Faraday Discussions

Cite this: DOI: 10.1039/d0fd00090f

PAPER

View Article Online
View Journal

Air quality and health benefits of China's current and upcoming clean air policies†

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Received 1st July 2020, Accepted 12th August 2020

DOI: 10.1039/d0fd00090f

China is currently in a crucial stage of air pollution control and has intensive clean air policies. Past strict policies have demonstrated remarkable effectiveness in emission control and fine particulate matter ($PM_{2.5}$) pollution mitigation; however, it is not clear what the continuous benefits of current policies are for the future. Here, we summarize China's currently implemented, released, and upcoming clean air policies and estimate the air quality and health benefits of the implementation of these policies until 2030. We found that China's current and upcoming clean air policies could reduce major pollutant emissions by 14.3–70.5% under continued socio-economic growth from 2010 to 2030. These policies could decrease the national population-weighted $PM_{2.5}$ concentrations from 61.6 μg m^{-3} in 2010 to 26.4 μg m^{-3} in 2030 (57.2% reduction). These air quality improvements will ensure that over 80% of the population lives in areas with $PM_{2.5}$ levels below the current annual $PM_{2.5}$ air quality standard (*i.e.*, 35 μg m^{-3}) and will avoid 95.0 (95% CI, 76.3, 104.2) thousand premature deaths in 2030. We also point out several inadequacies of current clean air policies, suggesting that more ambitious control actions are needed to better protect public health with an increasing ageing population. Our findings could provide quantitative insights that can be used to better address air pollution issues in China and other developing countries.

1. Introduction

As one of the largest developing countries in the world, China is confronted with the common but tough issue of sustainable development that considers both rapid socio-economic improvement and the ability to maintain an ecologically friendly environment.[1,2] Over recent decades, although extensive industrial

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† Electronic supplementary information (ESI) available. See DOI: 10.1039/d0fd00090f

construction and fossil fuel combustion have caused severe air pollution,[3,4] a series of strict clean air policies have been adopted to fight pollution and protect public health to a large extent.[5–7] The past decades have not only witnessed extraordinary economic growth but also the effectiveness of air pollution control measures; the annual average SO_2 and $PM_{2.5}$ concentrations decreased by 69% and 50%, respectively, from 2013 to 2019. On the other hand, China's present-day air quality still does not meet the National Ambient Air Quality Standard (NAAQS)[8] and is far from the air quality guidelines suggested by the World Health Organization (WHO).[9] The government proposed the goal of building 'a beautiful China' and is scheduled to achieve the $PM_{2.5}$ air quality standards (*i.e.*, 35 $\mu g\ m^{-3}$) by 2035 in most regions. Therefore, China's efforts to reduce air pollution will be continued and even enhanced in the future. Assessing the air quality and health benefits of China's current and upcoming clean air policies, especially for the near future until 2030, is quite important for helping the government to optimize future clean air plans and better achieve air quality goals. It would also provide insights for other developing countries seeking to address and balance the issues of socio-economic development and pollution control.

Previous studies have broadly and comprehensively evaluated China's historical clean air policies and revealed their remarkable contributions to rapid pollutant emission reductions, air quality improvements and public health benefits at the national, provincial and city levels.[6,10–14] Some studies have conducted sensitivity simulations to evaluate measure-by-measure contributions of the released clean air actions.[5,15] However, all these post-evaluation studies are conducted with historical data and focused on the accomplished effects of the clean air actions, and are unable to analyse the continuous impact of these policies on future emissions and air quality. Utilizing the latest global emission scenarios, the Representative Concentration Pathways (RCPs) and the Shared Socio-economic Pathways (SSPs) developed by the Coupled Model Intercomparison Project (CMIP), some studies projected China's future emission trajectories and estimated the relevant air quality and health benefits considering certain mitigating constraints.[16–18] However, these emission scenarios largely lack detailed information on air pollution control in China and failed to capture the rapid emission reductions seen in recent years.[19] Thus, assessments using these global scenarios are quite limited and unable to quantify the potential benefits of China's current and upcoming clean air policies, especially for the near future (*i.e.*, 2015–2030). Hence, to date, the potential contributions of China's current and upcoming clean air policies to future air quality and health are still unclear.

In this study, by integrating the emission projection model, chemical transport model (CTM) and exposure mortality model, we comprehensively estimated the future air quality and health benefits of China's current and upcoming clean air policies. We first briefly reviewed China's historical air pollution control process, and designed a clean air policy route from 2010 to 2030 by considering all the released and upcoming air pollution control policies (Section 1). The medium road taken from the SSPs (*i.e.*, SSP2), the stabilized climate constraints obtained from the RCP (*i.e.*, RCP4.5), and China's clean air policy packages were combined to generate China's policy-based air pollution mitigation pathway (Section 2). We next projected and analysed China's emission variations due to clean air actions with the Multi-resolution Emission Inventory for China (MEIC) and the Dynamic Emission Projection of China (DPEC) model (Section 3.1). Utilizing the WRF-

CMAQ chemical transport simulation system and the observation-based $PM_{2.5}$ hindcast dataset, we estimated China's $PM_{2.5}$ exposure pathway from 2010 to 2030 under local clean air policies (Section 3.2). Finally, the relevant health benefits were quantified with the Global Exposure Mortality Model (GEMM) (Section 3.3). A discussion of uncertainty and a comprehensive review of the conclusions are provided in Section 4.

2. Methods and data

Fig. S1† shows the methodology framework of this study. In the emission sector, China's historical emissions were provided by the MEIC model (http://www.meicmodel.org), which contains China's anthropogenic emissions from 1990 up to now.[6] China's future energy and socio-economic development were obtained from the CMIP6 scenario ensembles.[20] We chose the SSP2-45 mitigation pathway, which combined the RCP4.5 climate constraints and the SSP2 socio-economic assumptions,[21] to simulate China's energy evolution during 2015–2030 through the China-focused version of the Global Change Assessment Model (GCAM-China).[22] Coupled with the energy outputs and China's air pollution control policies (Fig. 1), we projected China's anthropogenic emission pathways during 2015–2030 by the DPEC model.[23] These anthropogenic emissions were then transformed into the chemical transport model-required formats with the time factors (including monthly, daily and hourly time factors), spatial allocation factors (*e.g.*, county-level populations, GDP, and road networks) and species proxies (including the proxies of particulate matter and volatile organic compounds) from the MEIC model. Next, we established the WRF-CMAQ modelling system to simulate China's $PM_{2.5}$ air quality variations during 2010–2030 under the estimated emission pathways. We applied the final reanalysis data (http://rda.ucar.edu/data/ds083.2/) from the National Center for Environmental Prediction (NCEP) to drive the meteorology simulations with the WRF model and used the global-scale GEOS-Chem simulations as the chemical boundary conditions. The gridded global CMIP6 emissions[24] were adopted to drive the chemical boundary simulations. To reduce the uncertainty of future $PM_{2.5}$ exposure projection, we utilized the observation-based $PM_{2.5}$ Hindcast Dataset (PHD, http://www.meicmodel.org/dataset-phd.html)[25] to provide the historical $PM_{2.5}$ exposure from 2010 to 2015, and used the simulated $PM_{2.5}$ concentration variations to project the future $PM_{2.5}$ air quality pathway based on the PHD. Finally, we estimated $PM_{2.5}$-related premature deaths with the GEMM.[26] China's historical age structures, gender distributions, and baseline mortalities from 2010 to 2015 were collected from the Global Burden of Disease database (GBD, http://www.healthdata.org/gbd/gbd-2017-resources). Historical population counts and distributions were derived from the Gridded Population of the World dataset (GPWv4, https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11/data-download). Future age structures and gender distributions during 2020–2030 were taken from the SSP database (version 2.0, https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about), and the baseline mortality rates were obtained from the World Population Prospects (https://population.un.org/wpp/Download/Standard/Population/). Future population variations (including population counts and distributions) under the SSP2 pathway were obtained from the Inter-Sectoral Impact Model Comparison

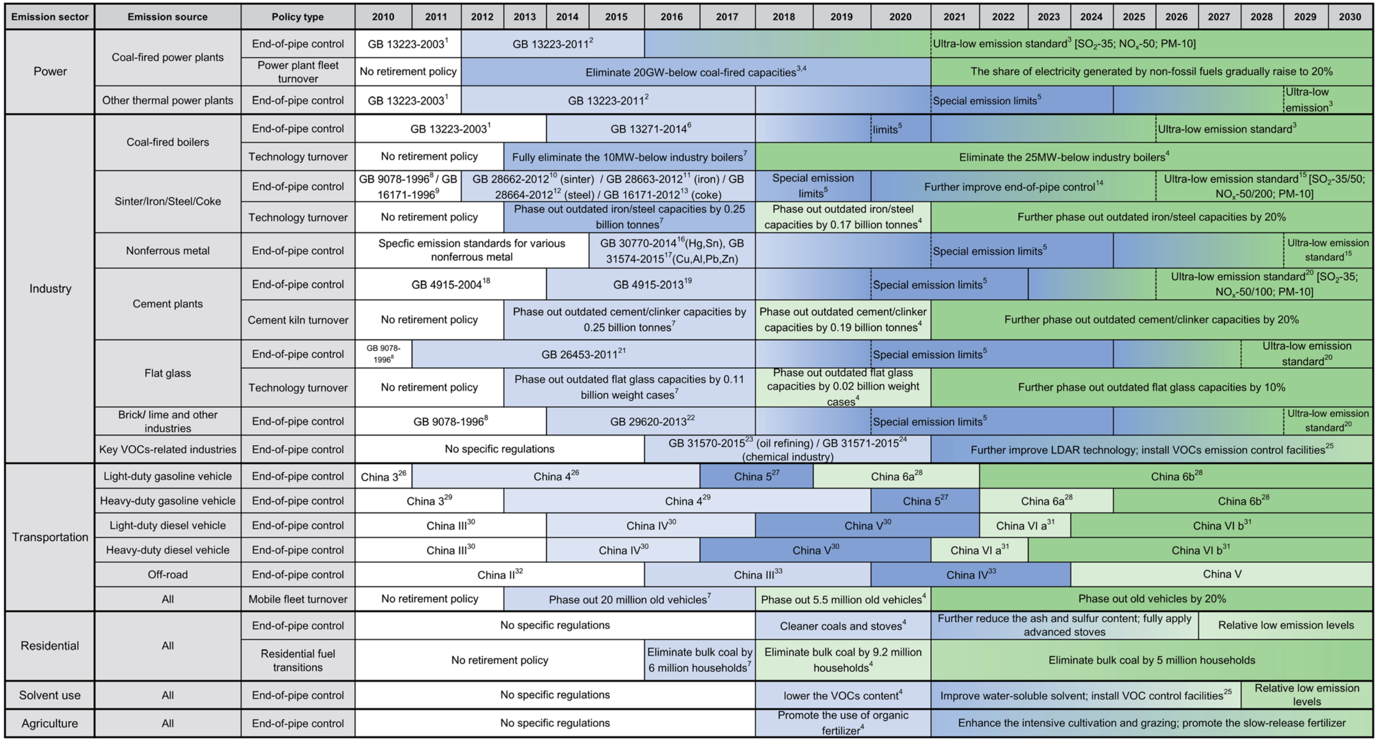

Fig. 1 Summary of China's released and upcoming clean air policies during 2010–2030. The gradient colors (in the order of white, light blue, blue, light green, and green) reflect the transition and enhancement of each policy from one stage to another during certain years. References in Fig. 1: [1]GB 13223-2003, Emission

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Project.[27] The above-mentioned models and databases are described in detail in the following sections.

2.1 Summary of China's released and upcoming clean air policies

China's air pollution control and management processes have been extraordinarily improved since 2010. In 2012, the government updated the ambient air quality standards and added $PM_{2.5}$ concentration limits, which, for the first time, shifted China's clean air focus from the control of single pollutant emissions to integrated air quality management. At the 19th CPC (Communist Party of China) National Congress in 2017, the government proposed the goal of building 'a beautiful China' and further emphasized realizing this goal by 2035. To address the severe $PM_{2.5}$ pollution and meet the air quality targets, a series of special clean air plans, such as the action plan of air pollution prevention and control (2013–2017) and the three-year action plan for winning the war to protect blue skies (2018–2020), have been successively promulgated and greatly accelerated China's efforts to reduce air pollution. Furthermore, driven by the goal of building 'a beautiful China', these efforts to reduce air pollution will be continued and even enhanced.

We collected a broad array of information on China's released and upcoming clean air policies, including various emission standards, integrated and sector-specific air pollution control policies and plans since 2010 (Fig. 1). In brief, coal-fired power plants have the most rigorous pollution control measures in this period; they fully met the emission standard of GB 13223-2011 during 2012–2015 and will be able to gradually accomplish ultra-low emissions by 2020. In addition, coal-fired power plants with capacities below 20 GW will be fully eliminated by 2020. Other thermal plants should be able to meet special emission limits and ultra-low emission standards by 2025 and 2030. Key industry sectors, including coal-fired industry boilers, iron, steel, coking and cement, have implemented strict control processes and should be able to achieve ultra-low emissions nationwide by 2025. Outdated iron and cement capacities, representing 0.33 and 0.41 billion tonnes, respectively, were phased out from 2013 to 2020 and a further 20% will be eliminated from 2020 to 2030. In addition, industry boilers below 10 MW will be fully eliminated by 2017, and those below 25 MW will be gradually phased out by 2030. For other industry sectors (*i.e.*, nonferrous metals, brick, lime, glass), the application of highly effective flue gas desulphurisation (FGD), selective catalytic reduction (SCR), and fabric filter (FAB) end-of-pipe technologies will be increased by 30–45% from 2015 to 2030. Leak detection and repair (LDAR) technologies for petrochemical enterprises and volatile organic compound (VOC) control facilities for other chemical industries will be broadly improved by 2030. For the transportation sector, four typical on-road vehicles have specific standard upgrading routes planned for this period (Fig. 1), and will all achieve the current strictest China 6 (China VI) standards by 2025. However, pollution control for off-road vehicles is relatively loose and projected to meet China V standards by 2030. For the residential sector, a total of 15.2 million households no longer burned bulk coal during 2015–2020, eliminating approximately 24 million tonnes of bulk raw coal. From 2020 to 2030, an additional 5 million households will stop burning bulk coal, and this will reduce the amount of bulk raw coal by nearly 8 million tonnes. The sulphur and ash content created by residential coal will also decrease.

There were no specific regulations for the solvent use and agriculture sectors in the policies released from 2010 to 2017, but several focused improvements were introduced after 2018.

2.2 Estimates of historical and future emissions

Data on China's historical anthropogenic emissions and the relevant activity rates, pollution control distributions and efficiencies from 2010 to 2015 are provided by the MEIC model. MEIC is a technology-based bottom up air pollutant and greenhouse gas inventory of nearly 700 anthropogenic sources, which is developed and maintained by Tsinghua University. MEIC offers abundant emission data for China from 1990 to the present with high spatial resolution, and has been broadly applied in scientific research, policy assessment and air quality management. More detailed information about the MEIC model can be found in Zheng *et al.* (2018).[6]

China's future anthropogenic emissions from 2015 to 2030 are projected using the DPEC model. The DPEC model is composed of an activity rate projection module and a technology turnover emission projection module. The former is driven by the GCAM-China model, which can simulate energy system evolution under different climate targets and socio-economic assumptions. The latter is developed using technology-based turnover methods for major emission sources, which can emulate the future evolution of combustion, manufacturing, and end-of-pipe control technologies under different clean air policies. More detailed information about the DPEC model can be found in Tong *et al.* (2019).[23] Socio-economic development, energy evolution and pollution control are three major aspects that need to be configured in the DPEC model. In this study, we adopt the SSP2 intermediate road[28] as future socio-economic assumptions to maximally reduce other effects and better assess the benefits of pollution control policies. Considering that China promulgated the Nationally Determined Contributions (NDC)[29] which committed to achieving a peak in carbon dioxide emissions around 2030, we selected the most appropriate RCP4.5 (ref. 30) as the climate constraint to simulate the energy system evolution. The configurations used for future pollution control followed China's policy routes shown in Fig. 1. China's future emissions estimated by the DPEC model were further transformed into the CMAQ-required format with the time factors, spatial factors and species proxies in the MEIC model. Future gridded anthropogenic emissions for other countries were derived from the SSP database[24] (https://tntcat.iiasa.ac.at/SspDb).

2.3 CMAQ model configuration

The Weather Research and Forecasting model version 3.9 (WRFv3.9, http://www.2.mmm.ucar.edu/wrf/users/wrfv3.9/) and the Community Multi-scale Air Quality model version 5.2 (CMAQv5.2, https://github.com/USEPA/CMAQ/blob/5.2/CCTM/docs/Release_Notes/) were applied to establish the chemical transport modelling system in this study. The simulation domain contains mainland China and some parts of South and East Asia (Fig. S2†), with a horizontal spatial resolution of 36 km × 36 km. The vertical resolution has 23 sigma levels from the surface to the tropopause (approximately 100 mb) for the WRF simulation (with 10 layers below 3 km), and it is collapsed into 14 layers by using the Meteorology–Chemistry Interface Processor (MCIP) for chemical transport modelling.

The configurations of the WRF and CMAQ models generally follow those in our previous studies.[5,13,15] The initial and boundary conditions of the WRF model were obtained from the NCEP final reanalysis data (http://rda.ucar.edu/data/ds083.2/). The radiation, cloud microphysics, planet boundary-layer (PBL), and land-surface schemes were selected as the RRTM, WSM6, ACM2, and Pleim–Xiu options, respectively. The meteorological conditions were fixed at the 2015 level in all core simulations, and both observational and soil nudging were conducted to revise the meteorology simulation. The CMAQ simulations utilized CB05, the regional acid deposition model and AERO6 as the gas-phase, aqueous-phase and aerosol mechanisms, respectively. The photolytic rates were calculated online, and the boundary conditions were provided by the GEOS-chem outputs. Similar configurations have been proven to have good performance in air quality simulations.[13,15]

Biogenic emissions were obtained from the Model of Emission of Gases and Aerosols from Nature (MEGAN v2.1),[31] windblown dust emissions were calculated using the CMAQ model, and open fire emissions were obtained from the fourth-generation global fire emissions database (GFED4, https://www.geo.vu.nl/~gwerf/GFED/GFED4/).[32] Considering the minimal changes in natural emissions in the future, we fixed the above-mentioned natural emissions at the base year (*i.e.*, 2015) level in all simulations.

2.4 Estimates of historical and future $PM_{2.5}$ exposure

The $PM_{2.5}$ concentrations for 2010 and 2015 were derived from the observation-based PHD (http://www.meicmodel.org/dataset-phd.html). The PHD provides annual $PM_{2.5}$ concentrations across China from 2000 to 2016 with a horizontal resolution of $0.1° \times 0.1°$ and was shown by several studies to have good performance and accuracy.[25,33]

Future ambient $PM_{2.5}$ concentrations for 2020, 2025 and 2030 were projected by combining the historical PHD concentrations and the WRF-CMAQ model-simulated future $PM_{2.5}$ concentrations. To match the PHD spatially, we downscaled all the CMAQ simulations into a $0.1° \times 0.1°$ grid using the offline ordinary kriging method. This downscaling and calibration of the raw CMAQ simulations could decrease the bias.[25] We then calculated the ambient $PM_{2.5}$ of future years with the base year (*i.e.*, 2015) PHD estimation and the future year CMAQ-simulated variation ratios.

In addition to the ambient $PM_{2.5}$ concentrations, future population growth and distribution also have important effects on future $PM_{2.5}$ exposure. Population data for the 2010–2015 period were derived from the GPWv4 dataset with a horizontal resolution of 1/120 degrees (approx. 1 km). To match the ambient $PM_{2.5}$ spatially, we aggregated the GPWv4 population into a $0.1° \times 0.1°$ grid. Estimates for future population growth and distributions under the SSP2 pathway were obtained from ISI-MIP[27] with a resolution of 0.5 degrees and a continuous time series from 2015 to 2100. We also downscaled these grids to $0.1° \times 0.1°$ to spatially match the other datasets.

The future $PM_{2.5}$ exposure in a certain region was then estimated as the population-weighted average ambient $PM_{2.5}$ concentration using the following formula

$$\mathrm{PE}_{(r,j)} = \frac{\sum_{i\in r}\left(\mathrm{ePOP}_{(i,j)} \times \mathrm{aPM}_{2.5(i,j)}\right)}{\sum_{i\in r}\mathrm{ePOP}_{(i,j)}}$$

where $\mathrm{PE}_{(r,j)}$ represents the total $PM_{2.5}$ exposure in region r in year j. $\mathrm{ePOP}_{(i,j)}$ and $\mathrm{aPM}_{2.5(i,j)}$ represent the exposed population and the ambient $PM_{2.5}$ concentration in grid i in year j, respectively.

2.5 Estimates of the health impact

In this study, we used the GEMM[26] to estimate future $PM_{2.5}$-related premature deaths. Based on the long-term observations in the high-level $PM_{2.5}$ polluted regions, the C–R relationships provided by the GEMM functions significantly extend the ambient $PM_{2.5}$ distribution ranges and are more suitable for studies on China.[5] The core model of the GEMM is built to calculate premature deaths caused by non-communicable diseases and lower respiratory infections (NCD + LRI). The relative risk (RR) of NCD + LRI in the GEMM NCD + LRI parameterizations is dependant on the ambient $PM_{2.5}$ concentration (C), and can be calculated using the following formula

$$\mathrm{RR}(C) = \begin{cases} \exp\left\{\dfrac{\theta \log\left(\dfrac{C - C_0}{\alpha} + 1\right)}{1 + \exp\left\{\left(\dfrac{\mu - C - C_0}{\nu}\right)\right\}}\right\}, & C > C_0 \\ 1, & C \leq C_0 \end{cases}$$

where C represents the annual average $PM_{2.5}$ concentration; C_0 is the threshold $PM_{2.5}$ concentration, and we use 2.4 $\mu g\ m^{-3}$ in this study.[5] The values of θ, α, μ and ν are obtained from Burnett's work[26] to determine the shape of the C–R relationship (Table S1†). The RR of NCD + LRI is calculated for every 5 year age bracket, from 25 to more than 85 years old. Then the premature deaths for population group p (age-specific and gender-specific) in grid i could be calculated as follows

$$M_{p,i}(C_i) = P_{p,i} \times B_{p,e} \times \frac{\mathrm{RR}_p(C_i) - 1}{\mathrm{RR}_p(C_i)}$$

where $P_{p,i}$ represents the population count of population group p in grid i; $B_{p,e}$ represents the national baseline mortality rate of NCD + LRI for population group p; $\mathrm{RR}_p(C_i)$ represents the relative risk of NCD + LRI for population group p at the $PM_{2.5}$ exposure level of C_i.

The factors used to estimate premature deaths were obtained as follows. Historical (*i.e.* 2010, 2015) population age structures, gender distributions (Table S2†), and baseline mortality rates (Table S3†) were obtained from the GBD2017 studies (http://www.healthdata.org/gbd/gbd-2017-resources). Future (*i.e.*, 2020, 2025, 2030) baseline mortality rates were obtained from the World Population Prospects (2019) with medium variant (https://population.un.org/wpp/Download/Standard/Population/) (Table S3†). Future age structures and gender distributions were collected from the SSP database (version 2.0) (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=30) (Table S2†). The data sources for historical and future population counts and distributions are introduced in Section 2.4.

3. Results

3.1 Emissions for 2010–2030 under China's clean air policies

3.1.1 Emission trends. Fig. 2 shows China's emission trends together with socio-economic variations from 2010 to 2030. SSP2 is a middle road scenario with moderate economy and population growth.[28] Combined with the modest climate target of RCP4.5, energy consumption and generation generally follow current trends and fossil fuel dependencies.[30] Following this global SSP2-RCP4.5 pathway, China's socio-economy during 2015–2030 would develop at a similar rate to the present-day, and the GDP, population and fossil fuel consumption would increase by 252.9%, 4.7% and 9.3%, respectively, from 2010 to 2030. Consequently, CO_2 emissions would increase to 12.0 Gt in 2030, 35.6% higher than those in 2010. However, twenty years of clean air actions would facilitate notable pollutant emission reductions, with relative decreases of 70.0% for SO_2, 51.8% for NO_x, 61.7% for $PM_{2.5}$, 17.9% for non-methane volatile organic compounds (NMVOCs), and 14.3% for NH_3 during this period.

The specific trajectory varies for different pollutants. Owing to the 12th five-year plan and a series of upgraded emission standards, especially in the power and iron sectors, the major air pollutants SO_2, NO_x and $PM_{2.5}$ have started to decrease since 2012. SO_2 and $PM_{2.5}$ emissions show the most significant decrease from 2012 to 2020, with relative change ratios of 61.5% and 41.8%, respectively, which are largely due to nationwide ultra-low emission upgrades by power plants and the extensive management of industrial boilers. The decreasing trend of NO_x emissions is relatively stable, dominated by continuous, sequential control measures in the power, industry and transportation sectors. In contrast, the reductions in NMVOCs and NH_3 are relatively moderate. A reduction in NH_3 emissions of merely 1.5 million tonnes is achieved from 2010 to 2030, indicating inadequate pollution controls in the agriculture sector. Similarly, a reduction in

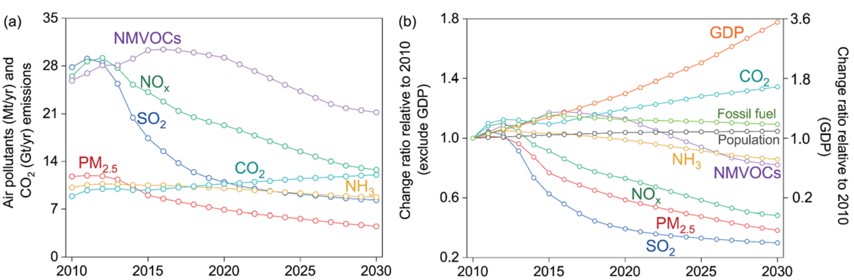

Fig. 2 China's emission and socio-economic development trends during 2010–2030 under the policy-based air pollution mitigation pathway. (a) and (b) show the absolute magnitudes and the relative change ratios respectively. Data from 2010 to 2015 are provided by the MEIC model (emissions), Chinese Energy Statistics (fossil fuels), and the National Bureau of Statistics (GDP and population). Data from 2015 to 2030 are simulated in this study, using the DPEC model (emissions), the GCMA-China model (fossil fuels), and the SSP2 assumption (GDP and population).

NMVOCs of only 17.9% is achieved in this period, and NMVOCs continued to increase from 2010 to 2017, with an emission peak of 30.6 million tonnes, 18.3% higher than in 2010. Considering that NMVOCs and NH_3 are important precursors of ambient $PM_{2.5}$ pollution, their insufficient pollution control and reduction rates might offset the remarkable reductions in other pollutant emissions (*e.g.*, SO_2, NO_x) to some extent.[34,35] Therefore, future clean air plans should pay more attention to NMVOCs and NH_3 emission control.

3.1.2 Evolution of sectoral emissions. Fig. 3 shows detailed sector-specific emission reductions from 2010 to 2030 under China's clean air policies. Clean air measures in the industry and power sectors are the main source of SO_2 emission reductions in this period. In particular, coal-fired industrial boilers and power plants contribute to reductions in SO_2 of 6.0 and 5.3 million tonnes, representing 31.1% and 27.7% of the total reduction, respectively. Residential coal burning and major industry sectors, including iron and steel, coal-fired heating, cement, brick, lime, and coke, also achieve remarkable reductions in SO_2. The high NO_x emissions in 2010 decrease mainly due to power and transportation

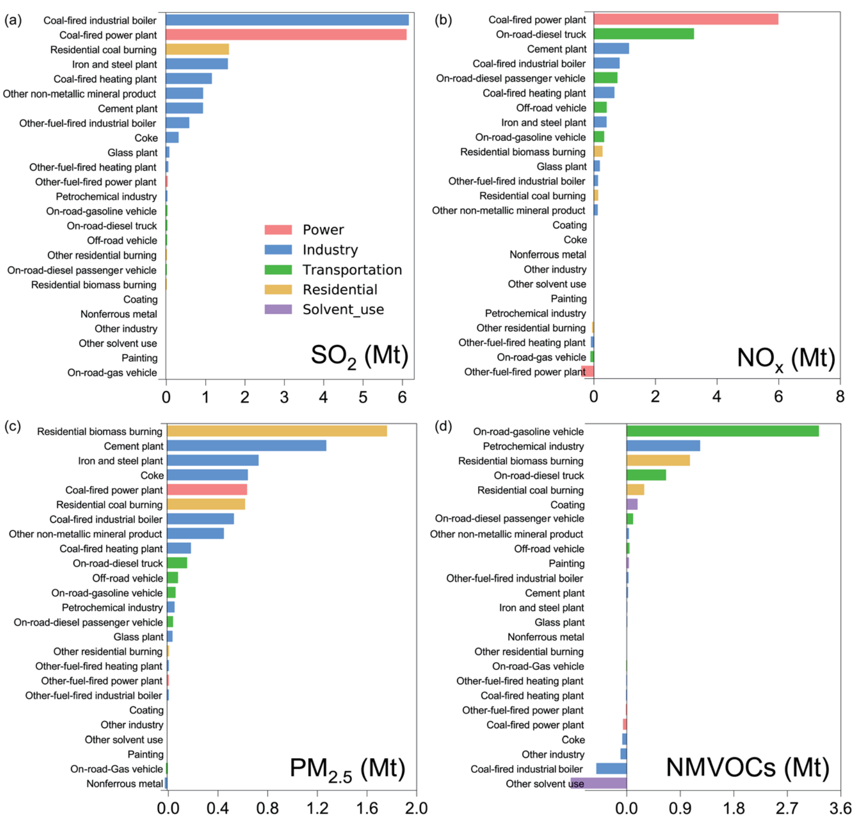

Fig. 3 Detailed sector-specific emission reductions in China resulting from clean air policies during 2010–2030. (a), (b), (c) and (d) present the emission reductions for SO_2, NO_x, $PM_{2.5}$, and NMVOCs, respectively, and the individual sectors are aggregated into power (red), industry (blue), transportation (green), residential (yellow), and solvent use (purple).

sector-related pollution control measures; NO_x emissions from coal-fired power plants and on-road diesel trucks decrease by 6.7 and 4.7 million tonnes, respectively, accounting for almost 70% of the total reduction. The industry and residential sectors are major contributors to the primary $PM_{2.5}$ emission reductions. Within the industry sector, the cement, iron and steel, coke, coal-fired industrial boiler, brick, and lime sectors contribute most to the primary $PM_{2.5}$ reductions (Table S4†), accounting for 50.3% in total. $PM_{2.5}$ emissions from residential biomass and coal burning decrease by 2.4 million tonnes, representing another large proportion (33.2%) of the total $PM_{2.5}$ emission reductions. For NMVOCs emission control, on-road gasoline vehicles, the petrochemical industry and residential biomass burning are the top three contributors with reductions of 3.2, 1.1 and 1.1 million tonnes, respectively, representing over 95% of total NMVOCs reductions. Although the major air pollutant emissions from most source sectors see a significant reduction from 2010 to 2030 due to the clean air actions, it is worth noting that pollutant emissions in some sectors continue to increase in this period, for example, $PM_{2.5}$ emissions from nonferrous metals, NO_x emissions from gas-fuel-fired power and heating plants, and NMVOCs emissions from coal-fired industrial boilers and other solvent use. These increases are largely due to increasing future activity rates and limited pollution control, suggesting that upcoming clean air measures should pay more attention to these sectors.

The series of clean air actions focusing on various source sectors lead to different emission fractions from 2010 to 2030. Table S5† summarizes pollutant emission trends by aggregated sectors (*i.e.*, power, industry, residential, transportation, solvent use, and agriculture) in this period. Clean air policies are most effective in the power and transportation sectors, and their emission proportions of most pollutants decrease remarkably during 2010–2030. Emission reductions in the industry sector are relatively moderate compared with the power and transportation sectors. The industry sector still represents the largest proportion of SO_2 and $PM_{2.5}$ emissions in 2030. Furthermore, its contributions to NO_x and NMVOCs emissions increase to 45% and 35%, respectively. This indicates that the industry sector still has great potential for emission reduction for future long-term air quality improvements. In contrast, as the total emissions decrease, the residential and solvent use sectors gradually represent larger proportions. For example, the contribution of solvent use to NMVOCs emissions dramatically increases from 27% to 40% during 2010–2030, becoming the most prominent NMVOCs emitter in 2030. Inadequate control of solvent use pollution would offset tailpipe NMVOCs emission reductions (*e.g.*, in the petrochemical industry) to some extent, thus resulting in limited NMVOCs reductions compared to other air pollutants (Fig. 2).

3.1.3 Spatial patterns. Owing to different territorial industrial and socio-economic characteristics, high-level emissions and severe air pollution vary across different regions in China. Therefore, China's clean air actions are deployed according to particular regional features as well as historical pollution degrees. Several key regions, namely Beijing–Tianjin–Hebei and surroundings (BTHs, including Beijing, Tianjin Municipality, and Hebei, Shandong, Henan and Shanxi provinces), Fenwei Plain (FWP, including Shanxi and Shaanxi provinces), Yangtze River Delta (YRD, including Shanghai Municipality, and Anhui, Jiangsu and Zhejiang provinces), Pearl River Delta (PRD, including Guangdong province), and Sichuan Basin (SCB, including Sichuan province and Chongqing

Municipality) (Fig. S2†), are particularly emphasized in China's pollution control process.

Fig. 4 illustrates the spatial variations in emission intensities across China due to clean air actions during 2010–2030. SO_2 emission intensities in 2010 were high around most of northern and southern China and extremely high in Shanxi, Shandong, Jiangsu and Hubei provinces (Fig. 4a). These high levels were largely due to extensive coal combustion in industrial and residential processes. Clean air actions have significant effects in most key regions, particularly in Shandong, Jiangsu and Hebei provinces (Fig. 4c), where SO_2 emission intensities decrease by 66.7–74.9% from 2010 to 2030. In 2030, the SO_2 emission intensity of all provinces generally shrinks by an order of magnitude, and that of Beijing is even similar to that of Inner Mongolia (Fig. 4b). However, BTHs is still a high-intensity area across the whole country; in addition, the SO_2 emission intensity of Ningxia and Guizhou provinces increases with the national decrement, which is largely induced by insufficient pollution control in residential burning. Owing to the highly homologous emission sources, the $PM_{2.5}$ emission intensity distribution

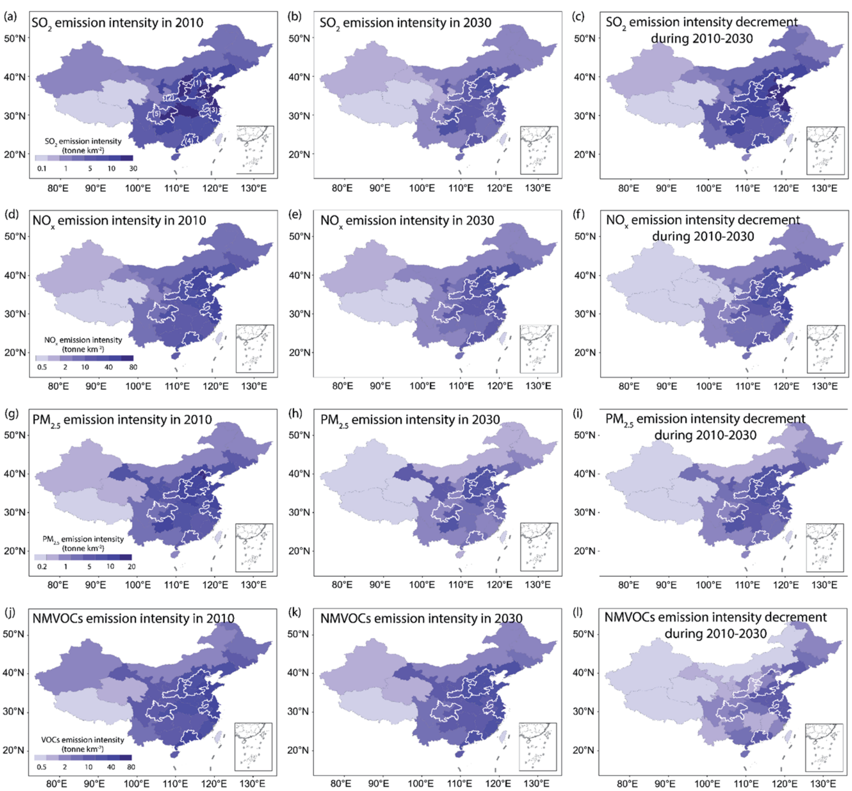

Fig. 4 Spatial variations of emissions in China resulting from clean air policies during 2010–2030. (a), (d), (g) and (j) present the emission intensities of SO_2, NO_x, $PM_{2.5}$, and NMVOCs by province in 2010, and (b), (e), (h) and (k) present those in 2030. (c), (f), (i) and (l) display the corresponding decrement in emission intensity by province from 2010 to 2030. Five key regions are highlighted with bold white outlines (1: BTHs, 2: FWP, 3: YRD, 4: PRD, 5: SCB).

and variations are basically similar to those of SO_2 (Fig. 4g–i), in that the high-intensity regions in 2030 and the decrement from 2010 to 2030 are both gathered around the BTHs regions, as well as the Ningxia, Gansu and Guizhou provinces. The NO_x and NMVOCs emission intensities have similar spatial distributions. Because of their numerous vehicles, and cement and petrochemical industrial plants, the BTHs, YRD and PRD regions had higher intensities in 2010, especially in megacities such as Beijing and Shanghai (Fig. 4d and j). Clean air policies result in remarkable decreases in NO_x intensity in the BTHs and YRD regions from 2010 to 2030, with relative change ratios of 50.2–59.8% (Fig. 4f). The largest decreases in NMVOCs intensity occur in Shanghai and Beijing Municipality, as well as Guangdong, Shandong, Henan, and Liaoning provinces (Fig. 4l). Compared with the decrease in intensity of the other pollutants, the decrease in NMVOCs emission intensity is relatively small from 2010 to 2030, calling for more enhanced pollution control for the next stage. In 2030, the BTHs and southeast coastal regions would be high-intensity areas for both NO_x and NMVOCs emissions (Fig. 4e and k).

3.2 Air quality benefits

China has long been confronted with severe $PM_{2.5}$ pollution. In 2010, the annual mean population-weighted $PM_{2.5}$ concentration was up to 61.6 μg m^{-3} (Fig. 5), 76% higher than the NAAQS (*i.e.*, 35 μg m^{-3}). More than 91.5% of the population (631.7 million people) was exposed to $PM_{2.5}$ levels above 35 μg m^{-3}, and even worse, almost 30% of the population was exposed to $PM_{2.5}$ levels above 75 μg m^{-3}, which could pose high risks to public health through injuring the respiratory and cardiovascular systems.[9,36,37]

Fig. 5 shows that the $PM_{2.5}$ exposure across China would decrease rapidly under clean air policies from 2010 to 2030 (Fig. 5b). Exposure to $PM_{2.5}$ levels above 75 μg m^{-3} would be basically eliminated by 2020 (Fig. 5a), and the annual mean population-weighted $PM_{2.5}$ concentration also decreases most prodigiously over the five-year interval from 2015 to 2020, with a reduction of 13.5 μg m^{-3} (24.6%). However, the population-weighted $PM_{2.5}$ concentration in 2020 is still 6.4 μg m^{-3}

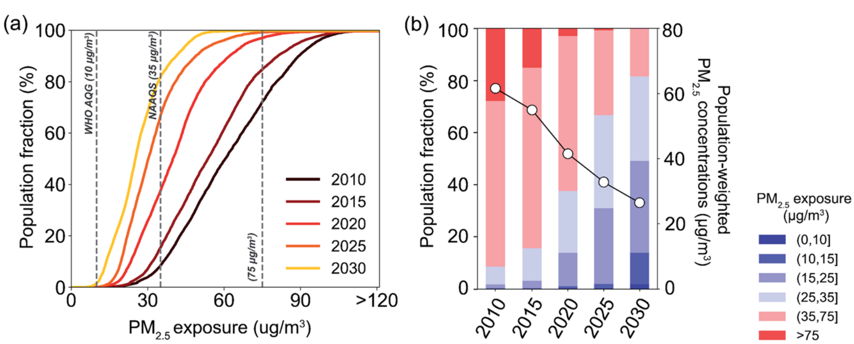

Fig. 5 $PM_{2.5}$ air quality improvements over China as a result of clean air policies during 2010–2030. (a) shows the cumulative distributions of annual mean $PM_{2.5}$ exposures from 2010 to 2030 with five-year intervals. (b) displays the population fractions exposed to different $PM_{2.5}$ pollution levels, and the annual mean population-weighted $PM_{2.5}$ concentrations in China from 2010 to 2030.

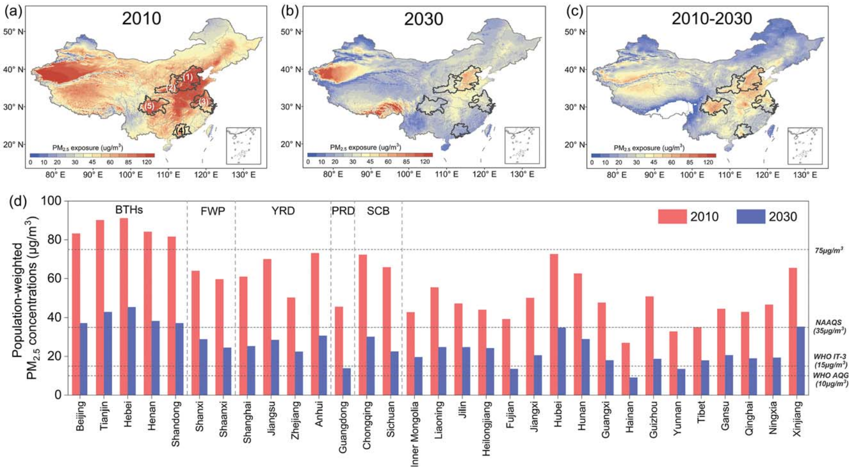

Fig. 6 Spatial variations of annual mean $PM_{2.5}$ concentrations in China as a result of clean air policies during 2010–2030. (a), (b) and (c) show simulated annual mean $PM_{2.5}$ concentration maps for 2010 and 2030, and the difference (2010 minus 2030), respectively. (d) shows the annual mean population-weighted $PM_{2.5}$ concentrations of each province in 2010 and 2030. Five key regions are highlighted with bold grey outlines (1: BTHs, 2: FWP, 3: YRD, 4: PRD, 5: SCB).

(18.4%) higher than the NAAQS, and more than 60% of the population would be exposed to $PM_{2.5}$ concentrations exceeding 35 μg m^{-3}. Current pollution control measures could help China attain the NAAQS by 2025; the population-weighted $PM_{2.5}$ concentration could decrease to 32.7 μg m^{-3}, and over 65% of the population could live in clean air that satisfies the NAAQS. In 2030, the average $PM_{2.5}$ exposure could further decrease to 26.4 μg m^{-3}, indicating that national clean air policies could reduce the population-weighted $PM_{2.5}$ concentration by 35.2 μg m^{-3} (57.2%) from 2010 to 2030. By then, the majority of China's population (81.7%, 1143.5 million people) would be exposed to $PM_{2.5}$ levels below the NAAQS.

Although the current and upcoming clean air policies could catalyse the achievement of the NAAQS at the national level, the $PM_{2.5}$ concentration varies markedly in different provinces and regions. Fig. 6 illustrates the spatial variations of annual mean $PM_{2.5}$ concentrations as a result of clean air policies from 2010 to 2030. Similar to the emission spatial distributions, the $PM_{2.5}$ air pollution was extremely serious in the BTHs, YRD, and SCB regions in 2010, and the FWP and PRD regions also had several pollution hotspots (Fig. 6a). Due to the clean air actions, the above regions exhibit remarkable decrements in $PM_{2.5}$. As a result, most $PM_{2.5}$ pollution hotspots are eliminated in 2030, and the annual mean $PM_{2.5}$ concentrations across the majority of China's mainland are reduced to below 40 μg m^{-3} (Fig. 6b). Fig. 6d further quantifies the annual mean population-weighted $PM_{2.5}$ concentrations in 2010 and 2030 for each province. Except for Hainan, Yunnan and Tibet provinces, for which the population-weighted $PM_{2.5}$ concentrations were less than the NAAQS in 2010, all provinces exhibited $PM_{2.5}$ levels that exceeded the NAAQS. Even worse, the population-weighted $PM_{2.5}$ concentrations in the BTHs region were 6.6–16.1 μg m^{-3} (8.8–21.5%) higher than 75 μg m^{-3}. Twenty years of efforts to reduce air pollution contribute to a 17.1–48.5 μg m^{-3} (44.9–69.7%) decrement in population-weighted $PM_{2.5}$ in all provinces compared with 2010. The most significant declines occur in the BTHs (44.5–48.5 μg m^{-3}, 51.2–58.3%) and YRD regions (31.7 μg m^{-3}, 69.7%), while relatively inapparent reductions occur in western and southern China (*e.g.*, Hainan, Yunnan, Tibet, and Xinjiang provinces). Benefitting from the clean air policies, a total of 27 provinces (87%) could achieve the NAAQS by 2030, and 4 provinces could even attain the WHO Interim Target-3 (*i.e.*, 15 μg m^{-3}). However, the population-weighted $PM_{2.5}$ concentrations of Tianjin, Hebei, Henan, and Shandong still exceed the NAAQS by 2.1–9.4 μg m^{-3} (6.2–26.9%) in 2030. In addition, the population-weighted $PM_{2.5}$ concentrations of Beijing, Hubei and Xinjiang are merely close to the NAAQS, indicating high risks of failing to meet the NAAQS in these regions. Notably, the $PM_{2.5}$ exposures of most regions in 2030 are still far from the WHO Air Quality Guideline (*i.e.*, 10 μg m^{-3}) or the Interim Target-3 (*i.e.*, 15 μg m^{-3}).[9] These results all suggest that although China's current and upcoming clean air actions could result in the majority of the population being exposed to levels below 35 μg m^{-3}, a boost in pollution control is still needed to fulfil the NAAQS in all regions by 2030 and to achieve the ultimate long-term air quality improvements.

3.3 Health benefits

Fig. 7 shows the $PM_{2.5}$-related health benefits in China as a result of clean air policies from 2010 to 2030. There were 2.18 (95% CI, 1.83, 2.51) million premature deaths in 2010 due to outdoor $PM_{2.5}$ exposure (Fig. 7a). Because of the limited mitigation of $PM_{2.5}$ exposure from 2010 to 2015, $PM_{2.5}$-related premature deaths increased to 2.28 (95% CI, 1.91, 2.63) million in 2015, along with the ageing population. From 2015 to 2030, $PM_{2.5}$-related premature deaths gradually decrease and fall to 2.09 (95% CI, 1.73, 2.43) million in 2030. The relatively moderate changes in $PM_{2.5}$-related premature deaths are largely influenced by rapid population ageing. To better evaluate the health benefits of China's clean air policies from 2010 to 2030, we conduct a set of sensitivity simulations of future premature deaths with the 2010 level fixed population (including population

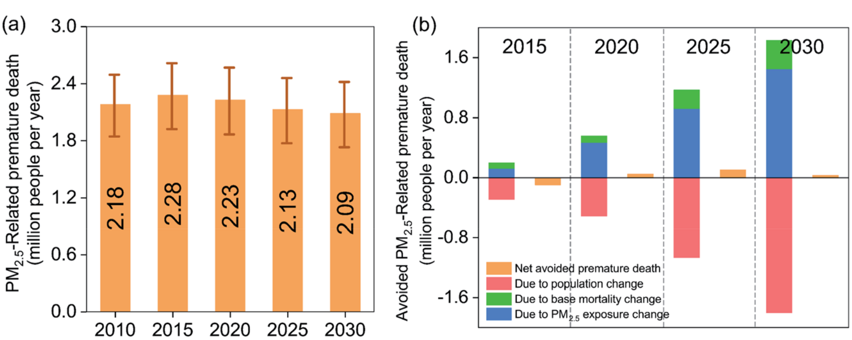

Fig. 7 $PM_{2.5}$-related health benefits in China as a result of clean air policies during 2010–2030. (a) shows the $PM_{2.5}$-related premature deaths in China from 2010 to 2030; (b) shows the avoided $PM_{2.5}$-related mortalities due to future population, base mortality, and $PM_{2.5}$ exposure changes and their integrated net values in China from 2015 to 2030 compared with 2010.

count, distribution and age structure), baseline mortality, and $PM_{2.5}$ exposure. Then, we normalize and decompose the corresponding impact of each factor on future premature death variations. As Fig. 7b shows, without mitigation of $PM_{2.5}$ exposure and a decrease in baseline mortality rate, $PM_{2.5}$-related premature deaths would strikingly increase with the rapidly ageing population; more than 4.02 million $PM_{2.5}$-related premature deaths would occur in 2030, 1.89 million (86.7%) more than in the base year (*i.e.*, 2010). However, clean air actions and medical care improvements would largely protect the public from exposure to air pollution and prevent 1.53 and 0.41 million premature deaths, respectively, in 2030. Consequently, the adverse effects induced by the ageing population are vastly offset by clean air actions and medical care improvements, which finally avoid 0.04 million $PM_{2.5}$-related premature deaths in 2030 compared with 2010. In addition, the relative contribution of $PM_{2.5}$ exposure mitigation to the total avoided premature deaths is gradually enlarged from 2015 to 2030 (Fig. 7b). In 2015, the avoided premature deaths due to the base mortality decrement and $PM_{2.5}$ exposure mitigation accounted for 61% and 39% of total avoided deaths, respectively, while in 2030, the contribution of $PM_{2.5}$ exposure mitigation increases to 80%, avoiding nearly 3.7 times (1.12 million) more premature deaths than the base mortality decrement. This indicates that efforts to reduce air pollution are indispensable and crucial for protecting public health, particularly in the context of the rapidly ageing population and increased population vulnerability to air pollution in the future.

Given the spatial disparities in future populations, emissions and $PM_{2.5}$ exposure variations, the $PM_{2.5}$-related health benefits vary in different regions. Fig. 8 displays the spatial variations of $PM_{2.5}$-related premature deaths in China from 2010 to 2030. The key BTHs (0.58 million), YRD (0.37 million), SCB (0.18 million) and PRD (0.15 million) regions experienced more than half of the national total $PM_{2.5}$-related premature deaths in 2010, and the number of deaths was especially high in Henan (0.19 million) and Shandong (0.18 million) provinces. If no clean air policies were implemented, the $PM_{2.5}$-related premature deaths in all provinces would increase by 84.0–91.3% in 2030 with the rapidly ageing population. Specifically, in Hebei, Shandong, Henan, Jiangsu, Guangdong, and Sichuan provinces, more than 0.11–0.16 million additional premature deaths would occur compared with 2010, indicating that the ageing population and increased pollution-related population vulnerability have more serious effects in these regions. Implementation of clean air policies alleviates $PM_{2.5}$-related premature deaths in all provinces to varying degrees. Taking the $PM_{2.5}$ exposure-fixed simulations as a reference, clean air actions could avoid 1.0–162.1 thousand premature deaths in 2030 among all provinces. Henan, Shandong, Hebei, Jiangsu, Guangdong, and Sichuan have the most considerable health benefits, avoiding 109.2–162.1 thousand premature deaths compared with the reference. In addition, for relatively clean regions such as Hainan, Yunnan, and Tibet provinces, for which the population-weighted $PM_{2.5}$ concentrations were well below the NAAQS in 2010, clean air policies also have noteworthy health benefits. Compared with the reference, nearly 1.0–49.7 thousand (10.0–58.5%) premature deaths could be avoided, suggesting that continuous air pollution control would also play an important role in protecting public health in the regions in which NAAQS is achieved. Considering the negative impact of the ageing population, compared with 2010, 21 provinces can completely offset the adverse effects of the

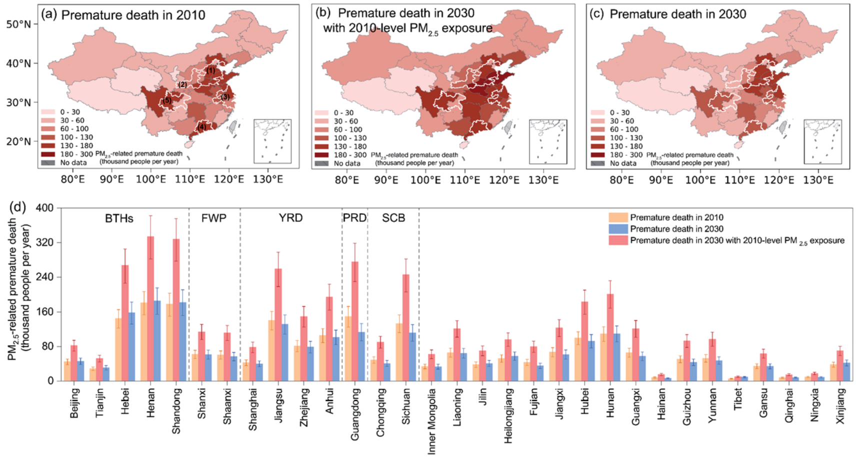

Fig. 8 Spatial variations of $PM_{2.5}$-related premature deaths in China during 2010–2030. (a) and (c) show the spatial distributions of $PM_{2.5}$-related premature deaths in 2010 and 2030, respectively, and (b) shows that in 2030 but with 2010 level $PM_{2.5}$ exposure. (d) shows the $PM_{2.5}$-related premature deaths in each province in 2010 and 2030. Five key regions are highlighted with bold white outlines (1: BTHs, 2: FWP, 3: YRD, 4: PRD, 5: SCB).

ageing population through clean air actions, which avoids 0.4–36.1 thousand premature deaths in 2030. However, in the BTHs region and Jilin, Heilongjiang, Tibet, and Xinjiang provinces, the $PM_{2.5}$ exposure mitigations cannot entirely neutralize the effects of the ageing population, and $PM_{2.5}$-related premature deaths instead increase by 1.0–13.3 thousand, suggesting that these regions need stricter clean air actions to better protect public health.

4. Discussion and concluding remarks

Our study reviewed and illustrated China's clean air policy routes from 2010 to 2030, analysed the short-term emission reductions and the mitigation of $PM_{2.5}$ exposure by local pollution control policies, and quantified the relevant health benefits accrued in this period. The findings demonstrated the enormous positive effects of China's clean air policies on emission control, showing a reduction in major pollutant emissions by 14.3–70.5% under adequate socio-economic development with a 252.9% increase in the GDP and a 9.3% increase in fossil fuel consumption from 2010 to 2030. Significant air quality benefits are obtained: China's annual mean population-weighted $PM_{2.5}$ concentration would decrease from 61.6 to 26.4 μg m^{-3} in this period. In particular, clean air policies could enable the majority of China's population (over 80%) to live in areas where the air quality meets the NAAQS (*i.e.* 35 μg m^{-3}) in 2030. In addition, remarkable health benefits are gained, especially in the context of the ageing population in the future, which would lead to 1.89 million additional premature deaths in 2030. With continuous clean air actions, $PM_{2.5}$-related premature deaths could remain stable under the adverse effects of the ageing population and even decrease by 0.09 million in 2030. The notable potential future air quality and health benefits of China's clean air actions are quite informative for other developing countries confronted with both air pollution and socio-economic development issues.

For the future, our results also suggest challenges and opportunities for China's upcoming efforts to reduce air pollution. First, although most pollutant emissions (*i.e.*, SO_2, NO_x, $PM_{2.5}$) decrease considerably from 2010 to 2030, the control of some important pollution precursors, NH_3 and NMVOCs, is relatively inadequate. For example, the inadequate NMVOCs emission control might increase the atmospheric oxidizing capacity due to the non-linear response of ozone generation to NO_x and NMVOCs emissions. Consequently, more secondary pollution (*e.g.* the formation of secondary organic aerosols) might occur and partly offset the contributions of other primary emission reductions to $PM_{2.5}$ pollution control.[34] Similarly, NH_3 plays an important role in secondary inorganic aerosol formation, and the limited NH_3 emission control might also reduce the effectiveness of $PM_{2.5}$ pollution mitigation through SO_2 and NO_x emission reduction.[35] Strengthening NH_3 and NMVOCs emission control should be highlighted in China's upcoming clean air plans. Second, along with the reduction in overall pollutants, the proportion of emissions from the residential and solvent use sectors gradually increases. These highly scattering and domestic emission sources are more difficult to control than the power and industry sectors, and deserve more attention and innovation. The third point is about regional disparities. Despite the fact that the BTHs region has the most significant pollutant reductions, it still has the highest emission intensities in 2030. Consequently, although the national population-weighted $PM_{2.5}$ concentrations could attain the NAAQS by 2025, those of most BTHs provinces are still as high as 37.1–44.4 $\mu g\ m^{-3}$ in 2030. This is largely due to the heavy industry structure and the highly fossil fuel-dependent energy structure in this region. Apart from stricter and more innovative pollution control measures and standards than the current plans, the BTHs region calls for ambitious clean energy transitions to achieve the $PM_{2.5}$ air quality goals as scheduled. Finally, from a public health point of view, the current annual $PM_{2.5}$ air quality standard (*i.e.*, 35 $\mu g\ m^{-3}$) is still much higher than the WHO air quality guidelines (*i.e.*, 10 $\mu g\ m^{-3}$), which could pose certain risks for public health. Efforts to reduce air pollution should be strengthened in all provinces to better prevent the adverse effects of the increasing ageing population in the future.

Our analysis is subject to several uncertainties and limitations. First, in this research, the future energy evolution was derived from the global RCP4.5 scenario, which is a moderate climate mitigation pathway for stabilization of radiative forcing at 4.5 W m^{-2} in 2100.[30] Although the energy inputs were calibrated with China's base year statistical data, the model is relatively poor at capturing information from some energy-related clean air policies (*e.g.*, eliminating the residential bulk coal by nearly 20 million households during 2015–2030, Fig. 1). Therefore, the benefit estimations might be underestimated to some extent. Furthermore, considering that China has joined the Paris agreement and pledged to the NDC commitment, even the well below 2 °C climate targets, future climate policies will play an indispensable role in mitigating air pollution. More comprehensive investigations should be conducted in the future to better explore the integrated influence of climate and environmental policies on air quality. Second, the meteorological conditions of 2015 were applied in all the future year simulations. The model ignored the impact of meteorological changes, as well as climate effects, on future air quality estimations. For instance, adverse meteorological conditions due to climate change could lead to more severe pollution exposure in 2030, which in turn calls for more ambitious clean air actions. Third, the inherent uncertainty of the WRF-CMAQ model, such as missing mechanisms and inaccurate simulations of secondary organic aerosols, would also affect the findings.

Author contributions

Q. Z. designed the study; K. H. designed China's clean air policy routes; J. C. obtained the data and performed the analysis with the support of D. T., Y. L., B. Z., and G. G.; Q. Z., J. C. and D. T. wrote the paper.

Conflicts of interest

The authors declare no competing interests.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (41921005, 41625020, and 91744310), the National Research Program for key issues in air pollution control (DQGG0201) and the Energy Foundation.

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