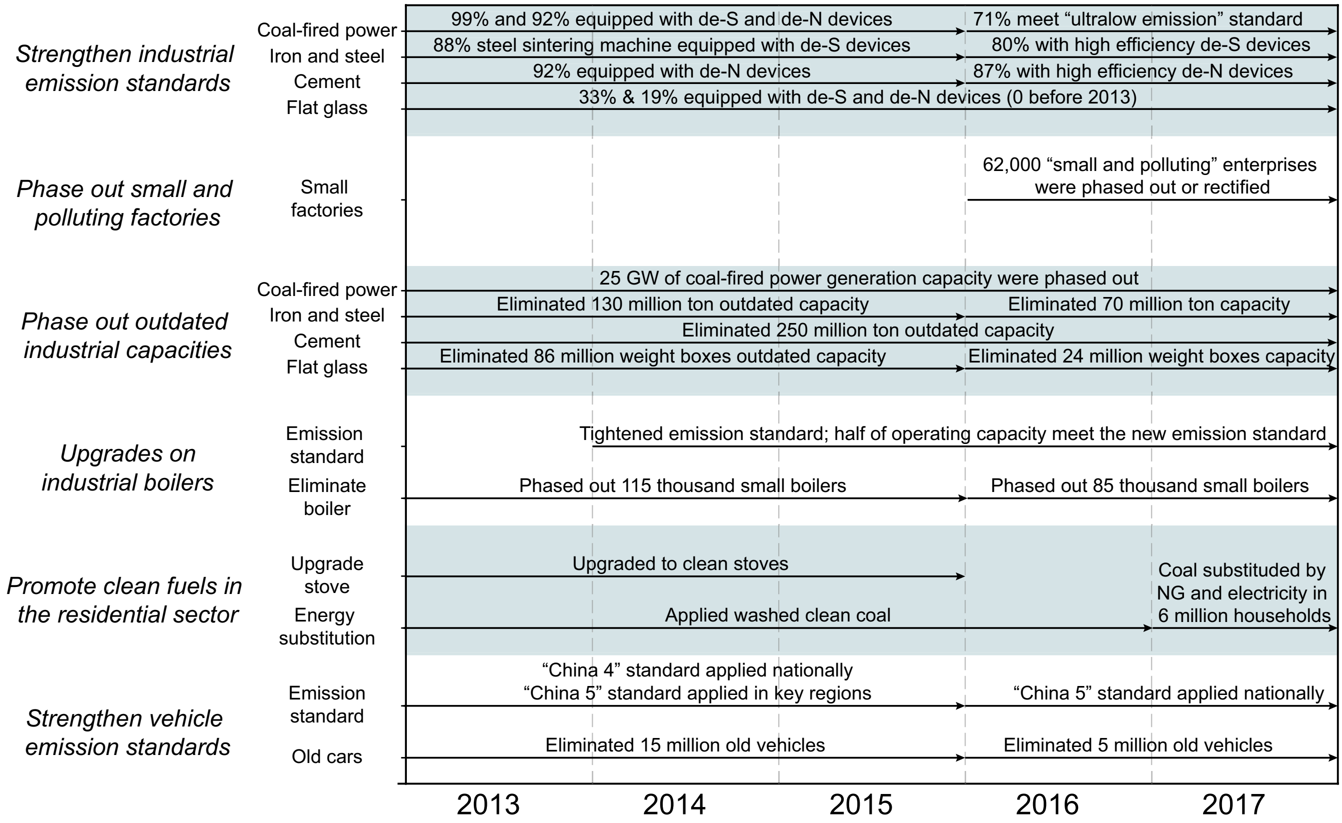

Fig. 1. Summary of major air pollution control measures taken between 2013 and 2017. De-S, desulfurization; De-N, denitrification; NG, natural gas.

Results

Improved $PM_{2.5}$ Air Quality from 2013 to 2017. Fig. 2 *A* and *B* shows the spatial distribution of the simulated annual mean $PM_{2.5}$ concentrations over China in 2013 and 2017 (maps for 2014 to 2016 are presented in the *SI Appendix*, Fig. S6). In both years, high levels of $PM_{2.5}$ concentrations were observed in northern and central China, especially in the BTH and surrounding regions, where the emission intensity is the highest in the country (25). As illustrated in Fig. 2*C*, from 2013 to 2017, significant reductions in $PM_{2.5}$ concentrations occurred across the nation as a result of considerable reductions in the emissions of major air pollutants. According to a recent estimate of the MEIC model (*SI Appendix*, Fig. S7) (18), from 2013 to 2017 national emissions of SO_2, NO_x, and primary $PM_{2.5}$ decreased by 59%, 21%, and 33%, respectively.

The national annual population–weighted mean $PM_{2.5}$ concentration (unless stated otherwise, the $PM_{2.5}$ concentrations reported hereafter correspond to simulated population-weighted mean $PM_{2.5}$ concentrations) was predicted to decrease from 61.8 μg/m^3 (95% CI: 53.3–70.0) in 2013 to 42.0 μg/m^3 (95% CI: 35.7–48.6) in 2017, which represents a 32% reduction (95% CI: 30–33%). The highest decrease in $PM_{2.5}$ was observed in the BTH region, with a simulated value of 38% (95% CI: 36–45%); the reductions in the YRD and PRD (Guangdong Province) were 27% (95% CI: 24–32%) and 21% (95% CI: 17–35%), respectively. Our results show that the annual $PM_{2.5}$ concentrations decreased nationally and regionally in all years except in the PRD in 2017 (*SI Appendix*, Fig. S8). The rebound in 2017 $PM_{2.5}$ concentration in the PRD can be explained by the unfavorable meteorological conditions (*SI Appendix*, Figs. S9–S11).

Meteorological Impact on $PM_{2.5}$ Concentrations between 2013 and 2017. Fig. 3 *A*–*D* presents the frequency of air stagnation days and the modeled meteorologically driven $PM_{2.5}$ anomaly by region for each month between 2013 and 2017. The occurrence of air stagnation, which is an integrated indicator of wind speed, boundary layer height (PBL), and occurrence of precipitation (26), is generally positively correlated with $PM_{2.5}$ concentrations (*SI Appendix*, section S7). For instance, broadly reported severe haze episodes occurred in the BTH and YRD regions (27, 28) in January 2013. These events were associated with severe air stagnation conditions represented by low wind speeds, low PBL, and high humidity (28–30). Low wind speeds and low PBL suppressed the removal of $PM_{2.5}$, as could be expected from weak ventilation conditions, and high humidity promoted the formation of secondary aerosols via aqueous-phase aerosol chemistry (28–30). Similar unfavorable meteorological conditions and severe regional $PM_{2.5}$ pollution episodes were observed in February 2014 and December 2016 in the BTH and in November/December 2013 in the YRD (15, 31, 32). In contrast, favorable regional meteorological conditions associated with a high frequency of northerly wind flows in December 2017 led to low $PM_{2.5}$ concentrations

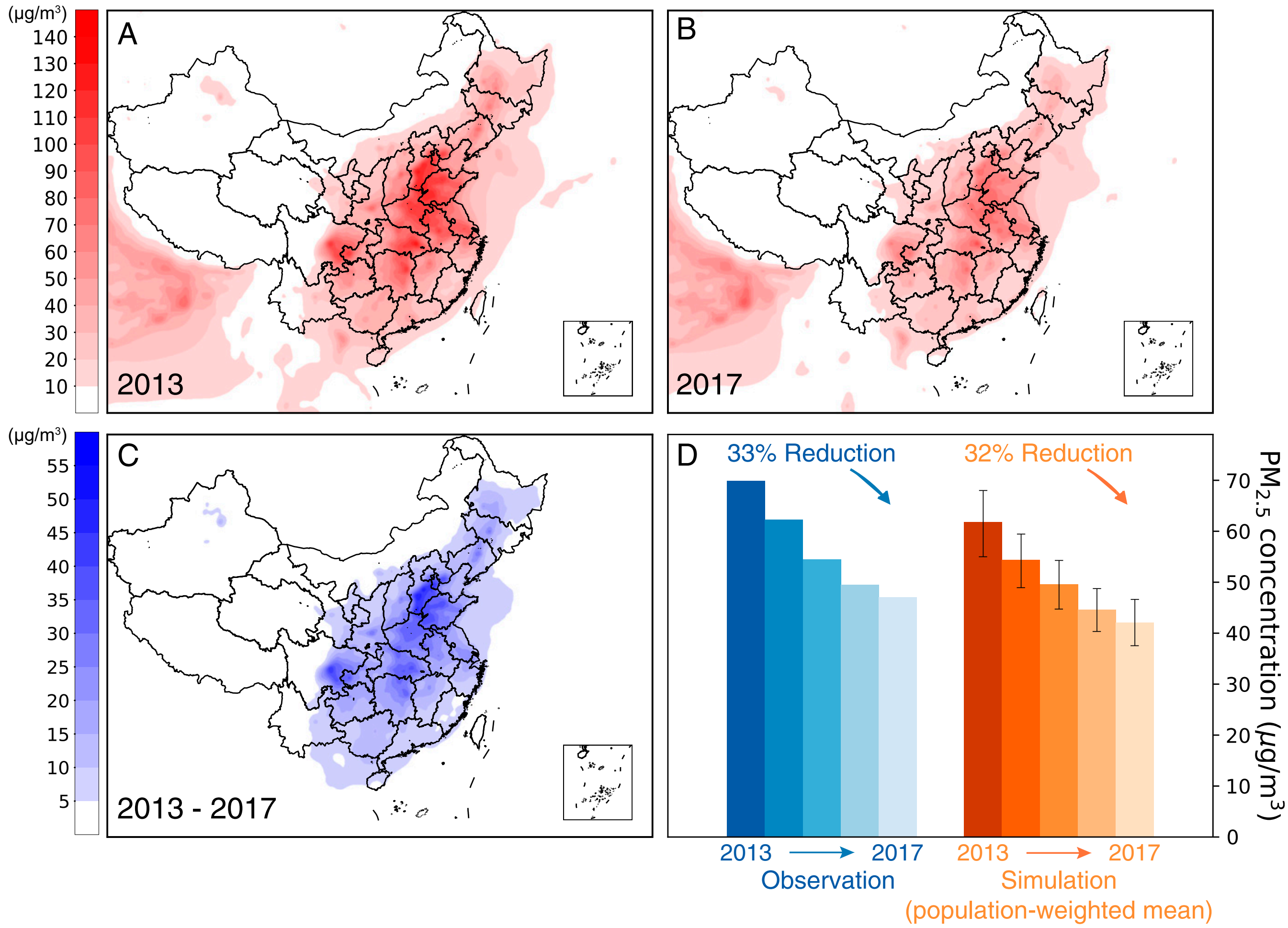

Fig. 2. Variations in China's $PM_{2.5}$ concentrations from 2013 to 2017. (*A* and *B*) Distributions of annual mean $PM_{2.5}$ concentrations in China in 2013 and 2017. (*C*) Reductions of annual mean $PM_{2.5}$ concentrations between 2013 and 2017 (positive value). (*D*) Observed national annual mean $PM_{2.5}$ concentrations calculated based on samples from continuously operated sites and simulated national annual population-weighted mean $PM_{2.5}$ concentrations. Error bars: uncertainty ranges (95% CI) of model estimates.

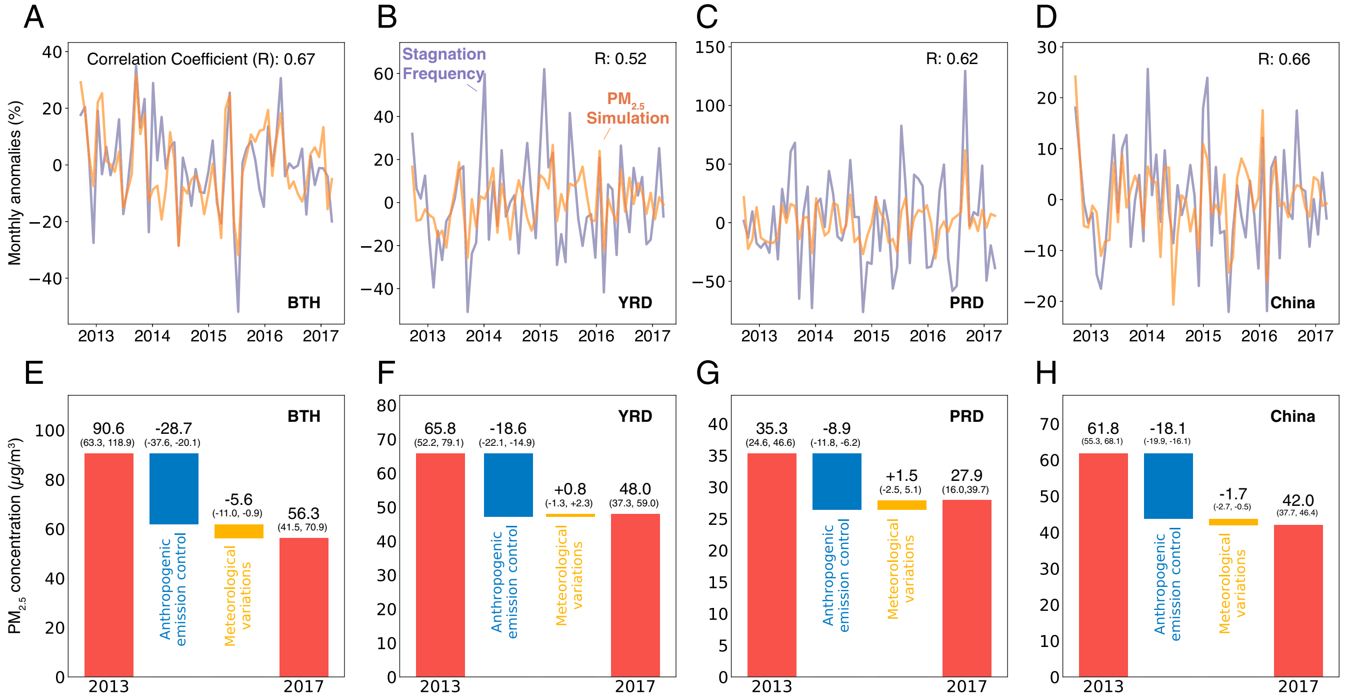

Fig. 3. Meteorologically driven interannual variations in $PM_{2.5}$ concentrations. (*A–D*) Monthly percentage anomalies of simulated meteorologically driven interannual $PM_{2.5}$ variations (population-weighted) and occurrence frequency of air stagnation days (population-weighted) from their 2013–2017 means for individual months in the BTH, YRD, and PRD regions and all of China. (*E–H*) Variations in annual population-weighted mean $PM_{2.5}$ concentrations and anthropogenic and meteorological drivers of $PM_{2.5}$ variations between 2013 and 2017 for the BTH, YRD, PRD, and all of China; values in parentheses represent uncertainty ranges of estimates (95% CI).

in the BTH (33). Variation in meteorological conditions can dominate monthly $PM_{2.5}$ anomalies at a regional scale. For example, model results show that 70% of $PM_{2.5}$ reduction in December 2017 in the BTH region compared to December 2016 could be attributed to variation in meteorological conditions.

However, variation in meteorological conditions had less impact on the 5-y $PM_{2.5}$ trends (i.e., from 2013 to 2017; Fig. 3 *E–H*). We estimated that variation in meteorological conditions led to reduced $PM_{2.5}$ concentrations by 5.6 μg/m^3 (95% CI: 0.9–11.0) in the BTH region between 2013 and 2017, contributing to 16% of total decrease in $PM_{2.5}$ concentrations for the same period. Meteorological conditions in 2017 in the YRD and PRD regions were more unfavorable compared to 2013 and counteracted the decrease in $PM_{2.5}$ concentrations from 2013 to 2017 (*SI Appendix*, Fig. S12). Nationally, we estimated that meteorological conditions could explain 9% of the total decrease in $PM_{2.5}$ concentrations from 2013 to 2017, thereby demonstrating that the improvement in $PM_{2.5}$ air quality was dominated by abatements in anthropogenic emissions rather than interannual variation in meteorological conditions. Our results are consistent with recent studies about meteorological impacts on China's $PM_{2.5}$ pollution (14–16).

Anthropogenic Impact and Measure-Specific Benefits. Fig. 4 shows the environmental and public health benefits of the Action Plan. Our estimates suggest that, with the 5-y implementation of the 6 control measures, national emissions of SO_2, NO_x, and primary $PM_{2.5}$ were reduced by 16.4, 8.0, and 3.5 Tg, respectively (*SI Appendix*, Table S4 and Fig. 4 *A–C*). Consequently, the national annual $PM_{2.5}$ concentration decreased by 17.4 (95% CI: 15.4–19.0) to 42.0 μg/m^3 (95% CI: 35.7–48.6), and the number of $PM_{2.5}$-related excess deaths decreased by 0.41 million (95% CI: 0.38–0.43) to 1.98 million (95% CI: 1.85–2.09) in 2017 (Fig. 4 *D* and *E*). All of the 3 key regions displayed considerable declines in $PM_{2.5}$ concentrations and related deaths due to emission abatements (*SI Appendix*, Figs. S13–S15 and Table S5). The most evident reductions in $PM_{2.5}$ concentrations occurred in the BTH (both in magnitude and in percentage) because of the strict regional $PM_{2.5}$ reduction requirements and the aggressive control actions applied in the BTH (*SI Appendix*, section S1). The identified environmental and public health benefits at both national and regional scales demonstrate the effectiveness of the Action Plan.

Among the 6 control measures, strengthening industrial emission standards, upgrades on industrial boilers, phasing out outdated industrial capacity, and promoting clean fuels in the residential sector were estimated to be the major effective control measures, together accounting for 92% of the national abatements in annual $PM_{2.5}$ concentrations and related excess deaths, because of their considerable contributions to the emission abatements of all 3 major pollutants. Notably, these major effective measures mostly target the industrial sector, highlighting the industry-dominant emission structure in China and the efficacy of emission controls in industrial sectors (including the power sector) from 2013 to 2017. The contributions of the control measures in the key regions were similar to the contributions at the national scale (*SI Appendix*, Fig. S13 and Table S4), although discrepancies in the effectiveness of control measures existed in different regions due to differences in industrial structure, emission structure, and focus of control measures.

Strengthen industrial emission standards. Strengthened emission standards for thermal power plants and all emission-intensive industrial sectors (e.g., iron and steel, cement) were enacted from 2013 to 2017, and these standards led to large-scale applications of strict end-of-pipe (EOP) control devices in the corresponding industries (Fig. 1 and *SI Appendix*, section S1). For example, by the end of 2017 more than 95% of the coal-fired power plants in China were equipped with flue gas desulfurization (FGD) and selective catalytic reduction (SCR) or selective noncatalytic reduction (SNCR) systems, and 71% of coal-fired power generation capacity met "ultra-low emission" standards, with emission levels of major air pollutants similar to those from gas-fired power plants (18). In addition, more

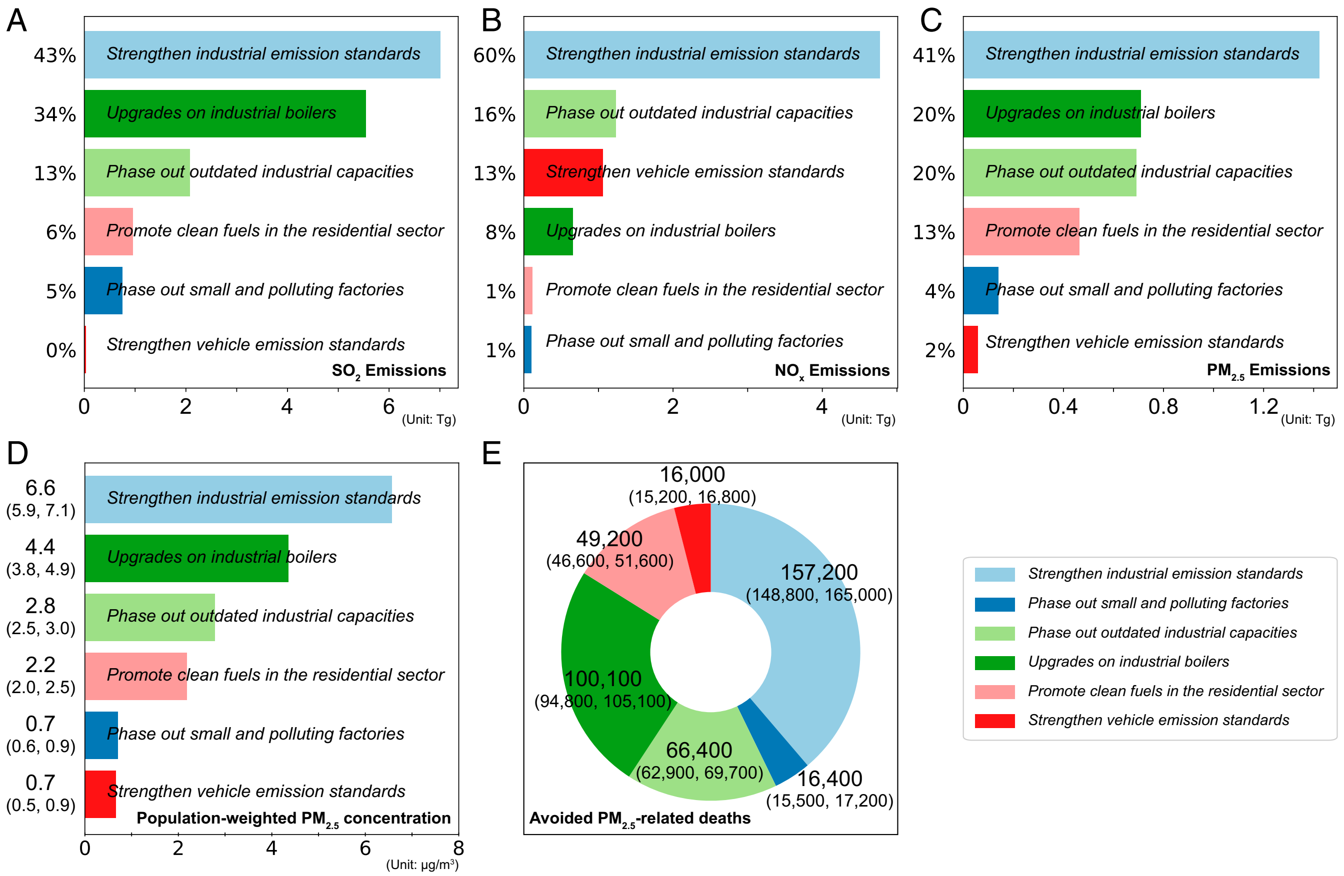

Fig. 4. Measure-specific contributions to emission reductions, $PM_{2.5}$ abatements, and avoided excess deaths. (*A*–*C*) Fractional contribution of each measure to reductions in SO_2, NO_x, and $PM_{2.5}$ emissions, respectively. (*D*) Contribution of each measure to national population-weighted mean $PM_{2.5}$ concentrations (μg/m^3). (*E*) Avoided national $PM_{2.5}$-attributable excess deaths from the 6 clean air measures. All numbers labeled in *E* depict the measure-specific avoided excess deaths. Values in parentheses in *D* and *E* represent uncertainty ranges of the estimates (95% CI).

than 80% of steel-sintering machines and cement kilns were equipped with FGD and SCR (or SNCR) systems, respectively, yielding a 90% attainment rate for flue gas emissions from emission-intensive industrial sectors. Consequently, strengthened industrial emission standards were estimated to be the most significant contributor to air quality improvements and related health benefits. We estimated that, nationally, this measure led to reductions of 7.01 Tg (43% of total abatements) for SO_2, 4.77 Tg (60%) for NO_x, and 1.42 Tg (41%) for primary $PM_{2.5}$ emissions, and contributed to a 6.6-μg/m^3 reduction (95% CI: 5.9–7.1) in the annual $PM_{2.5}$ concentration, which further led to a decrease of 157,200 (95% CI: 148,800–165,000) in the number of $PM_{2.5}$-related deaths in 2017. Strengthening industrial emission standards was also the most effective measure in reducing $PM_{2.5}$ concentrations and related deaths in all 3 key regions due to the prominent role in emissions abatements (*SI Appendix*, Figs. S13–S15).

Upgrades on industrial boilers. Industrial coal boilers are major sources of emissions, especially SO_2, because of their considerable coal consumption (18). From 2013 to 2017, more than 200,000 small coal boilers (≤7 MW) were shut down and all small coal boilers in urban areas were phased out. Large operating boilers were extensively equipped with SO_2 and particulate control devices after enforcement of the new emission standard (i.e., GB 13271–2014) in 2014 (Fig. 1). Consequently, considerable emission abatements were obtained: abatements of 5.54 Tg (34% of all abatements) and 0.71 Tg (20% of all abatements) in SO_2 and primary $PM_{2.5}$ emissions, which further reduced the national annual $PM_{2.5}$ concentration by 4.4 μg/m^3 (95% CI: 3.8–4.9) and contributed to 25% of the total abatements in $PM_{2.5}$-related deaths.

Phase out outdated industrial capacity. Unlike other EOP-targeted measures (e.g., strengthening industrial emission standards), this measure focused on structural adjustments by gradually phasing out outdated or inefficient technologies and capacities in various industrial sectors. For example, 200 million tons of outdated iron and steel production capacity and 250 million tons of outdated cement production capacity were eliminated between 2013 and 2017 (Fig. 1). Consequently, this structure-focused measure led to a 2.8-μg/m^3 (95% CI: 2.5–3.0) decline in national annual $PM_{2.5}$ concentrations and contributed 16% of the total abatements in deaths in 2017 as a result of the 2.08-, 1.23-, and 0.69-Tg abatements in SO_2, NO_x, and primary $PM_{2.5}$ emissions, respectively.

Promote clean fuels in the residential sector. The residential sector is a notable contributor to $PM_{2.5}$ pollution in China, especially in northern China during heating seasons (34, 35). To resolve this issue, advanced stoves and clean coal were promoted nationwide from 2013 to 2016. The substitution of coal with natural gas and electricity was further promoted in 2017, affecting 6 million households nationwide, among which 4.8 million households were located in the BTH and surrounding regions (Fig. 1). Therefore, the benefits of promoting clean fuels in the residential sector were prominent in the BTH. We estimated that this measure has reduced 0.14 Tg of SO_2 (11% of total abatements) and 0.1 Tg (20%) of primary $PM_{2.5}$ emissions, respectively, in the BTH and consequently reduced the regional annual $PM_{2.5}$ concentration by 7.0 μg/m^3 (95% CI: 5.0–9.0), and contributed to 25% of regional abatements in $PM_{2.5}$-related deaths (*SI Appendix*, Figs. S13–S15). Our results are in line with Liu et al. (35), who found that reducing emissions from the residential sector in the BTH region could introduce considerable regional $PM_{2.5}$ air quality improvements. The benefits of promoting clean fuels in the residential sector were also evident at the national scale (reduced national annual mean $PM_{2.5}$ concentrations by 2.2 μg/m^3 (95% CI: 2.0–2.5) in 2017 and contributed 12% of national abatements in $PM_{2.5}$-related deaths) because of the notable contribution to abating national primary $PM_{2.5}$ emissions (13%).

Phase out small and polluting factories. Driven by tightened emission standards, this measure aimed to replace small and highly polluting factories with large facilities equipped with clean production technologies and advanced pollution control equipment, with a focus on northern China (Fig. 1). From 2016 to 2017, more than 62,000 small and polluting factories in the BTH and adjacent regions were eliminated or renovated (Fig. 1), which yielded 10, 3, and 9% of regional abatements in SO_2, NO_x, and $PM_{2.5}$ emissions, respectively. Consequently, phasing out small and highly polluting factories reduced annual $PM_{2.5}$ concentrations in the BTH by 1.9 μg/m^3 (95% CI: 1.2–2.5) and contributed 7% to regional abatements in $PM_{2.5}$-related deaths. However, limited air quality and health benefits were obtained from this measure at the national scale, as it was generally a regional measure.

Strengthen vehicle emission standards. This measure was a prominent contributor to NO_x abatements (1.06 Tg, 13% of all national abatements). This shift was mainly a result of fleet turnover triggered by the strengthened emission standards in the transportation sector (i.e., China 4 and China 5 emission standards implemented between 2013 and 2017) and the forced elimination of old vehicles. For example, from 2013 to 2017, more than 20 million old and "yellow-label" vehicles (i.e., gasoline and diesel vehicles that fail to meet the China 1 and China 3 standards) were eliminated (18). However, the effects of the strengthened vehicle emission standards regarding national air quality improvement (0.7 μg/m^3, 95% CI: 0.5–0.9) and health benefits (4% of the national abatements in $PM_{2.5}$-related deaths) were hindered by the complex nonlinear response of the $PM_{2.5}$ concentration to NO_x emissions (36). The benefits from this measure were also limited in all 3 regions, but the contribution to total air quality improvements was slightly higher in the PRD because it contributed 19% to regional NO_x abatements in the PRD.

Discussion and Policy Implications

In 2013, China launched the toughest-ever clean air action plan to resolve serious and extensive air pollution issues. Our study quantified the contribution of different pollution control policies to the rapid improvement in $PM_{2.5}$ air quality across China from 2013 to 2017, thereby highlighting the effectiveness of the Action Plan. Based on a measure-by-measure approach, strengthening industrial emission standards, upgrades on industrial boilers, phasing out outdated industrial capacities, and promoting clean fuels in the residential sector were identified as the 4 major effective measures in mitigating emissions, improving $PM_{2.5}$ air quality, and reducing $PM_{2.5}$-related mortality.

Our study was subject to a number of uncertainties and limitations. First, only 6 major control measures were considered, which might have underestimated the total benefits of the Action Plan. The benefits of fugitive dust control were not investigated here due to lack of a fugitive dust emission inventory over the whole of China. Second, the bottom-up emission estimates were subject to uncertainties due to incomplete knowledge of activity rates and emission factors. The uncertainty of MEIC emissions was estimated to be 12% for SO_2, 31% for NO_x, and 107% for primary $PM_{2.5}$ (95% CI) (37, 38). Third, the applied GEMM function assumes equivalent toxicity for all chemical species in $PM_{2.5}$ (4), indicating that the estimated mortality abatements from the control measures were not differentiated by the components or sources of abated $PM_{2.5}$ concentrations. Uncertainties of the simulated $PM_{2.5}$ concentrations and estimated $PM_{2.5}$-related deaths were quantified following the approach documented in the *SI Appendix*, section S12.

Despite the remarkable air quality improvements introduced by the Action Plan, air pollution in China remains severe. For example, 64% of 338 prefecture-level cities in China failed to meet the national standard for annual $PM_{2.5}$ level in 2017. Therefore, continuous and effective emission control measures are still of high priority. Future clean air actions should be designed based on the experiences of the Action Plan implemented from 2013 to 2017 and should overcome its deficiencies. Based on measure-specific analysis, our results bear out several important policy implications for designing future clean air policies. First, the measures that were successful in abating emissions from industrial and residential sectors should remain in place because these 2 sectors remained major sources of pollutant emissions in 2017 (Fig. 4 and *SI Appendix*, Fig. S7 and Table S4); however, the power sector is no longer a dominant contributor to the emissions of any pollutants due to implementation of the ultralow emission standards. In the future, the successful experiences of the ultralow emission standards for power plants should be expanded to other major industrial sectors and clean fuel actions in the residential sector in the BTH region should be implemented nationwide. Second, our analysis found that control measures implemented from 2013 to 2017 were mainly focused on end-of-pipe emission control while actions on energy structure adjustment played a relatively minor role. Coal still dominated China's energy consumption as of 2017. We suggest that future policies should pay more attention to introducing renewable fuels, from which can be achieved persistent emission reductions as well as benefits in greenhouse gas mitigation. Third, strict measures for coal combustion sources, relatively less effective measures on mobile sources (mainly diesel trucks and off-road engines), and lack of control measures in the agriculture sector led to larger reductions in SO_2 emissions than NO_x and NH_3 (*SI Appendix*, Fig. S16) from 2013 to 2017. As a consequence, a larger reduction in sulfate than nitrate was revealed in our model simulations and confirmed by recent in situ observations for the same period (*SI Appendix*, Fig. S17 and refs. 39–41). Future actions focusing on NO_x abatements from on-road diesel vehicles and off-road gas vehicles (42) and NH_3 abatements in the agriculture sector should be implemented. Forth, control measures on nonmethane volatile organic compound (NMVOC) emissions were absent between 2013 and 2017, resulting in persistent growth of NMVOC emissions and ozone formation potential during the same period (43). This may have contributed to the increase in surface O_3 concentration from 2013 to 2017 under VOC-limited conditions (44). Moreover, weakened aerosol uptake of hydroperoxy radicals due to $PM_{2.5}$ reduction has been proposed as a major mechanism of O_3 increase (44). Given that $PM_{2.5}$ pollution is expected to continuously improve in the future, tailored control measures for NMVOC emissions are crucial for mitigating $PM_{2.5}$ and O_3 pollution at the same time. Last but not least, many developing countries are now suffering similar air pollution problems following rapid economic development. For example, rising emissions from coal and vehicles are mixed with biomass-burning plumes in India and Southeast Asia (17, 45, 46). Our measure-specific analysis sheds light on developing effective clean air policies in these countries. In 2018, China promulgated the Three-Year Action Plan for Winning the Blue Sky Defense Battle (47) to continue its efforts in battling air pollution. With implementation of the measures proposed above, cleaner air in China in the upcoming years is expected.

Materials and Methods

Methods and Data. In this work, we built an integrated analysis framework (*SI Appendix*, Fig. S18) to evaluate the air quality improvements and health benefits of clean air actions in China (i.e., the 6 measures listed in Fig. 1) from 2013 to 2017. We first used the WRF-CMAQ model (20, 21) to simulate the variations in $PM_{2.5}$ concentrations from 2013 to 2017, during which period contributions from anthropogenic and meteorological factors were separated through scenario analysis. We then estimated the accumulated benefits of the 5-y implementation of each major control measure in 2017. Measure-specific emission abatements were quantified by applying the MEIC model (18) with data collected from the Ministry of Ecology and Environment of China (*SI Appendix*, Table S6) as inputs (19). Reductions in $PM_{2.5}$ concentrations introduced by each measure were then evaluated using the WRF-CMAQ model, and the number of $PM_{2.5}$-attributable excess deaths avoided by each measure was further quantified using the newly developed GEMM (4).

As shown in *SI Appendix*, Table S1, the WRF-CMAQ modeling system was utilized to simulate $PM_{2.5}$ concentrations in 4 groups of scenarios. The *BASE* scenario group provided baseline simulations from 2013 to 2017, from which variations in $PM_{2.5}$ concentrations could be derived. With additional information provided by the *FixEmis* scenarios (scenarios with fixed 2017 emissions and varying meteorological conditions from 2013 to 2017), the contributions of interannual meteorological variations and anthropogenic emission abatements to the 2013–2017 $PM_{2.5}$ variations were separated. The air quality improvements in 2017 introduced by each measure were further derived based on the *MEAS* scenario and the *NoCtrl* scenario groups. Details of the methods and datasets are described in the *SI Appendix*. To evaluate CMAQ model performance, we compared simulated meteorological parameters, total $PM_{2.5}$ concentrations, and $PM_{2.5}$ chemical composition concentrations with ground observations (*SI Appendix*, sections S3 and S4).

Data Availability. Gridded monthly emission inventory used in this study and gridded CMAQ model output of monthly mean $PM_{2.5}$ concentrations are available from http://www.meicmodel.org/dataset-appcape.html. The surface $PM_{2.5}$ observation data used in this study can be accessed from http://beijingair.sinaapp.com. Ground observations of meteorological data are obtained from the National Climate Data Center (NCDC) (ftp://ftp.ncdc.noaa.gov/pub/data/noaa/).

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