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Future Projection of Mortality From Exposure to $PM_{2.5}$ and O_3 Under the Carbon Neutral Pathway: Roles of Changing Emissions and Population Aging

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Key Points:

- Carbon neutralization was projected to lead to synergistic reductions in CO_2, $PM_{2.5}$ and O_3 in China in the future
- Mortality caused by $PM_{2.5}$ and O_3 will increase by 38.1% in China from 2015 to 2060 under carbon neutrality because of population aging
- Relative to carbon neutrality pathway, deaths in 2060 in China under SSP5-8.5 would be higher by about 3,520.0 thousand

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

A global chemical transport model GEOS-Chem was applied to examine the concentrations of $PM_{2.5}$ and O_3 in China, related health burdens and the relative importance of changes in air pollutants and population aging over 2015–2060 under carbon neutral pathway (Shared Socioeconomic Pathway limiting end-of-century radiative forcing to 1.9 W m^{-2}, SSP1-1.9). Results showed synergistic reductions of 100.0%, 72.0%, and 24.4% in net CO_2 emission, concentration of annual mean $PM_{2.5}$, and the 90th maximum daily average 8-hr (MDA8) O_3 over China, respectively, during 2015–2060. Pollutants-related deaths owing to changes in pollutants and population were simulated to increase by 38.1% over 2015–2060 because of population aging. Over 2015–2060, sensitivity studies showed that the decline in pollutants alone would mitigate deaths by 5,172.7 thousand, while the population aging alone would increase deaths by 2,633.3 thousand. Carbon neutrality will avoid 3,520.0 thousand deaths in 2060 relative to a higher-carbon pathway (SSP5-8.5).

Plain Language Summary

The achievement of carbon neutrality by 2060, a goal proposed by Chinese government, will influence air quality and associated health burden in the future. Meanwhile, population aging is going to be a big challenge for the country to face. In this study, we assessed the changes in concentrations of $PM_{2.5}$ and O_3 and associated health impacts of different age populations from 2015 to 2060 using GEOS-Chem model and exposure-response functions. Contributions to premature deaths due to decline in pollutants and population aging were further quantified, respectively. We also compared the results based on carbon neutrality (SSP1-1.9) with those simulated from a pathway with higher CO_2 emission (SSP5-8.5) to figure out the environmental and health benefits of carbon neutrality. Our results suggested that the decline in $PM_{2.5}$ and O_3 benefited from carbon neutrality would mitigate the increase in mortality owing to population aging from 2015 to 2060. The increase in premature deaths caused by population aging alone under SSP1-1.9 will be less than that under SSP5-8.5. Our study highlighted the importance of implementing carbon neutral measures from the environmental and health perspectives.

1. Introduction

Observed concentrations of well-mixed greenhouse gases (GHGs) have been increasing from human activities and due to human activities and have caused a global warming of 1.07°C (0.8°C–1.3°C) in 2010–2019 relative to 1850–1900. (IPCC, 2021). Global fossil CO_2 emissions grew at a rate of 1.5% yr^{-1} during 2008–2017, and China was responsible for 27% of global fossil fuel emissions in 2017 (Le Quéré et al., 2018). For the long-term and sustainable development of the national economy, China aims to reach its peak carbon emission before 2030 and then to be carbon neutral by 2060. Since CO_2 is co-emitted with air pollutants (Zheng et al., 2018), it is of interest to investigate the fine particulate matter ($PM_{2.5}$) and ozone (O_3) air quality and the associated health impacts under carbon neutral pathway. Currently, observed concentrations of $PM_{2.5}$ and O_3 are high in China. For example, annual mean $PM_{2.5}$ concentration over Beijing-Tianjin-Hebei and surrounding regions was 43 μg m^{-3} and the 90th percentile of MDA8 O_3 was 171 μg m^{-3} in 2021 (Bulletin on the State of the Ecological Environment, 2021; https://www.mee.gov.cn/hjzl/sthjzk/).

Projection of future air quality needs future emissions for air pollutants. Shared Socioeconomic Pathways (SSPs) have been developed to provide distinctly different pathways about future socioeconomic development (Riahi et al., 2017; van Vuuren et al., 2014). The SSPs consist of five representative scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) spanning 2015–2100 and the emissions have been integrated in the Climate Model Intercomparison Project's Phase 6 (CMIP6) database (Gidden et al., 2019). The SSP1-1.9 scenario has the lowest global carbon emissions from 2015 to 2060 and China's CO_2 emissions will be net-zero in 2060 (Figure S1 in Supporting Information S1). The emissions of pollutants and CO_2 under carbon neutral pathway over China developed by Cheng et al. (2021) are consistent with those under SSP1-1.9. Therefore, in this work, we used SSP1-1.9 to represent carbon neutral pathway in China. Future air quality and associated health effect under SSP1-1.9 were examined and then compared with those from a higher carbon emitting pathway (SSP5-8.5). Although future climate change can also influence future air quality, changes in future emissions have been found to have a dominant role in influencing future levels of pollutants (Colette et al., 2013; Jiang et al., 2013; Kelly et al., 2012; Lee et al., 2015; Val Martin et al., 2015).

Several studies have estimated the future concentrations of air pollutants in China under carbon neutral pathway. Combining with the best available pollution control technologies, assumptions of social economy, and other settings under SSP1-1.9 pathway, Cheng et al. (2021) designed the carbon neutral pathway in China and reported that the annual mean population-weighted $PM_{2.5}$ concentrations in 72% cities in China would achieve the goal of below 10 μg m^{-3} by 2060 by using the Weather Research and Forecasting-Community Multiscale Air Quality (WRF-CMAQ) model accompanied by $PM_{2.5}$ Hindcast Dataset (PHD). On the basis of Chinese Academy of Environmental Planning Carbon Pathway (CAEP-CAP), Shi et al. (2021) simulated future air quality in China under carbon neutrality using the WRF-Comprehensive Air Quality Model with Extensions (WRF-CAMx) with the meteorology fixed at present (year 2019). Their results showed that the national annual mean concentrations of $PM_{2.5}$ and 90th percentile of MDA8 O_3 would be 11.0 and 93.0 μg m^{-3} in 2060, respectively. However, the regional transport models used in above studies could not consider the impacts of transboundary transport from other countries that have been shown to be important (Wang & Liao, 2022; N Zhang et al., 2018; Zheng et al., 2017). Therefore, in this work, we applied a global 3-D chemical transport model (Goddard Earth Observing System Chemical Transport Model, GEOS-Chem) to simulate the changes in concentrations of $PM_{2.5}$ and O_3 and from 2015 to 2060 under SSP1-1.9 driven by future changes in anthropogenic emissions.

The assessment of health impact from exposure to air pollutants depends on the concentrations of pollutants, baseline mortality rate (BMR), population (population size and population structure), and concentration-response functions (Burnett et al., 2014). By using the Global Exposure Mortality (GEMM) model with the population in 2015, BMR from WHO in 2016, and the simulated $PM_{2.5}$ and O_3 concentrations during 2012–2017 from the GEOS-Chem model, Dang and Liao (2019) estimated that the premature deaths in China in 2017 were 268.3 thousand fewer than those in 2012 as a result of the implemented clean air actions with fixed population in 2015. By using the BMR in 2017 from the Institute of Health Metrics and Evaluation and Integrated Exposure−Response (IER) model, the data of variation in population, and the pollutant concentrations simulated from the WRF-CMAQ model, Liu et al. (2021) estimated that the reductions in pollutant levels driven by emission changes could avoid 2,115.0 thousand deaths in 2050 under SSP1-2.6 compared to SSP5-8.5, which would be two orders of magnitude greater than that caused by the difference in climate between these two scenarios. From a long-term perspective, the premature deaths caused by population aging will be important. Geng et al. (2021) showed that population aging alone increased the $PM_{2.5}$-related deaths in China by 927.0 thousand from 2002 to 2017. However, few previous studies have estimated the health effects of future changes in air pollutants with population aging.

The scientific goals of this work include: (a) To simulate the future (2015–2060) changes in concentrations of $PM_{2.5}$ and O_3 in China driven by future changes in emissions under carbon neutrality (SSP1-1.9) with fixed meteorology for year 2015, using a global chemical transport model (GEOS-Chem); (b) To estimate the pollutant-related premature deaths during 2015–2060 under SSP1-1.9; (c) To quantify the contributions to premature deaths from emission changes and population aging during 2015–2060. All the environmental and health benefits of achieving the goal of carbon neutrality are compared with the results simulated with a higher level of carbon emitting pathway (SSP5-8.5).

2. Methods

2.1. Observed Concentrations of $PM_{2.5}$ and O_3

Hourly surface $PM_{2.5}$ and O_3 observations in 2015 in China were downloaded from the China National Environmental Monitoring Center (CNEMC) (https://quotsoft.net/air/) with the data collected from 1,484 sites. For data quality control, we deleted the missing and negative values and removed the sites with less than 80% valid data. The daily mean $PM_{2.5}$ concentration of a site was calculated only when there were more than 20 hr of valid data during that day and MDA8 O_3 concentration was calculated when there were at least 14 8-hr moving averages for the day. The data above were then used to calculate monthly mean and annual mean concentrations to evaluate the model performance. The concentrations of surface-layer O_3 were transformed from ppbv to μg m^{-3} under standard conditions (temperature = 273.0 K, pressure = 1,013.3 hPa).

2.2. GEOS-Chem Model

The simulations of $PM_{2.5}$ and O_3 from 2015 to 2060 under SSP1-1.9 and SSP5-8.5 were carried out using the nested version of the GEOS-Chem model (version 11-01, http://wiki.seas.harvard.edu/geos-chem/index.php/GEOS-Chem_v11-01). The nested domain for Asia (70–150°E, 10°S–55°N) has a horizontal resolution of 0.5° latitude by 0.625° longitude and 47 vertical layers up to 0.01 hPa. Tracer concentrations at the lateral boundaries were provided by global GEOS-Chem simulation with a horizontal resolution of 2.0° × 2.5° and were updated every 3 hr. The assimilated meteorological data of 2015 from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) was used to drive the model. The detailed mechanisms applied in GEOS-Chem were described in Text S1 in Supporting Information S1.

2.3. Emissions

Global anthropogenic and open burning emissions of nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), sulfur dioxide (SO_2), ammonia (NH_3), organic carbon (OC), and black carbon (BC) under SSP1-1.9 and SSP5-8.5 for 2015 and each decade of 2020–2060 were downloaded from the website https://esgf-node.llnl.gov/projects/input4mips/. The emissions have a horizontal resolution of 0.5° latitude by 0.5° longitude. Meanwhile, the monthly mean concentrations of CH_4 averaged over every 15 degrees of latitude provided by SSPs database under both pathways were also used as inputs in GEOS-Chem. For air pollutants, anthropogenic emissions are from eight sectors (agriculture, energy, industrial, transportation, residential and commercial, solvent production and application, waste, and international shipping) and open burning emissions are from four sectors (agricultural waste burning on fields, forest burning, grassland burning, and peat burning). Emissions of CO_2 in China during 2015–2060 were obtained from the website https://tntcat.iiasa.ac.at/, with emissions from seven sectors of energy, industrial, transportation, residential and commercial, solvent production and application, and waste. For more information about net emission of CO_2 in China, please see Figure S2 and Table S1 in Supporting Information S1.

Figure S1 in Supporting Information S1 shows the net emissions of CO_2 from China, Asia, and the whole of the world from 2015 to 2100 under scenarios of SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Under SSP1-1.9, the net emission of CO_2 from China will be -0.7×10^2 Tg in 2060, which is the only scenario with the net emission of CO_2 in China being negative by 2060. The reason for the negative emission in 2060 is that technologies such as carbon capture are considered in SSP1-1.9. SSP5-8.5 is the scenario with the highest carbon emissions, and the net emission of CO_2 was projected to be 1.9×10^4 Tg in 2060 and to peak by 2070 in this scenario.

Anthropogenic and open burning emissions (related to land-use scenarios) of different species in China under SSP1-1.9 and SSP5-8.5 generally would decrease from 2015 to 2060 except for NH_3 (Figure S3 in Supporting Information S1). Relative to 2015, emissions of NO_x, NMVOCs, CO, SO_2, OC, and BC in China in 2060 would change, respectively, by −82.9%, −88.8%, −69.5%, −96.6%, −66.8%, and −85.9% under SSP1-1.9 and by −24.0%, −24.3%, −53.4%, −67.3%, −64.1%, and −54.4% under SSP5-8.5 (Table S2). Emissions of NH_3 under both pathways will peak in 2030 and then turn to decrease. The total emission of NH_3 in China in 2060 was projected to change by −4.9% under SSP1-1.9 and by 4.4% under SSP5-8.5 relative to 2015.

2.4. Health Impact Assessment

The health impacts caused by pollutants ($PM_{2.5}$ and O_3) were assessed as premature human mortalities using the following equation:

$$\Delta \text{Mort} = \text{BMR} \times \text{Pop} \times \text{AF} \quad (1)$$

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where ΔMort is the premature deaths due to $PM_{2.5}$ or O_3 exposures, BMR is the baseline morality rate for a specific disease, and Pop is the exposed population. AF is the attributable fraction defined as 1 − 1/RR, where RR is relative risk. The annual cause-specific and age-specific baseline mortality rates (BMR) for noncommunicable diseases (NCD), lower respiratory infections (LRI), and respiratory in 2015 were obtained from Dang and Liao (2019) (Table S3 in Supporting Information S1). The RR(*C*) and corresponding parameters for estimation of mortality caused by $PM_{2.5}$ and O_3 were obtained from Burnett et al. (2018) and Anenberg et al. (2010), respectively (Text S3 in Supporting Information S1).

Total number of China's age-specific population from 2015 to 2060 was download from SSPs Database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=30). The gridded population data for 2015 at the 0.5° × 0.5° resolution from Global Population for World (GPW) data set (https://sedac.ciesin.columbia.edu/data/collection/gpw-v4/sets/browse) was regridded to 0.5° × 0.625° to be consistent with the resolution of the simulated concentrations of air pollutants. The gridded age-specific population datasets for 2015–2060 were obtained through multiplying the population of different age groups by the distribution of population densities for China in 2015 from GPW.

Figure S4 shows that SSP1-1.9 and SSP5-8.5 have similar size and structure of population during 2015–2060. Under SSP1-1.9 (SSP5-8.5), the total population of aged 25 and over in China would increase from 937.5 (937.4) million in 2015 to 1099.5 (1100.0) million in 2040 and then start to decrease. It was projected that the proportions of population aged 60 and over will continue to increase from 2015 (22.6%) to 2,060 (57.7%) under both pathways, indicating that the China's population will be rapidly aging.

2.5. Numerical Experiments

We designed a set of numerical experiments (Tables S4 and S5 in Supporting Information S1) to explore the changes in concentrations of $PM_{2.5}$ and O_3 and the associated health impacts in China driven by emission variations from 2015 to 2060 under SSP1-1.9, and then compare with those simulated for SSP5-8.5. There was a 6-month spin-up for each case in this study. The BASE experiment was simulated with the emissions and meteorological conditions in 2015 under SSP1-1.9 as the baseline to reproduce the air pollutants in 2015 and for the evaluation of the model performance. For 2020–2060 with 10-year interval, the simulations used future anthropogenic emissions and open burning emissions under SSP1-1.9 and SSP5-8.5 scenarios but fixed natural emissions and meteorological conditions at year 2015 levels (referred to as FUTE experiments). The differences in pollutant concentrations between carbon neutral and high carbon emission pathway can be obtained by comparing the results simulated from FUTE experiments based on SSP1-1.9 and SSP5-8.5 scenarios.

Three experiments were further designed to quantify the driving factors of the health impacts of air pollutants under different scenarios (Table S5 in Supporting Information S1): (a) the SENS experiment with concentrations of $PM_{2.5}$ and O_3, size of population, and structure of population varied from 2015 to 2060 whereas BMR fixed at 2015 level, (b) the SENS_FixConc experiment which was the same as SENS except for the concentrations of pollutants were fixed at 2015, and (c) the SENS_FixStruc which was the same as SENS but the structure of population was fixed at 2015. The differences between SENS and SENS_FixConc (SENS_FixStruc) can present the contributions of pollutant's concentrations (population structure) to health burdens caused by exposures of $PM_{2.5}$ and O_3.

3. Results

3.1. Model Performance

To evaluate the model performance, five regions of city clusters with large population and serious air pollution in China were selected, including Beijing-Tianjin-Hebei Region (BTH), Yangtze River Delta Region (YRD), Pearl River Delta Region (PRD), Sichuan Basin Region (SCB), and Fenwei Plain (FWP). The locations of these regions are shown in Figure S5 in Supporting Information S1.

Figure S6 shows the comparisons between the simulated and observed daily mean concentrations of $PM_{2.5}$ in above regions for year 2015. The model can reproduce well the daily concentrations of $PM_{2.5}$ in the 5 regions with correlation coefficients (*R*) of 0.61–0.72 and normalized mean biases (NMBs) of −7.6% to +27.4% (Figure S6 in Supporting Information S1). $PM_{2.5}$ concentrations were observed to peak in winter (December–January–

February) in all the regions with the highest daily value of 107.9 μg m^{-3} in February in PRD and of 316.6 μg m^{-3} in December in BTH due to the strengthened anthropogenic emissions as well as the low temperatures favoring nitrate ammonium formation (Dang & Liao, 2019).

Figure S7 in Supporting Information S1 shows the comparisons between the simulated and observed daily concentrations of MDA8 O_3 in above regions for year 2015. The model also captured the variations in MDA8 O_3 concentrations for the 5 regions with R values of 0.72–0.90 and NMB values ranging from +20.1% to +42.5% (Figure S7f in Supporting Information S1). Such positive biases were also reported in other studies attributed to the artificial mixing of O_3 precursors in model grids which caused higher O_3 production efficiency (Lu et al., 2019; Wild & Prather, 2006; Young et al., 2018; Yu et al., 2016). Driven by enhanced photochemical O_3 production owing to high temperatures and strengthened biogenic emissions of NMVOCs, BTH, YRD, SCB, and FWP had the highest values of MDA8 O_3 concentrations in summertime (June to August). PRD had the highest values in October (Figure S7c in Supporting Information S1) because of the large precipitation and hence low O_3 concentration in June related to the East Asian summer monsoon (Fu et al., 2019).

3.2. Air Quality in China From 2015 to 2060 Under SSP1-1.9 and SSP5-8.5 Pathways

According to the Technical Regulation for Ambient Air Quality Assessment and the Report on the State of the Ecology and Environment in China, air quality meets the national standards (Grade II) at a specific location when the annual mean concentration of $PM_{2.5}$ is less than 35 μg m^{-3} and the 90th percentile of annual MDA8 O_3 concentrations is below 160 μg m^{-3}. Emissions of CO_2 in China and air quality over the five polluted regions and China from 2015 to 2060 under SSP1-1.9 and SSP5-8.5 are presented in Figure 1. The concentrations of pollutants of China were calculated by averaging over all grid cells in China and the mask file were obtained from https://gadm.org/download_country_v3.html.

As shown in Figure 1, under SSP1-1.9, the concentrations of $PM_{2.5}$ and O_3 over the five regions were simulated to decrease along with the declining CO_2 emissions during 2015–2060. The annual mean $PM_{2.5}$ concentration averaged over China would change from 29.3 μg m^{-3} in 2015 to 8.2 μg m^{-3} in 2060 (a 72.0% decrease) because of the large reductions in emissions of aerosols and aerosol precursors along with the decreases in CO_2 emissions (Figure 1a). Relative to 2015, the changes in $PM_{2.5}$ in 2060 over BTH, YRD, PRD, SCB, FWP were simulated to be −75.5%, −74.3%, −75.8%, −75.5%, and −74.9%, respectively. All the regions would meet the $PM_{2.5}$ air quality standard by 2040. With respect to O_3, the 90th percentile of national mean MDA8 O_3 concentrations would decrease from 144.4 μg m^{-3} in 2015 to 109.2 μg m^{-3} in 2060, and the values in BTH, YRD, PRD, SCB, FWP would decrease by 27.3%, 27.6%, 33.1%, 33.1%, and 31.8%, respectively. The O_3 levels in the 5 regions can meet the air quality standard by 2030. Therefore, carbon neutralization can lead to synergistic reductions in CO_2, $PM_{2.5}$ and O_3.

Under SSP5-8.5, with the significant increases in CO_2 emissions in China from 2015 to 2060 (+80.7%), annual mean concentrations of $PM_{2.5}$ over BTH, YRD, PRD, SCB, FWP and the whole country were projected to decrease by 30.6%, 26.2%, 34.2%, 43.1%, 34.1%, and 24.6%, respectively. As a result, $PM_{2.5}$ air quality in the five regions, except for PRD, won't meet the national standard by 2060 (Figure 1d). From 2015 to 2060, the 90th percentile concentrations of MDA8 O_3 over BTH, YRD, PRD, SCB, FWP and China were simulated to change by +8.6%, +7.6%, +5.2%, −0.5%, +2.9% and +10.7%, respectively. Such increase under SSP5-8.5 pathway was also reported in a study that used CMIP6 datasets (Wang et al., 2022). O_3 air quality can't meet the standard by 2060 in all the five regions under SSP5-8.5 pathway (Figure 1d).

3.3. Changes in Annual Premature Deaths Caused by $PM_{2.5}$ and O_3 Exposures in China From 2015 to 2060 Under SSP1-1.9 and SSP5-8.5 Pathways

Figure 2 shows the age-specific premature deaths caused by $PM_{2.5}$ and O_3 over China during 2015–2060 under SSP1-1.9 and SSP5-8.5 pathways. The total mortality caused by $PM_{2.5}$ and O_3 exposures was 2,939.3 (95% CI: 2,860.0–3,015.7) thousand in 2015 under both scenarios in response to the similar pollutant levels and population. The deaths owing to $PM_{2.5}$ and O_3 exposures were, respectively, 2,700.1 (95% CI: 2,687.2–2,713.1) thousand and 239.2 (95% CI: 172.7–302.7) thousand in 2015 over China, which are consistent with the results from Dang and Liao (2019).

Dominated by the growth of $PM_{2.5}$-related deaths (especially for the people older than 60) under SSP1-1.9 pathway, the total pollutants-related premature deaths were projected to increase continuously from 2015 to 2060

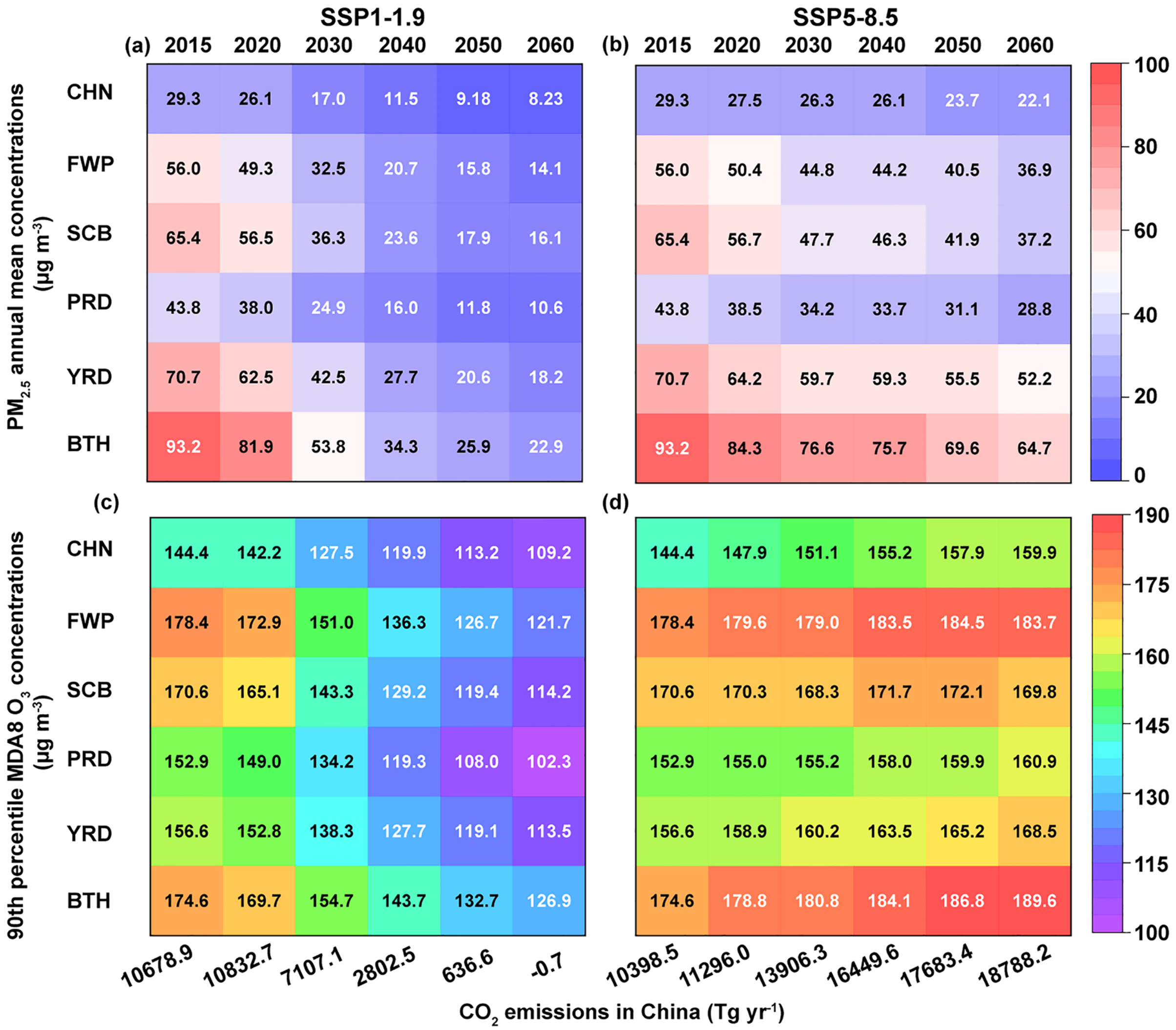

Figure 1. (a) The total CO_2 emissions in China (bottom) and the simulated annual mean concentrations of $PM_{2.5}$ under SSP 1–1.9 scenario. (b) Same as (a) but for SSP 5–8.5 scenario. (c) The 90th percentile MDA8 O_3 averaged over the regions of BTH, YRD, PRD, SCB and FWP and China (CHN) during 2015–2060 under SSP 1–1.9 scenario. Panel (d) same as (c) but for SSP 5–8.5 scenario.

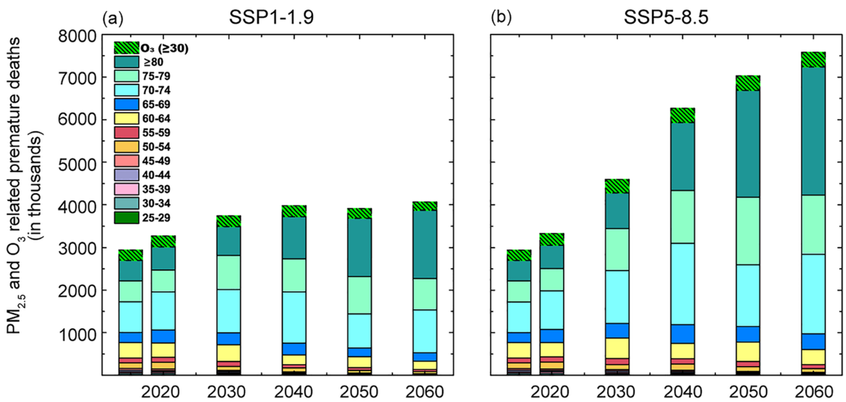

Figure 2. Age-specific premature deaths caused by $PM_{2.5}$ and O_3 (bright green with black slant lines) over China from 2015 to 2060 under pathways of (a) SSP1-1.9 and (b) SSP5-8.5.

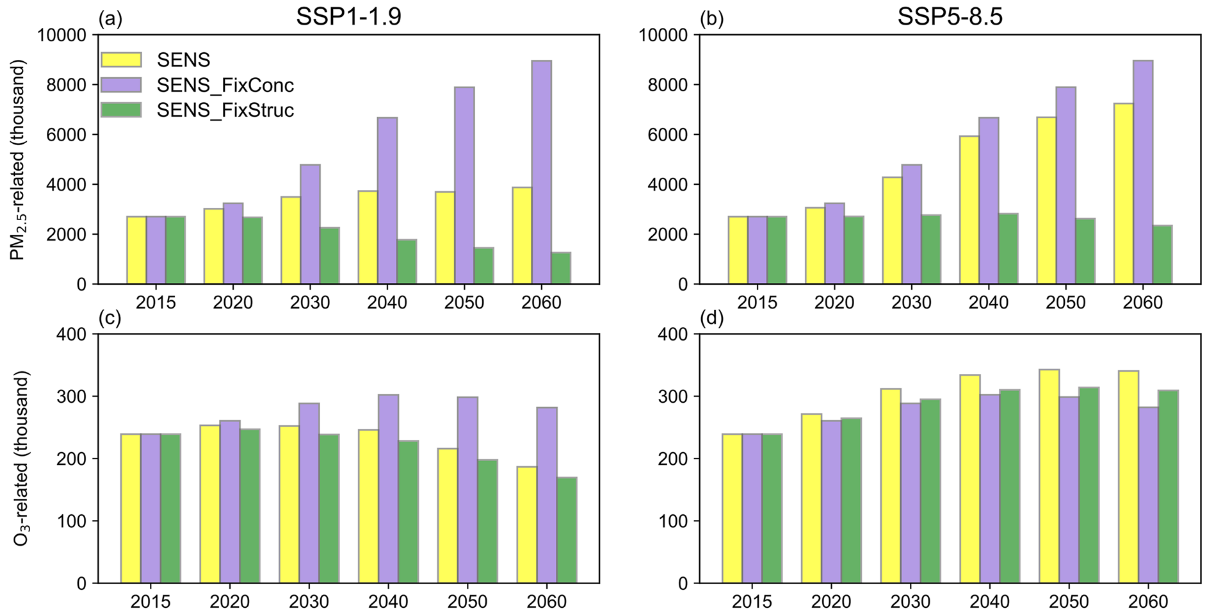

Figure 3. Premature deaths assessed from SENS (yellow), SENS_FixConc (purple, concentrations of pollutants were fixed at year 2015), and SENS_FixStruc (green, population structures were fixed at year 2015) in China from 2015 to 2060 for premature deaths from (a) $PM_{2.5}$ under SSP1-1.9, (b) $PM_{2.5}$ under SSP5-8.5, (c) O_3 under SSP1-1.9, and (d) O_3 under SSP5-8.5.

(+38.1%) except for a slight drop in 2050 due to a slight decrease in population. Premature deaths by O_3 exposures over China were simulated to peak in 2020 (253.2 (95% CI: 182.6–321.0) thousand) and then to decrease in response to the decline in MDA8 O_3 concentrations. Overall, even though the concentrations of pollutants would drop drastically under SSP1-1.9, the premature deaths were simulated to increase, indicating the important role of population aging from 2015 to 2060.

The SSP5-8.5 pathway would be of a more significant increase in total premature deaths over China caused by pollutants relative to those under SSP1-1.9. Model results showed that, from 2015 to 2060, the total premature deaths would increase by 157.9% due to the dominated deaths caused by $PM_{2.5}$ exposure. The premature deaths caused by O_3 exposure were projected to increase consistently to 340.5 (95% CI: 248.8–426.7) thousand (+42.4%) in 2060 along with the rising MDA8 O_3. By comparing the results from the two pathways, development based on SSP1-1.9 pathway can avoid 3,520.0 (95% CI: 3,466.8–3,568.7) thousand premature deaths including 3,366.1 (95% CI: 3,350.4–3,381.7) thousand from $PM_{2.5}$ and 153.9 (95% CI: 116.4–187.0) thousand from O_3.

Figure 3 shows the premature deaths assessed from SENS, SENS_FixConc and SENS_FixStruc. We attributed the pollutants-related premature deaths to changes in concentrations of pollutants (or population structure) over China by the difference in premature deaths between SENS and SENS_FixConc (or between SENS and SENS_FixStruc). As shown in Figures 3a and 3b, without changes in $PM_{2.5}$ concentrations, $PM_{2.5}$-related deaths will increase sharply under both pathways from 2015 to 2060 over China and reach 8,951.0 (95% CI: 8,906.8–8,994.8) and 8,958.0 (8,913.8–9,001.9) thousand in 2060, respectively, under SSP1-1.9 and SSP5-8.5 pathway. The differences between SENS and SENS_FixConc indicate that the future decline in $PM_{2.5}$ concentrations would mitigate premature deaths, especially for the SSP1-1.9 pathway. The benefits would be 5,077.6 (95% CI: 5,054.9–5,100.1) thousand and 1,718.5 (95% CI: 1,711.5–1,725.5) thousand in 2060, respectively, under SSP1-1.9 and SSP5-8.5 pathway. Comparisons of the results from SENS and SENS_FixStruc show that the change in population structure (population aging) will increase $PM_{2.5}$-related premature deaths significantly, especially for SSP5-8.5 pathway. The increase was estimated to be 1.9 times (4,897.3 (4,871.8–4,922.6) thousand) that under SSP1-1.9 (2,616.1 (95% CI: 2,601.4–2,630.7) thousand) in 2060.

When MDA8 O_3 concentrations were fixed at 2015 (Figures 3c and 3d), O_3-related premature deaths will peak in 2040 (about 302.2 thousand) under both scenarios and then turn to decline, which is consistent with the changes in total population over 30. As shown in Figure S4 in Supporting Information S1, the population with age over 30 will peak in 2040 (about 1033.1 million). The difference between SENS and SENS_FixConc shows that the decline in MDA8 O_3 concentrations under SSP1-1.9 can reduce O_3-related premature deaths by 95.1 (95% CI: 71.1–118.7) thousand in 2060, while premature deaths under SSP5-8.5 would keep increasing from 2020 to 2060 (an increase of 58.4 (95% CI: 45.0–69.7) thousand in 2060) owing to the upward trend of MDA8 O_3 level (Figure 3d). Relative to the results in SENS, the premature deaths in SENS_FixStruc would be lower in both scenarios from 2020 to 2060, indicating that the changes in population structure would increase O_3-related deaths in the future. Relative to SENS, population aging in 2060 would cause 17.2 (95% CI: 12.2–22.1) and 31.3 (95% CI: 22.9–39.2) thousand O_3-related deaths, respectively, under SSP1-1.9 and SSP5-8.5 pathways. It is worth noting that, by 2060, the premature deaths due to the increases in MDA8 O_3 will be higher than those due to population aging under SSP5-8.5, reflecting the significance of O_3 air quality improvement in the future.

Under SSP1-1.9, with changes in both concentrations of pollutants and population structure, the total premature deaths caused by both $PM_{2.5}$ and O_3 exposures in China would increase from 2,939.3 (95% CI: 2,860.0–3,015.7) thousand in 2015–4,060.0 (95% CI: 3,984.2–4,134.4) thousand (+38.1%) in 2060. Sensitivity experiments showed that, by 2060, changes in concentrations and population structure would lead to approximately −5,172.7 thousand and +2,633.3 thousand deaths, respectively. Under SSP5-8.5, the increase in premature deaths over 2015–2060 caused by both $PM_{2.5}$ and O_3 exposures would be 4,640.7 thousand; changes in concentrations and population structure would cause about −1,660.2 thousand and +4,928.7 thousand deaths, respectively. It should be noted that the contributions from pollutant concentrations and population structure to premature deaths are not linear.

4. Conclusions

Concentrations of $PM_{2.5}$ and O_3 and the associated health impacts in China from 2015 to 2060 under carbon neutral scenario (SSP1-1.9) and the higher carbon emitting pathway (SSP5-8.5) were examined using a global transport chemical model GEOS-Chem. The regional and annual mean $PM_{2.5}$ concentrations (annual 90th percentile of regional mean MDA8 O_3 concentrations) over BTH, YRD, PRD, SCB, FWP, and China were simulated to be, respectively, 93.2 (174.6), 70.7 (156.6), 43.8 (152.9), 65.4 (170.6), 56.0 (178.4), and 29.3 (144.4) μg m^{-3} in 2015. Under SSP1-1.9 pathway, relative to 2015, annual and regional mean concentrations of $PM_{2.5}$ in 2060 would decrease by, respectively, 75.5%, 74.3%, 75.8%, 75.5%, 74.9%, and 72.0% and the 90th percentile MDA8 O_3 concentrations would drop by, respectively, 27.3%, 27.6%, 33.1%, 33.1%, 31.8% and 24.3% over the regions listed above. $PM_{2.5}$ and O_3 air quality in all regions under SSP1-1.9 would meet the current national standard by 2040 and 2030, respectively.

Under SSP1-1.9, the total premature deaths attributable to $PM_{2.5}$ and O_3 exposures in 2015 were simulated to be approximately 2,939.3 thousand (about 2,700.1 and 239.2 thousand caused by $PM_{2.5}$ and O_3, respectively). Over 2015–2060, out of expectation, total premature deaths would exhibit an increasing trend even under carbon neutral pathway. Over 2015–2060, while the declining concentrations of $PM_{2.5}$ and O_3 would avoid 5,172.7 (95% CI: 5,126.1–5,216.8) thousand deaths, population aging would increase premature deaths by 2,633.3 (95% CI: 2,613.6–2,652.7) thousand in the whole of China.

$PM_{2.5}$ and O_3 air quality from 2020 to 2060 under SSP5-8.5 pathway were simulated to be worse and can't achieve the current air quality standard by 2060 in the studied polluted regions. Relative to SSP1-1.9, in 2060, premature deaths by $PM_{2.5}$ and O_3 would all be higher by 3,366.1 (95% CI: 3,350.4–3,381.7) thousand and 153.9 (95% CI: 116.4–187.0) thousand, respectively. Our study highlighted the importance of implementing carbon neutral measures from the environmental and health perspectives. It should be noted that the results shown here are driven by changes in emissions alone. The feedbacks between meteorology, climate and air pollutants are the subjects of near future studies.

Data Availability Statement

Data used in this study can be accessed publicly. Observations of $PM_{2.5}$ and O_3 concentrations can be obtained from the China National Environmental Monitoring Center (https://quotsoft.net/air/); the baseline mortality rates of diseases used in this study can be downloaded from Supporting Information S1 by using the DOI https://doi.org/10.1029/2019GL084605; the emission inventory from SSPs can be downloaded from the website https://esgf-node.llnl.gov/projects/input4mips/ with an registered account which is easy and quick to get; the gridded population can be obtained from the website https://sedac.ciesin.columbia.edu/data/collection/gpw-v4/sets/

browse which can be accessed easily with an user account; the population size can be obtained from SSPs database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=30) and it is free to download with an registered account which is easy and quick to get; the model output used in this study can be downloaded by using the DOI https://doi.org/10.5281/zenodo.8143765. We acknowledge the efforts of the GEOS-Chem, SSPs and CMIP6 working groups for developing the model and future scenarios.

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