The underappreciated role of transboundary pollution in future air quality and health improvements in China

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Abstract

Studies assessing the achievability of future air quality goals in China have focused on the role of reducing China's domestic emissions, yet the influence of transboundary pollution of foreign origins has been largely underappreciated. Here, we assess the extent to which future changes in foreign transboundary pollution would affect the achievability of air quality goals in 2030 and 2060 for China. We find that in 2030, under the current-policy scenario in China, transboundary contributions to population-weighted $PM_{2.5}$ in China would be reduced by 29% (1.2 μg m^{-3}) as foreign countries transition from the fossil fuel-intensive to the low-carbon scenario. By 2060, the difference would be increased to 45% (1.8 μg m^{-3}). Adopting the low-carbon instead of the fossil fuel-intensive pathway in foreign countries would avoid 10 million Chinese people from being exposed to $PM_{2.5}$ concentrations above China's Ambient Air Quality Standard (35 μg m^{-3}) in 2030 and 5 million Chinese people from being exposed to $PM_{2.5}$ concentrations above the World Health Organization Air Quality Guideline (5 μg m^{-3}) in 2060. Meanwhile, China adopting the carbon-neutral pathway rather than its current pathway would also be helpful to reduce transboundary $PM_{2.5}$ produced from the chemical interactions between foreign-transported and locally-emitted pollutants. In 2060, adopting a low-carbon pathway in China and foreign countries coincidently would avoid 63% of transboundary pollution and 386,000 associated premature deaths in China, relative to adopting a fossil fuel-intensive pathway in both regions. Thus, the influence of transboundary pollution should be carefully considered when making future air quality expectations and pollution mitigation strategies.

1. Introduction

Long-term exposure to ambient fine particulate matter ($PM_{2.5}$, particulate matter smaller than 2.5 μm in aerodynamic diameter) is the largest environmental risk factor for human health, with an estimated 4.1 million attributable deaths worldwide (7.3% of the number of global deaths in 2019; Murray et al., 2020). Countries have taken diverse actions to improve air quality and public health, including setting ambitious future air quality and/or climate goals. The European Commission set the 2030 air quality goal as reducing the number of $PM_{2.5}$-attributable premature deaths by at least 55% compared with 2005 levels, equivalent to reducing $PM_{2.5}$ concentrations to below 10 μg m^{-3} EU-wide (European Commission, 2022). The United States aims for a 50-52% reduction of greenhouse gas emissions relative to 2005 levels by 2030, which would avoid tens of thousands of premature deaths associated with $PM_{2.5}$ as a co-benefit (Burtraw et al., 2021). However, the achievability of air quality goals or the extent of health co-benefits of climate strategies is subject to large uncertainties as it is affected by a wide range of factors such as the domestic and global socioeconomic development pathways, energy choices, and air pollution control measures (Cheng et al., 2021b; O'Neill et al., 2020; Rao et al., 2017).

China is a key country to examine factors affecting the achievability of future air quality goals. On the one hand, China suffers from serious air pollution and adverse health effects, with more than a quarter of the world's total $PM_{2.5}$-associated premature deaths in 2015 estimated to occur in China (Zhang et al., 2019). Despite remarkable achievements of the 5-year Clean Air Action since 2013 (Zhang et al., 2019; Zheng et al., 2018a), annual mean $PM_{2.5}$ concentration in China still exceeded the newly revised World Health Organization (WHO) Air Quality Guideline (WHO, 2021; AQG; 5 $\mu g\ m^{-3}$) by 8 times by the end of the Clean Air Action in 2017. On the other hand, China has set the most challenging air quality and climate goals among all the developing countries in the world (Ascensão et al., 2018). In 2018, the Chinese government proposed the roadmap for The Beautiful China Initiative (The State Council of the People's Republic of China, 2016), which requires all cities to achieve the national ambient air quality standards (NAAQS, 35 $\mu g\ m^{-3}$) between 2030 and 2035 (The State Council of the People's Republic of China, 2016). In 2019, China further announced an ambitious climate commitment to achieve carbon neutrality by 2060. These policies have been regarded as interim steps towards the WHO AQG. Therefore, investigating potential pathways and factors shaping the future air quality in China could provide an excellent reference for other countries facing the dual challenges of economic development and environmental protection.

A number of studies seek to answer whether the air quality goals in China can be achieved in the future. These studies have been primarily focused on potential mitigation pathways to reduce China's domestic emissions. Cheng et al. (2021b) found that the nation's current emission control measures could reduce China's $PM_{2.5}$ levels to below 30 $\mu g\ m^{-3}$ by 2030, yet the benefits of such measures would be mostly exhausted by then (Cheng et al., 2021b; Xing et al., 2020). Xing et al. (2020) and Tang et al. (2022) suggested that the co-benefits of climate targets alone (even the most ambitious target of 1.5 ℃ limit in global warming) were not able to help China achieve the 35 $\mu g\ m^{-3}$ target by 2035. Instead, Cheng et al. (2021b) proposed that a combination of stringent clean air policies and ambitious climate targets (i.e., carbon neutrality by 2060 or a global warming limit of 1.5 ℃) could successfully reduce $PM_{2.5}$ to below 35 $\mu g\ m^{-3}$ by 2030 and to below 10 $\mu g\ m^{-3}$ (WHO interim target 4) by 2060. This would require a fundamental transformation of China's economic-environmental development pathway by phasing out polluting industries and moving towards renewable energy while implementing strict end-of-pipe emission control.

However, these previous studies have largely neglected how the future changes in foreign transboundary pollution would affect air quality in China, likely due to the perception that the relatively short lifetime of $PM_{2.5}$ (a few days) does not permit long-distance transport. This negligence would put into question the confidence of their estimated achievability of air quality goals in China. Due to large uncertainties in the future socioeconomic development pathways, environmental commitments, financial supports and technology capabilities, future emissions from China's neighboring countries might be highly variable, leading to different levels of transboundary impacts to China's air quality. For example, emissions in South Asia, Central Asia and Southeast Asia have been estimated to increase in the future by various projections

(International Energy Agency, 2021; Koplitz et al., 2017), due to their rapid-economic growth and a lack of clear commitments on energy choices, climate actions and air pollution control efforts. In this case, transboundary pollution from neighboring countries to China could potentially become increasingly important to affect the achievability of air quality goals in China. Alternatively, these surrounding countries may undergo a sustainable development pathway, facilitated in part by external financial aids and technology supports, leading to lowered transboundary pollution to China. Thus, the different prospects of transboundary pollution could be a significant yet highly uncertain factor in the achievement of future air quality goals in China.

In addition, the mechanism of transboundary pollution poses additional complexity to its impacts on China's air quality. Foreign emissions can affect air quality in China through direct transboundary transport in the atmosphere. Moreover, portions of foreign-transported pollution can also interact chemically with China's locally emitted pollutants. Xu et al. (2023) found that the transport and transformation of non-methane volatile organic compounds (NMVOCs) from foreign countries could enhance the atmospheric oxidizing capacity and facilitate the oxidation of Chinese nitrogen oxides (NO_x) to form nitric acid (HNO_3) and nitrate over North China (referred to as eastern China in that study), leading to considerable foreign contributions to China's air pollution.

The chemical interactions mean that the extent of transboundary pollution will depend on emission changes in China as well. Therefore, the influence of transboundary pollution on China's air quality in the future is a complex result of future emissions in China and in foreign countries, along with their interactions. However, whether the changes in transboundary pollution via direct transport and chemical interactions could affect the achievement of future air quality goals in China and to what extent the influence could be remain poorly understood.

Here, we assess the potential influences that transboundary pollution could make on the achievement of future air quality goals in China, considering the changes in direct pollution transport and in the interactions between transported and China's locally emitted pollution. We regard the air quality goal stated in The Beautiful China Initiative, which is that all cities have annual mean $PM_{2.5}$ concentrations below 35 $\mu g\ m^{-3}$ between 2030~2035 (The State Council of the People's Republic of China, 2016), as China's 2030 air quality goal. We also regard the WHO AQG (annual mean $PM_{2.5}$ below 5 $\mu g\ m^{-3}$) as China's 2060 air quality goal. We then discuss the likelihood of the achievement under currently proposed development pathways in China and foreign countries. As detailed in Method, given the large uncertainties on future emissions of a country (Rao et al., 2017), we consider three anthropogenic emission scenarios (low: SSP119, medium: SSP245, and high: SSP370; O'Neill et al., 2014) for foreign countries and two anthropogenic emission scenarios (current-policy and carbon-neutral; Cheng et al., 2021b; Tong et al., 2020) for China (Table 1), so as to understand transboundary pollution in China from the present (2015) to the future (2030 and 2060) under a wide range of plausible futures. We do not consider the effects of physical climate change (e.g., temperature and precipitation) on future transboundary pollution because Liu et al. (2021) found that future $PM_{2.5}$ changes in China driven by anthropogenic emission reduction was 7 times more than the changes due to meteorological fields by 2050 in both SSP126 and SSP585 scenarios. Other studies have also indicted that the impact of climate change on future $PM_{2.5}$ were smaller than those of anthropogenic emissions of pollutants (Hong et al., 2019; Jiang et al., 2013; Silva et al., 2017).

For each combination of foreign and Chinese anthropogenic emission scenarios, we simulate $PM_{2.5}$ concentrations at a 0.5° x 0.625° resolution using a chemical transport model (GEOS-Chem; http://www.geos-chem.org) that can represent the complex pollutant emissions and chemical reactions across a large spatial domain. Then, we correct the systematic bias in the model simulated $PM_{2.5}$ concentrations using a large set of ground-based observations of $PM_{2.5}$ in China; the same correction factor is applied to all present and future concentrations. Finally, we quantify the transboundary impacts on Chinese $PM_{2.5}$ under each emission scenario. We further quantify the corresponding transboundary impacts on public health in China, measured by premature deaths, using socio-demographic projections consistent with SSPs and the state-of-the-art concentration–response relationships (the GEMM model; Burnett et al., 2018).

2. Method

In this study, we use a set of data and models to investigate future air quality and health burden in China. Projected air pollutant emissions for foreign countries under SSP-RCP scenarios are obtained from the International Institute for Applied Systems Analysis (IIASA; Rao et al., 2017; Riahi et al., 2017) with updates on base year emissions and the harmonization year in this study. Projected air pollutant emissions for China are developed by Tong et al. (2020) and Cheng et al. (2021b). Ambient $PM_{2.5}$ concentrations under each scenario are simulated by the GEOS-Chem chemical transport model (http://www.geos-chem.org) and further corrected for systematic bias by a suite of ground-based observations (Xu et al., 2023). $PM_{2.5}$-associated mortalities are calculated using the Global Exposure Mortality Model (GEMM; Burnett et al., 2018).

2.1 Scenarios of future anthropogenic air pollutant emissions

Future pollutant emission outcome is a cumulative result of a range of variables including socio-economic development, technological change, efficiency improvements and policies directed at pollution control as well as alternative concerns including climate change, energy access, and agricultural production (Rao et al., 2017). The Shared Socioeconomic Pathways (SSP) includes 5 five distinctly different pathways about how the future might unfold in terms of major socioeconomic, demographic, technological, lifestyle, policy and institutional trends (O’Neill et al., 2014; van Vuuren et al., 2017). We select three scenarios to represent low, medium and high emission cases: SSP1 - sustainability, SSP2 - middle-of-the-road, SSP3 - regional rivalry. An assumption about the degree of air pollution control (strong, medium or weak) is included on top of the baseline pathway. Weak air pollution controls occur in SSP3, with medium controls in SSP2 and strong controls in SSP1 (Turnock et al., 2020). However, SSP scenarios do not include explicit climate policies (O’Neill et al., 2020). Instead, the Representative Concentration Pathways (RCPs) generate climate projections targeting at a range of climate forcing levels, such as 1.9 W m^2 (1.5 ℃ warming), 4.5 W m^2 (3 ℃) and 7.0 W m^2 (4 ℃) in 2100. Thus, the combination of SSP-RCP scenario framework depicts societal and climate futures in parallel and explores plausible futures of human activities, the changing climate and emissions (O’Neill et al., 2020).

Here, we use anthropogenic aerosol emissions projected under SSP-RCP scenarios for foreign countries. We select 3 scenarios to represent low, middle and high air pollutant emissions in plausible futures: SSP119 (a sustainable development pathway targeting at a rise of the global mean surface temperature below 1.5 ℃ from the pre-industrial levels by the end of the century), SSP245 (a business-as-usual development pathway with 3 ℃ warming), SSP370 (a regional-rivalry development pathway with 4 ℃ warming). Table 1 summarizes the scenario settings in more detail.

The original SSP-RCP anthropogenic emissions future projection starts from 2015. Here, we update the start year to 2019, which is the latest year that anthropogenic emissions from the Community Emissions Data System (CEDS; Hoesly et al., 2018) are available. Because CEDS historical emissions and SSP-RCP future emissions were developed upon different assumptions and methods, it is important to harmonize the two datasets to ensure smooth transitions between the two sets of emissions trajectories (Gidden et al., 2019). The update of the harmonization year from 2015 to 2019 in this study could better represent the actual emission trajectory between 2015 and 2019. We also use the most recently developed CEDS emissions version 2 (https://data.pnnl.gov/dataset/CEDS-4-21-21) to harmonize the future SSP-RCP emission projections as the new emissions can better represent the historical trend of pollutant emissions (https://github.com/JGCRI/CEDS/blob/master/documentation/Version_comparison_figures_v_2021_04_21_vs_v_2016_07_16(CMIP6).pdf). The final future SSP-RCP emissions for foreign countries used in this study are presented in Fig. S1a.

Future scenarios of anthropogenic pollutant emissions for China were developed by Tong et al. (2020) and Cheng et al. (2021b). We adopt these emissions instead of SSP-RCP emissions because Tong et al. (2020) and Cheng et al. (2021b) developed the emissions specifically to meet China's recent climate goals (i.e., 2030 carbon peak and 2060 carbon neutrality) and used parameters (i.e., emission factors, energy use, etc.) to reflect the most up-to-date pollutant control policies (i.e., clean air action since 2013) and technologies in China. Their emissions have been suggested to better capture China's $PM_{2.5}$ concentration decline during 2015–2019 than those driven by SSP-RCP emissions (Cheng et al., 2021a). We select two plausible scenarios: the current-policy scenario and the carbon-neutral scenario. The current-policy scenario seeks to achieve China's NDC pledges and the national $PM_{2.5}$ air quality goal (i.e. 35 μg m^{-3}) by 2030, elucidating China's future air pollution mitigation pathway towards all the released and determined upcoming clean air policies since 2015. The carbon-neutral scenario pursues China's carbon-neutral commitment and the WHO's old $PM_{2.5}$ guideline (10 μg m^{-3}) by 2060. It implements the best available end-of-pipe technologies and more stringent pollution control policies than the current-policy scenario. Future anthropogenic pollutant emissions for China under these scenarios are developed by firstly simulating China's future energy and socioeconomic evolution using the Global Change Assessment Model (GCAM-China) and then translating into pollutant emissions by the Dynamic Projection model for Emissions in China (DPEC; Tong et al., 2020). More details are summarized in Table 1. The actual future air pollutant emissions for China used in this study are presented in Fig. S1b.

2.2 Simulations of ambient $PM_{2.5}$ concentrations

We use the GEOS-Chem model to simulate $PM_{2.5}$ concentrations in China and other Asian countries under each emission scenario and year. Detailed descriptions of the model configurations can be found in Xu et al. (2023). Briefly, we use the Flex-Grid capability of the GEOS-Chem classic model v13.2.1 to simulate $PM_{2.5}$ concentrations over Asia and its adjacent regions (11° S–60° N, 30°–150° E; covering the entire Asia, eastern Africa and eastern Europe). We use MERRA-2 assimilated meteorological data provided by the Global Modeling and Assimilation Office (GMAO) at NASA Goddard Space Flight Center to drive the model. Our simulation is conducted at a horizontal resolution of 0.5° latitude × 0.625° longitude with 47 vertical levels between the surface and ~ 0.01 hPa. Chemical boundary conditions are taken from corresponding global simulations under each emission scenario in Table 2 at a resolution of 2° latitude × 2.5° longitude. The regeneration of boundary conditions under each emission scenario could ensure the inclusion of pollution transported from countries both within and outside the Flex-Grid domain as transboundary pollution to China. We spin up every simulation for 1 month to remove the effects of initial conditions.

Anthropogenic emissions for the base year (2015) for China are taken from the Multi-resolution Emission Inventory (MEIC) for 2015 (Zheng et al., 2018b), and for the rest of the world are taken from the Community Emissions Data System (CEDS) version 2 for 2015 (https://data.pnnl.gov/dataset/CEDS-4-21-21). For future simulations, anthropogenic emissions for China and foreign countries for each scenario are described above and are specified in Table 2. Other emissions are default in GEOS-Chem following Xu et al. (2023) and are fixed in all present and future scenarios.

We conduct simulations for January, April, July and October, and treat the mean of the four months as annual mean. Our meteorological fields are fixed to 2015 for all scenarios and years to exclude the influence of climate on the results. More details of our model configurations can be found in Table 2. We conduct two types of simulations: 1) baseline simulations (simulations with "Base_" prefix in Table 2) that include complete anthropogenic emissions for both China and foreign countries; 2) sensitivity simulations (simulations with "China_" prefix in Table 2) that exclude anthropogenic emissions for foreign countries from the baseline simulation. Baseline simulations calculate $PM_{2.5}$ concentrations in China that are driven by both Chinese and foreign emissions, while sensitivity simulations calculate $PM_{2.5}$ concentrations in China that are driven merely by China's domestic emissions. The impacts of transboundary pollution on China's $PM_{2.5}$ is calculated as the difference in China's $PM_{2.5}$ between a baseline simulation and a sensitivity simulation in a specified year and under a specified Chinese emission scenario.

We correct our simulated $PM_{2.5}$ concentrations under each scenario, based on a large set of ground-based observations of $PM_{2.5}$, because our simulated $PM_{2.5}$ concentrations are biased high by roughly 15.7% (Fig. S2). Descriptions and data screening method of our ground-based observations can be found in Xu et al. (2023). Further evaluations of $PM_{2.5}$ composition concentrations in China and $PM_{2.5}$ concentrations in other Asian countries with ground-based observations are presented in Xu et al. (2023). We correct simulated $PM_{2.5}$ concentrations in anthropogenic concentration-dominated grid cells (where anthropogenic emissions exceed natural emissions) by observations located in anthropogenic concentration-dominated grid cells. Similarly, we correct simulated concentrations in natural concentration-dominated grid cells (where natural emissions exceed anthropogenic emissions) by observations located in natural concentration-dominated grid cells. Natural and anthropogenic concentration-dominated grid cells in the model are shown in Fig. S3. To isolate anthropogenic concentration-dominated grid cells, we conduct a sensitivity that excludes natural emissions in China and in foreign countries. $PM_{2.5}$ concentrations from this sensitivity simulation are referred to as natural $PM_{2.5}$ concentrations. The difference between concentrations from the Base_2015 simulation (with complete natural and anthropogenic emissions) in Table 2 and the natural concentrations is the anthropogenic emission-contributed concentrations (anthropogenic concentrations). We scale anthropogenic concentrations by the average ratio of observed concentrations and simulated concentrations at each observation site that falls into an anthropogenically dominated grid cell. Concentrations before and after the correction for anthropogenic and all grid cells (including natural grid cells) are shown in Fig. S2. The overestimation in both anthropogenic and total $PM_{2.5}$ concentrations is removed after the correction.

We calculate sectoral contributions of foreign anthropogenic emissions to China's $PM_{2.5}$ concentrations under China's current-policy and foreign countries' SSP370 scenario at a resolution of 2° x 2.5° for January in 2030 and 2060. Sectoral contributions are calculated by taking the difference of a simulation that includes one sector of SSP370 foreign anthropogenic emissions (agriculture, industry, energy, traffic, residential combustion, solvent use, waste burning) at a time and a simulation without foreign anthropogenic emissions ("China_current_2030" and "China_current_2060" runs in Table 2).

We also conduct sensitivity simulations at a resolution of 2° x 2.5° to separate transboundary contributions to China's future $PM_{2.5}$ concentrations from anthropogenic emissions within or outside the Flex-Grid domain of the model under the current-policy and SSP370 scenario. Contributions of foreign anthropogenic emissions from within the Flex-Grid domain are calculated as the difference of a simulation without foreign anthropogenic emissions outside the Flex-Grid domain and a simulation without foreign anthropogenic emissions over the globe. Contributions of foreign anthropogenic emissions from outside the Flex-Grid domain are calculated as the difference between the total foreign contributions and foreign contributions from Flex-Grid countries.

2.3 Health impact assessment

We use the GEMM model (Burnett et al., 2018) to estimate premature deaths attributable to ambient $PM_{2.5}$ exposure for noncommunicable diseases (NCDs) and lower respiratory infections (LRIs) in China under each scenario. GEMM NCD+LRI calculates premature deaths associated with ambient $PM_{2.5}$ exposure (M) for each population subgroup s (by age and gender) in grid cell g as:

$$M_{s,g}\,(C_g) = B_s \times AF_s(C_g) \times P_g \tag{1}$$

where B_s is the national baseline mortality rate of NCD+LRI for the exposed population subgroup s. $AF_s(C_g)$ is the attributable fraction of NCD+LRI to $PM_{2.5}$ exposure at level C_g for population subgroup s. P_g represents the total exposed population in grid cell g. In particular AF was calculated as AF = (RR − 1)/RR, where RR is the relative risk of NCD+LRI attributable to ambient $PM_{2.5}$ exposure. The dependence of RR of NCD+LRI on $PM_{2.5}$ concentrations is calculated as

$$RR = e^{1+e^{\frac{\theta \times \ln(\frac{z}{\alpha}+1)}{(-\frac{z-\mu}{\nu})}}}, \text{ where } z = \max(0, C_g - 2.4) \quad (2)$$

where θ, α, μ and ν are fitted parameters of $PM_{2.5}$–mortality relationships. According to the GEMM model, the RR of NCD+LRI is calculated by age for adults aged from 25 to greater than 85 years in 5-year intervals.

In this study, we use the national baseline mortality data by age group and disease type from the Global Burden of Disease Results Tool 2017 version (GBD 2017; Institute for Health Metrics and Evaluation, 2017). For future baseline mortality, we use the age-specific baseline mortality rates projected by the International Futures (IFs) model v7.89 (Hughes et al., 2011). Population and age structure data for China for 2015 and future years are obtained from the SSP dataset (Samir and Lutz, 2017; Riahi et al., 2017), because China's current-policy scenario is built upon the SSP2 scenario and the carbon-neutral scenario is built upon the SSP1 scenario (Cheng et al., 2021b; Tong et al., 2020). The gridded population data for China on a 0.5° × 0.5° spatial resolution for 2015 and future years under each SSP scenario are developed by Huang et al. (2019). Future cause-and-effect relationship between $PM_{2.5}$ exposure and mortality follows the $PM_{2.5}$-mortality hazard ratio function in the GEMM model, which has been widely used in the calculation of $PM_{2.5}$-associated mortality in the future (Hong et al., 2019; Liu et al., 2021; Yang et al., 2022).

With the baseline mortality, the population data and the age-structure data, we calculate, grid cell by grid cell, the age-specific baseline mortality rate under present and future scenarios. The impacts of transboundary pollution on mortality in China is calculated as the difference between mortality associated with $PM_{2.5}$ simulated by the full anthropogenic emissions for China and foreign countries, and mortality associated with $PM_{2.5}$ simulated by excluding foreign emissions from the full anthropogenic emissions.

3. Results

3.1 Achievability of future air quality goals in China.

In 2015, the national mean population-weighted $PM_{2.5}$ over China is about 48 μg m^{-3} (Fig. 1) after the observation-based correction, consistent with previous studies (48~55 μg m^{-3}) that used various models (Burnett et al., 2018; Cheng et al., 2021a, 2021b; Tang et al., 2022; Zhang and Cao, 2015). The correction reduces the overestimation in the model by roughly 16% (Fig. S2); details about the correction approach are described in Method. From 2015 to 2030 and 2060, there is a remarkable decreasing trend in China's annual mean population-weighted $PM_{2.5}$ concentrations under plausible futures (Fig. 1). In 2030, achieving the 35 μg m^{-3} goal on a national average level would be feasible even under the fossil fuel-intensive pathways in China (current-policy) and foreign countries (SSP370), yet the most polluted provinces might not be able to achieve the goal under such scenarios (upper whiskers in Fig. 1). In 2060, achieving the

WHO AQG goal of 5 μg m^{-3} would be highly unlikely under any emission pathway analyzed in this study (Fig. 1).

Considering air quality goals at the city level in China (35 μg m^{-3} in 2015 and 2030; 5 μg m^{-3} in 2060), the fraction of cities achieving air quality goals increases considerably as China and foreign countries transition from the fossil fuel-intensive to the low-carbon pathway, yet the achievement is not fully attainable in all cities. In 2015, only 30% of 365 cities in the national $PM_{2.5}$ monitoring network has an annual mean population-weighted $PM_{2.5}$ below the 35 μg m^{-3} threshold (Fig. 2a). In 2030, the percentage increases considerably (Fig. 2b). Under the current-policy emission pathway in China (the current clean air policies and Nationally Determined Contribution pledges), roughly 65% of Chinese cities (average of the three foreign scenarios) is able to achieve the goal, doubling the percentage in 2015. Under the carbon-neutral emission pathway in China (stringent clean air policies and carbon neutrality commitments), the percentage further increases to about 92% (average of the three foreign scenarios). However, even the cleanest emission pathway in both China and foreign countries cannot allow all cities to attain the 35 μg m^{-3} goal. In 2060 (Fig. 2c), the WHO AQG goal of 5 μg m^{-3} is not achievable for the majority of cities (≥ 75%) in China. Emission pathways adopted by foreign countries can affect up to 6% of cities achieving the AQG goal, and the influence could be even larger over border regions (as will be shown in Fig. 3).

3.2 Transboundary impacts on $PM_{2.5}$ concentrations in China.

In 2015, transboundary pollution contributes about 3.8 μg m^{-3} population-weighted $PM_{2.5}$ to China (Fig. 3a), accounting for roughly 8% of the total population-weighted $PM_{2.5}$ (Fig. 4). In the future, transboundary pollution becomes increasingly important in China, as the share of transboundary pollution in China's total population-weighted $PM_{2.5}$ increases to 12%~22% in 2060 (Fig. 4).

For future $PM_{2.5}$ concentrations, the contribution of transboundary pollution to $PM_{2.5}$ in China decreases as foreign countries and China undergo the low-carbon pathways (Fig. 3a). In 2030, under the current-policy scenario in China, transboundary contributions to $PM_{2.5}$ in China would be reduced by 1.2 μg m^{-3} (29%) as foreign countries transition from the fossil fuel-intensive (SSP370) to the low-carbon (SSP119) scenario. By 2060, the difference would be increased to 1.8 μg m^{-3} (45%). The transboundary pollution will also depend on Chinese domestic emissions, because of their chemical interactions with foreign-transported pollution (Xu et al., 2023). In 2030, under the SSP370 scenario in foreign countries, transboundary contributions to $PM_{2.5}$ in China could be reduced by 0.6 μg m^{-3} (14%) as China transitions from the current-policy to the carbon-neutral scenario. In 2060, the $PM_{2.5}$ reduction could be increased to 1.8 μg m^{-3} (45%).

The direct atmospheric transport and the chemical interactions play different roles in transboundary pollution over different regions in China. Over North China (outlined in Fig. 3c-o), the influence of chemical interactions on transboundary pollution is prominent. Xu et al. (2023) found that foreign-transported NMVOCs could enhance the atmospheric oxidizing capacity and facilitated the oxidation of Chinese nitrogen oxides (NO_x) to form nitrate over North China. This feature persists in the future. Due to chemical interactions, North China is the region that is the most strongly affected by transboundary pollution in most scenarios. In 2030, transboundary pollution contributes 3 to 10 μg m^{-3} $PM_{2.5}$ concentrations to North China, even under China's carbon-neutral scenario (Fig. 3b and Fig. 3i-l), greatly increasing the difficulty for this region to achieve the 35 μg m^{-3} goal. Further reduction of transboundary pollution on North China requires the reduction of not only foreign anthropogenic emissions but also China's domestic emission. For example, in 2060, if China adopts the current-policy pathway (Fig. 3f-h), achieving the WHO AQG goal of 5 μg m^{-3} would be highly unlikely for the majority of North China, as transboundary pollution alone would contribute roughly 3~10 μg m^{-3} of $PM_{2.5}$ concentration (Fig. 3b and Fig. 3f-h). Alternatively, adopting the carbon-neutral rather than the current-policy pathway in China reduces roughly 41%~58% of transboundary $PM_{2.5}$ over North China in 2060 (Fig. 3b), making it possible for the region to achieve the 5 μg m^{-3} goal. Thus, a low emission pathway for China has a large co-benefit on reducing transboundary pollution exerted upon its populous northern area by reducing the aforementioned chemical interactions.

The western border provinces of Yunnan and Xinjiang (denoted in Fig. 3c-o) are also influenced substantially by transboundary pollution, with the magnitude of transboundary pollution determined predominantly by foreign (but not Chinese) emission pathways. For example, in 2060, under China's carbon-neutral emission pathway, transboundary $PM_{2.5}$ over Yunnan decreases from 6 μg m^{-3} to 3 μg m^{-3} (a 50% reduction) as the foreign pathway switches from fossil fuel-intensive (SSP370; Fig. 3m) to low-carbon (SSP119; Fig. 3o), reflecting the considerable impact of Southern Asian pollution to China (Jiang et al., 2013). Over Xinjiang, the transboundary pollution driven predominantly by direct atmospheric transport can reach 6 μg m^{-3} in many scenarios (i.e., current-policy plus SSP370 for 2030 and 2060; and carbon-neutral plus SSP245 for 2030), indicating the important influence of anthropogenic emissions from Central Asia in the future that has hardly been investigated in previous studies

As transboundary contributions are the largest under China's current-policy and foreign countries' SSP370 emission pathways (Fig. 3a), we further investigate major emission sectors in foreign countries that contribute to China's future $PM_{2.5}$ concentrations. We take January as an example because Xu et al. (2023) found that transboundary contributions to China's $PM_{2.5}$ were the largest in January. Fig. S4 reveals that agriculture, energy, industry, transportation and residential combustion emissions in foreign countries are major sources of transboundary pollution to China's national average future $PM_{2.5}$ concentrations in 2030 and 2060 January, and that these sectors contribute roughly evenly (15%~23% for each source). There is pronounced spatial heterogeneity in the source attribution. Solvent use emissions in foreign countries make roughly 3 times larger contributions to North China (18% in 2030 and 2060) than to the national average (6%-7% in 2030 and 2060). This is in line with the result of Xu et al. (2023) that the NMVOCs are the primary drivers of transboundary $PM_{2.5}$ over North China. Residential combustion in foreign countries contributes about 16% in 2030 and 10% 2060 more $PM_{2.5}$ to Yunnan province than to the entire China, as Yunnan is mostly affected by emissions from South Asia (Jiang et al., 2013) where residential combustion is intensive (McDuffie et al., 2020).

Transboundary pollution to China could arise from emissions of countries within and outside the Flex-Grid domain of the model. Thus, we conduct a sensitivity simulation driven by China's current-policy and foreign countries' SSP370 emissions in 2030 and 2060 as an example to explore the relative importance of anthropogenic emissions from countries within and outside the Flex-Grid domain for transboundary pollution to China. Fig. S5 shows that anthropogenic emissions from countries within the Flex-Grid domain dominate the transboundary pollution to China in all seasons (>80%), and their contributions remain in 2030 and 2060. Contributions of anthropogenic emissions from countries outside the Flex-Grid domain is larger in April and October when westerly winds prevail and wet deposition is not as strong as in July (Jiang et al., 2013; Leibensperger et al., 2011; Ni et al., 2018). North China is more influenced by emissions outside the Flex-Grid domain (13% in April and 24% in October) than China on average is (7% in April and 13% in October), indicating that North China is more influenced by emissions outside Asia, such as Europe and North America. Leibensperger et al. (2011) have also found that NO_x emission in the US could lead to an enhancement of $PM_{2.5}$ over North China.

3.3 Health threats by transboundary pollution in China.

Figure 5 shows our estimated $PM_{2.5}$-associated premature deaths in 2015 and the future. Our estimated $PM_{2.5}$-associated premature deaths in China in 2015 (2.03 million) is comparable with other studies (2 to 2.4 million; Burnett et al., 2018; Geng et al., 2021; Tang et al., 2022). Our estimated increasing trend of premature deaths in China from SSP370 to SSP119 is also consistent in previous works (Tang et al., 2022; Yang et al., 2022), which is driven primarily by population ageing (Fig. S6). Our estimated premature deaths in 2030 and 2060 under the current-policy emission scenario (2.68 to 2.82 million for 2030; 1.8 to 2.05 million for 2060) is substantially lower than those in Tang et al. (2022) (3.5 to 4 million for 2030; 6.5 to 7.5 million for 2060). The difference is primarily because Tang et al. (2022) fixed the baseline mortality rates in future years at the 2015 level, while our future baseline mortality rates from the IFs are projected on the basis of income, education and technology advancement, and other factors (Hughes et al., 2011).

The $PM_{2.5}$ concentrations contributed by transboundary pollution can lead to an extra number of people (i.e., excess population) exposed to $PM_{2.5}$ concentrations above the targeted air quality levels in China (35 $\mu g\ m^{-3}$ in 2015 and 2030; and 5 $\mu g\ m^{-3}$ in 2060), which may lead to potential health threats. In the future, the number of excess population due to transboundary pollution depends on both foreign and China's emission pathways (Fig. 6a). In 2030, with Chinese emissions following the carbon-neutral scenario, adopting the low-carbon (SSP119) rather than the fossil fuel-intensive pathway (SSP370) in foreign countries could avoid 10 million Chinese people from being exposed to $PM_{2.5}$ concentrations above 35 $\mu g\ m^{-3}$. In 2060, 5 million people could be avoided from being exposed to $PM_{2.5}$ concentrations above 5 $\mu g\ m^{-3}$ if the foreign scenario switches from SSP370 to SSP119. These results indicate remarkable health benefits that the low-carbon emission pathway in foreign countries would bring to China.

For a given future year and foreign emission scenario, the excess population due to transboundary pollution tends to be larger when China adopts the carbon-neutral pathway than when China adopts the current-policy pathway (Fig. 6a). This reflects the increasing influence of transboundary pollution on air quality in China as China's overall $PM_{2.5}$ concentrations drop sharply towards the air quality goals under the carbon-neutral pathway (Fig. 1).

Another measure of health threat that transboundary pollution could exert upon China is $PM_{2.5}$-related premature deaths. As shown in Fig. 6b, there is an obvious decreasing trend of transboundary-contributed $PM_{2.5}$-related premature deaths in China as foreign countries and

China transition from the fossil fuel-intensive to the low-carbon pathway. In 2030, adopting the low-carbon pathway (SSP119) in foreign countries would avoid 41% (178,000 under China's carbon-neutral pathway) to 45% (207,000 under China's current-policy pathway) of premature deaths that would occur under the fossil fuel-intensive pathway (SSP370) in foreign countries. In 2060, the avoidance would be as large as 76% (270,000 under China's current-policy pathway) to 91% (63,000 under China's carbon-neutral pathway). In addition, China's low carbon emission pathway could also bring considerable health benefits through reducing the chemical interaction-related transboundary pollution and associated premature deaths in China. In 2030, adopting the carbon-neutral pathway in China would avoid 99,000 (SSP245) to 211,000 (SSP119) people from transboundary pollution-associated premature deaths relative to adopting the current-policy emission pathway. In 2060, the avoided deaths would be 76,000 (SSP119) to 283,000 (SSP370). These findings highlight the considerable health benefits to China if foreign countries and China could adopt the low-carbon emission pathways coincidently.

4. Discussion

This study reveals the increasingly important role that transboundary pollution would play in the achievement of future air quality goals and the protection of public health in China. The magnitude of transboundary pollution depends on both Chinese and foreign emissions, given the direct pollution transport and the indirect impact through chemical interactions between transported and China's locally emitted pollutants. Adopting the low-carbon (SSP119) instead of the fossil fuel-intensive (SSP370) pathway in foreign countries would avoid millions of Chinese people (Fig. 6a) from being exposed to $PM_{2.5}$ concentrations above the targeted air quality levels in 2030 (35 $\mu g\ m^{-3}$) and 2060 (5 $\mu g\ m^{-3}$), and would avoid 63,000~270,000 of transboundary $PM_{2.5}$-associated mortality in China in 2060 (Fig. 6b). Adopting the carbon-neutral instead of current-policy pathway in China would avoid 76,000~283,000 premature mortality associated with transboundary pollution in 2060 (Fig. 6b). If China and foreign countries undergo the low-carbon pathways coincidently, transboundary pollution in China would be reduced by 63% relative to adopting a fossil fuel-intensive emission pathway in both regions (Fig. 4a), and could avoid 386,000 premature deaths in China (Fig. 6b). Cutting foreign emissions are particularly effective at reducing transboundary pollution upon the western border provinces of Yunnan and Xinjiang that are dominated by direct transport. Fully achieving the WHO AQG goal of 5 $\mu g\ m^{-3}$ over the populous North China would be possible only when both China and foreign counties adopt the low-carbon pathways (carbon-neutral and SSP119, respectively).

The importance of transboundary pollution is not confined in China. In the future, significant emission changes are expected in many developing countries, affecting air quality locally and in the downwind regions. These developing countries are often financially and/or technologically less capable to control emissions by themselves. Thus, enhanced external aids would be essential for these developing countries to undergo a low-carbon development in the future, which in turn would benefit air quality and public health of the entire globe. External aids could be done through global cooperation programs such as the Paris Agreement or through inter-regional collaboration such as the Belt and Road Initiative.

Uncertainties arise from several factors in this study. The future development pathway of a country is highly uncertain, leading to a wide spread of projected emission trajectories in the future. We thereby use a set of emission projections to represent the plausible range of future emissions. The simulation of $PM_{2.5}$ is subject to uncertainties in aerosol chemical and physical processes, such as the wet deposition of nitrate (Luo et al., 2020) and the simplified secondary organic aerosol formation scheme (Pai et al., 2020). Our correction to the simulated $PM_{2.5}$ concentrations using ground-based observations could reduce the uncertainty by 15% to 18% (Fig. S2). Future population and age structure change are projected based on their historical relationships with GDP and urbanization (O'Neill et al., 2020; Riahi et al., 2017). Thus, they may introduce biases if the future development of global GDP and urbanization deviates from the historical path (e.g., due to the emergence of anti-globalization (Dür et al., 2020) and regional rivalry (O'Neill et al., 2014; van Vuuren et al., 2014). There are additional uncertainties from $PM_{2.5}$-related death estimates due to the limited epidemiology evidence and statistical estimation of the GEMM model, such as the influences of particulate species and size on health outcomes (Burnett et al., 2018). We estimate the overall uncertainties of $PM_{2.5}$-related death in each scenario as 95% CI in the main text. Besides, we do not consider potential influences of climate change and the change of natural emissions on $PM_{2.5}$ and transboundary pollution, yet their influences are found small compared to the influence of anthropogenic emissions (Hong et al., 2019; Jiang et al., 2013; Liu et al., 2021; Silva et al., 2017).

Data availability

The global SSP-RCP emissions data for 2015 and future scenarios, and the area-weighted $PM_{2.5}$ concentrations in China for 2015 and future scenarios are available upon request to the corresponding author. All other data used in this study are publicly available and can be downloaded from the following links. (1) China's future emission scenarios 2015–2060: http://www.meicmodel.org/dataset-dpec.html. (2) Chinese future population data: https://www.scidb.cn/en/detail?dataSetId=73c1ddbd79e54638bd0ca2a6bd48e3ff&dataSetType=organization. (3) 2015 baseline mortality rate: https://gbd2017.healthdata.org/gbd-search/. (4) Future baseline mortality rate projection: https://www.ifs.du.edu/IFs/frm_MortCohorts/.

Code availability

The GEOS-Chem model v13.2.1 source code used for $PM_{2.5}$ concentration simulations is available at: http://www.geos-chem.org. The SSP-RCP emission harmonization source code is available at http://software.ene.iiasa.ac.at/aneris/. All computer codes generated during this study are available from the corresponding authors upon reasonable request.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (42075175), the China Postdoctoral Science Foundation (2021M700191) and the Peking University Boya Postdoctoral Fellowship.

Author contributions

J.L. led the study. J.X. and J.L. designed the study. J.X. performed the model simulations and conducted the data analysis. D.T. provided China's future emissions data. L.C. provided SSP-

RCP emission harmonization and health impact assessment methods. J.X. wrote the manuscript with inputs from J.L. All authors commented on the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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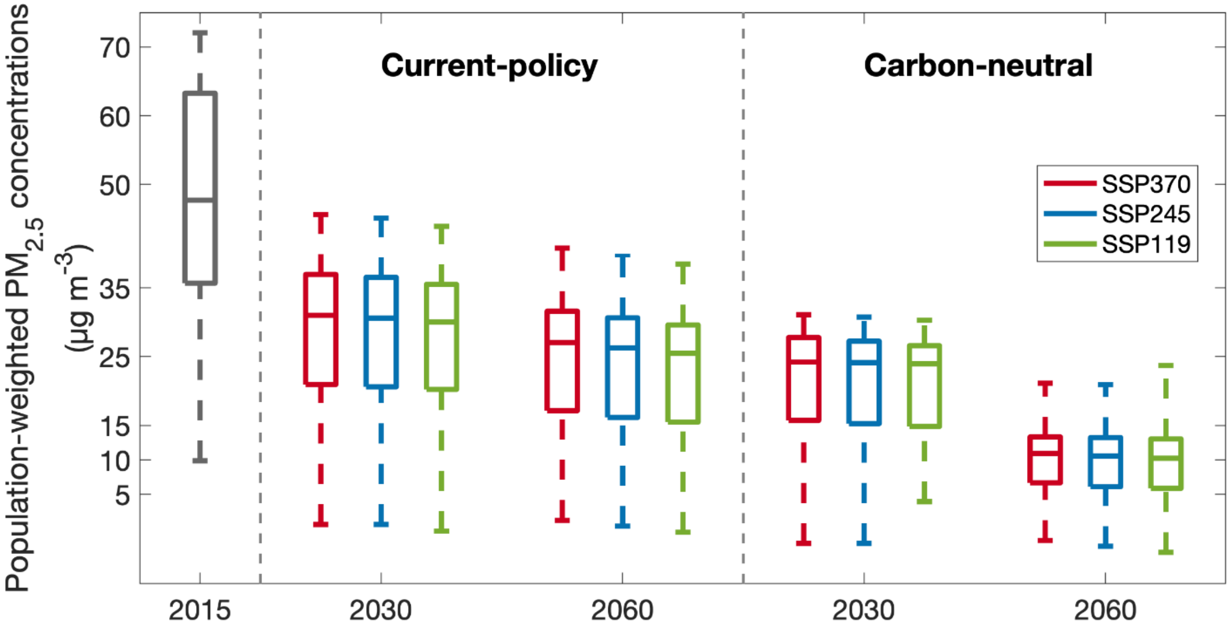

Figure 1. Population-weighted $PM_{2.5}$ concentrations over China. Box-and-whisker plots represent 5th, 25th, 75th, and 95th percentiles of provincial population-weighted $PM_{2.5}$ concentrations in 2015, 2030 and 2060. Lines in the middle of each box represent the national mean population-weighted $PM_{2.5}$ concentrations. Future emission scenarios in China are labeled as text at the top and in foreign countries are represented by colors according to the legend.

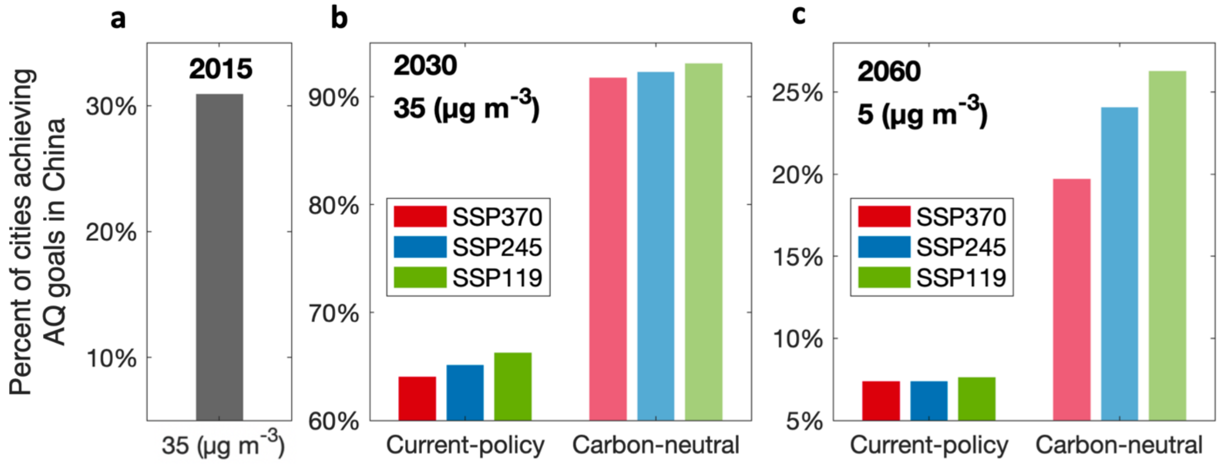

Figure 2. Percent of cities achieving air quality goals in China. **(a)** Percent of cities in China with an annual mean population-weighted $PM_{2.5}$ concentration below 35 μg m^{-3} in 2015. **(b-c)** Percent of cities with an annual mean population-weighted $PM_{2.5}$ concentration achieving the 35 μg m^{-3} goal in 2030 (b) and the 5 μg m^{-3} goal in 2060 (c). $PM_{2.5}$ concentrations are simulated under different future emission scenarios in China (current-policy and carbon-neutral) and foreign countries (represented by colors following the legend).

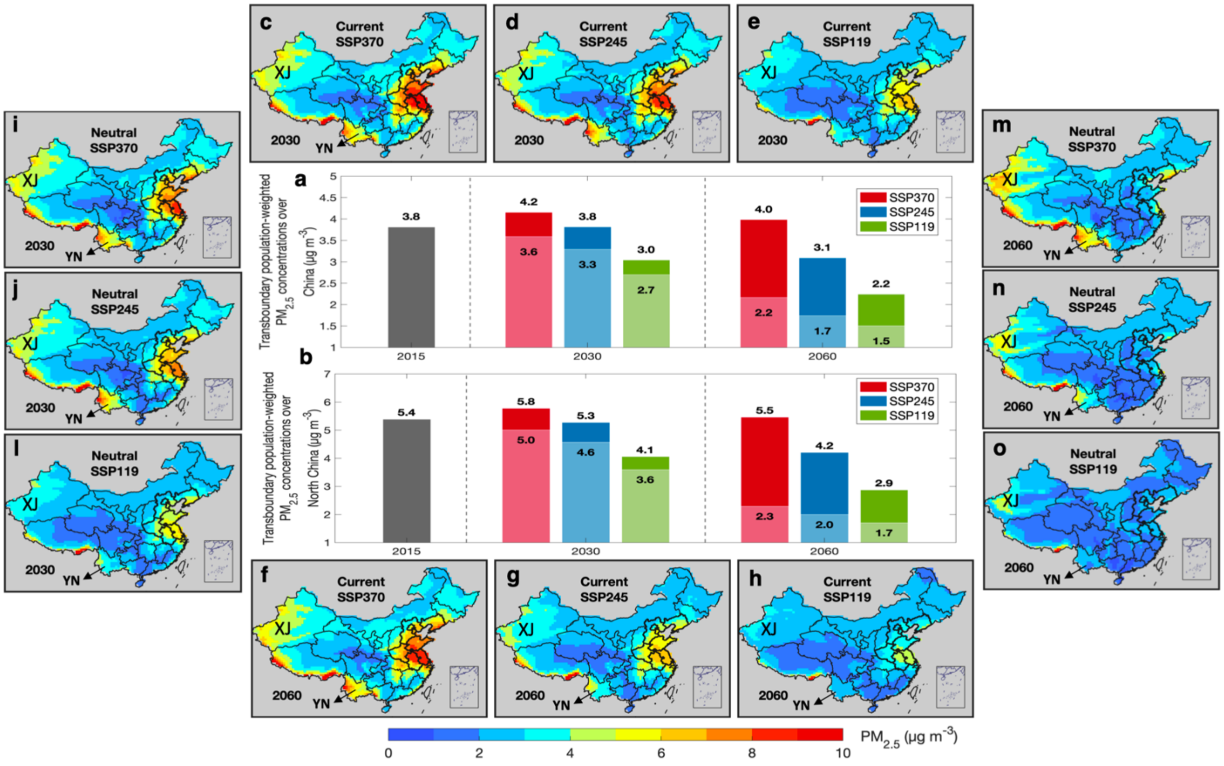

Figure 3. Contributions of transboundary pollution to $PM_{2.5}$ concentrations over China. **(a)** Transboundary contributions to national annual mean population-weighted $PM_{2.5}$ in China in 2015, 2030 and 2060. Future scenarios are estimated by different emission scenarios in China represented by light (carbon-neutral scenario) and dark shadings (current-policy scenario), along with different emission scenarios in other countries (SSP370, SSP245, SSP119) represented by colors according to the legend. Text on top of each bar represents the transboundary-contributed population-weighted $PM_{2.5}$ under China's current-policy emission scenarios. Text in the light shading of each bar represents the transboundary-contributed population-weighted $PM_{2.5}$ under China's carbon-neutral emission scenarios. **(b)** Same as a, but for North China. **(c-o)** Spatial distributions of transboundary-contributed annual mean $PM_{2.5}$ concentrations over China in 2030 and 2060 under different emission scenarios in China and in other countries. YN represents Yunnan province. XJ represents Xinjiang province. North China is outlined by thick black lines.

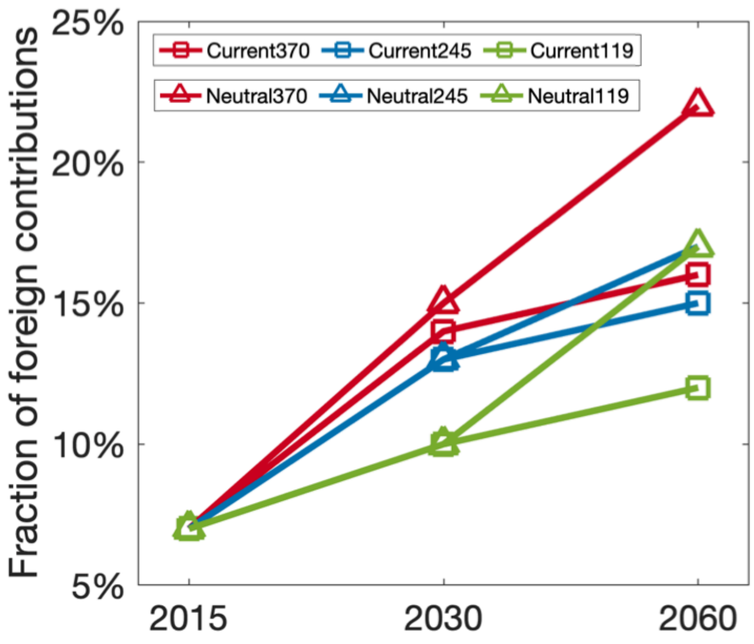

Figure 4. Fractional transboundary contributions to $PM_{2.5}$ concentrations over China. The percentage fraction of transboundary-contributed $PM_{2.5}$ in China's total population-weighted $PM_{2.5}$ in 2015, 2030 and 2060. Future anthropogenic emission scenarios are represented by different colors and markers following the legend.

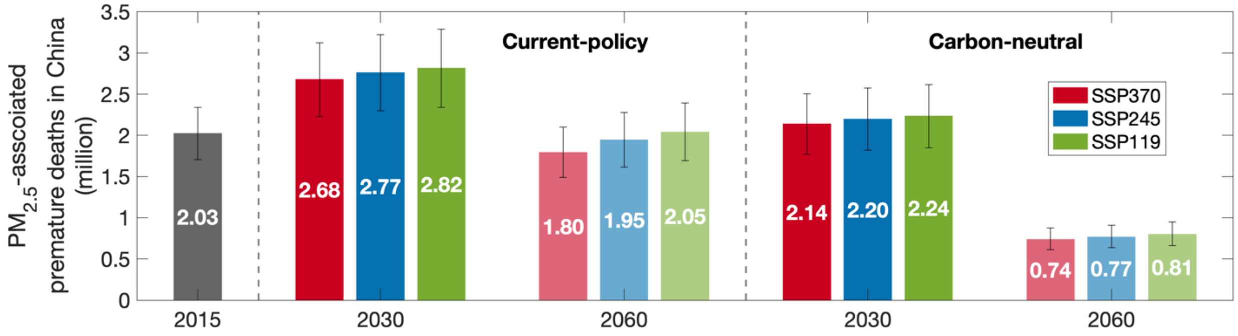

Figure 5. $PM_{2.5}$-associated premature deaths in China. Total $PM_{2.5}$-asscoiated premature deaths in China for 2015, 2030 and 2060 under each emission scenario in China (denoted as text at the top) and in other countries (represented by colors in the legend). Numbers denote the estimated deaths in each scenario. Error bars represent the 95% confidence interval of the RR function.

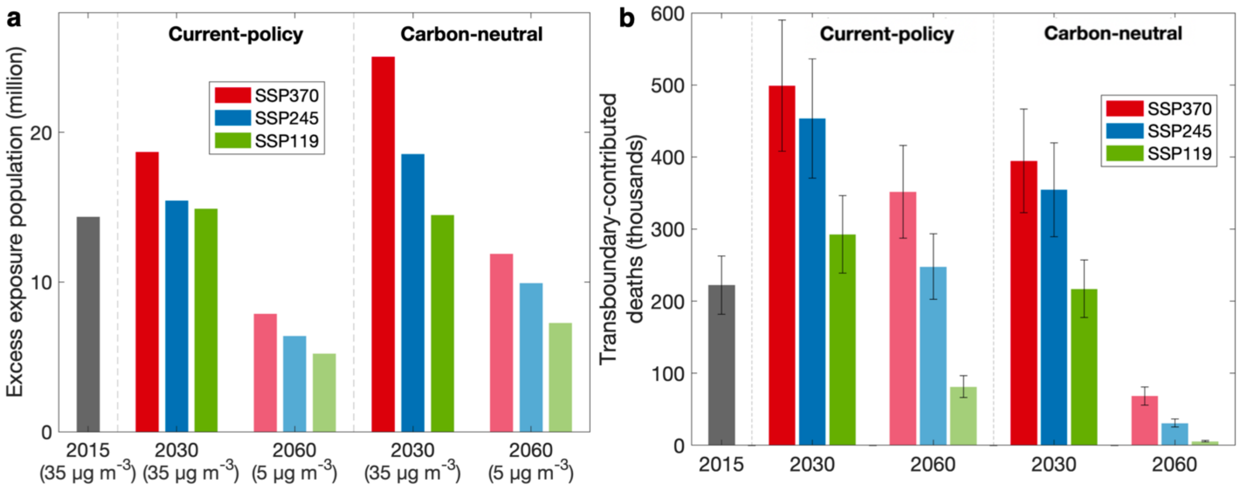

Figure 6. Potential health threats associated with transboundary pollution in China. **(a)** Population exposed to an annual mean population-weighted $PM_{2.5}$ concentration above the goals (35 μg m^{-3} for 2015 and 2030; 5 μg m^{-3} for 2060) due to transboundary contributions of $PM_{2.5}$ in China under different emission scenarios in China (denoted as text at the top) and in other countries (represented by colors in the legend). **(b)** Transboundary-contributed $PM_{2.5}$-related premature mortality in China under different emission scenarios in China (denoted as text at the top) and in other countries (represented by colors in the legend). Error bars represent the 95% confidence interval of the RR function.

Table 1. Description of future scenario settings

Scenarios	Socioeconomic pathway	Climate target	Pollution control strength	$PM_{2.5}$ emission level	Key features
Foreign					
SSP119	Sustainability	1.9 W m^{-2} (1.5 ℃)	Strong	Low	Strong economic growth via sustainable pathway. Incomes increase substantially and inequality within and between countries is greatly decreased. Significantly lower demand for energy- and resource-intensive agricultural commodities. Effective pollution controls result in substantial reductions in air pollutant emissions.
SSP245	Middle-of-the-road	4.5 W m^{-2} (3 ℃)	Medium	Medium	An intermediate case between SSP1 and SSP3.
SSP370	Regional rivalry	7.0 W m^{-2} (~4 ℃)	Weak	High	High inequity between countries. GDP growth is low and concentrated in current high-income nations, while population growth is focused in low- and middle- income countries. Energy system is coal-intensive. The implementation of pollution controls is delayed and less effective.
China					
Current-policy	Middle-of-the-road (SSP2)	4.5 W m^{-2} (3 ℃)	Medium	Medium	Achieve China's Nationally Determined Contribution (NDC) pledges and the national $PM_{2.5}$ air quality standard (i.e. 35 μg m^{-3}) by 2030, elucidating China's future air pollution mitigation pathway towards all the released and determined upcoming clean air policies since 2015.
Carbon-neutral	Sustainability (SSP1)	Net-zero CO_2 emissions in 2060	Strong	Low	Pursue China's carbon-neutral commitment and the WHO's old $PM_{2.5}$ guideline (10 μg m^{-3}) by 2060. It implements the best available end-of-pipe technologies and more stringent pollution control policies than the current-policy.

Table 2. Simulation configurations

Simulation type	Anthropogenic Emissions		Emission year	Met field year
	China	Foreign countries		
Base_2015	MEIC	CEDS	2015	2015
China_2015	MEIC	None		
Base_current_SSP119_2030	Current-policy	SSP119	2030	
Base_current_SSP245_2030	Current-policy	SSP245		
Base_current_SSP370_2030	Current-policy	SSP370		
China_current_2030	Current-policy	None		
Base_neutral_SSP119_2030	Carbon-neutral	SSP119		
Base_neutral_SSP245_2030	Carbon-neutral	SSP245		
Base_neutral_SSP370_2030	Carbon-neutral	SSP370		
China_neutral_2030	Carbon-neutral	None		
Base_current_SSP119_2060	Current-policy	SSP119	2060	
Base_current_SSP245_2060	Current-policy	SSP245		
Base_current_SSP370_2060	Current-policy	SSP370		
China_current_2060	Current-policy	None		
Base_neutral_SSP119_2060	Carbon-neutral	SSP119		
Base_neutral_SSP245_2060	Carbon-neutral	SSP245		
Base_neutral_SSP370_2060	Carbon-neutral	SSP370		
China_neutral_2060	Carbon-neutral	None		