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Projecting future health burden associated with exposure to ambient $PM_{2.5}$ and ozone in China under different climate scenarios

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ABSTRACT

Projecting future air pollution and related health burdens remains challenging because of the complex interactions among future emissions, population, and climate change. In this study, we estimated the premature deaths attributed to ambient fine particulate matter ($PM_{2.5}$) and ozone (O_3) from 2015 to 2100 under four socioeconomic climate scenarios based on an age-stratified assessment method. We found that $PM_{2.5}$ will decrease in all shared socioeconomic pathway (SSP) scenarios and O_3 will decrease in the SSP1-2.6 and SSP2-4.5 scenarios, contributing to a decrease in premature mortality together with the declining total population in China. However, the benefits of a decline in population size and $PM_{2.5}$ and O_3 concentrations over time will be largely offset by population aging, and premature death caused by $PM_{2.5}$ and O_3 will continue to rise till 2060–2080. This impact was greater for the O_3-related deaths than those for $PM_{2.5}$. Our study highlights the importance of future prevention strategies that must jointly improve air quality and susceptibility to aging.

1. Introduction

Ambient fine particulate matters ($PM_{2.5}$) and ozone (O_3) are harmful to human health and cause premature mortality from respiratory and cardiovascular diseases, and lung cancer (Hu et al., 2017; Wang et al., 2021a; Wang et al., 2021b). In China, the rapid economic development and intensive energy consumption have caused severe environmental pollution and health burdens. In 2015, $PM_{2.5}$ and O_3 exposure resulted in 4.2 million and 0.25 million premature deaths worldwide, respectively, among which 32–39 % occurred in China (Cohen et al., 2017; Li et al., 2018; Lin et al., 2018). The high burden of diseases caused by increased air pollution has always been an urgent issue that scientists and the government have committed to solving.

Changes in air pollution are influenced by various factors, including emissions, climate change, and socioeconomic factors. Affected by climate change, nitrogen oxide (NOx) and non-methane volatile organic compounds (NMVOCs) from biogenic emissions increase, contributing to the increasing effects on O_3 and $PM_{2.5}$, precursors concentrations (Nguyen et al., 2019). The study reported that every 10,000-t increase in CO_2 emissions reduction, $PM_{2.5}$ emissions reduction will increase by 3.3 t (Nguyen et al., 2019). Primary air pollutants reduction, such as NOx, VOCs can also impact ozone concentration. The Intergovernmental Panel on Climate Change (IPCC) report adopts a series of carbon dioxide (CO_2) emission scenarios (i.e., representative concentration pathways (RCPs)), to develop various climate scenarios using simulations (Moss et al., 2010). RCPs are a series of comprehensive enrichment and emission scenarios that are used as input parameters for prediction models of climate change under the influence of human activities in the

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21st century to describe future changes in population, socioeconomics, science and technology, energy consumption and land use., emissions of reactive gases, aerosols, and concentrations of atmospheric constituents (Meinshausen et al., 2020). Experiments performed as part of the coupled model intercomparison project (CMIP) and the aerosol chemistry model intercomparison project (ACMIP) have contributed significantly to the multimode evaluation of historical and future changes in air pollutants and projected future disease burdens (Shim et al., 2021). The sixth phase of the CMIP (CMIP6) scenario replaced the traditional four RCPs in the CMIP5 model with new emission scenarios driven by different socioeconomic climates. The shared socioeconomic pathways (SSPs) incorporate scientific combination scenarios of various SSPs: SSP1 (sustainability), SSP2 (middle of the road), SSP3 (regional rivalry), and SSP5 (conventional development)), and captured socioeconomic changes in population, urban density, education, land use, and wealth (IPCC 2021). The CMIP6 model integrates multiple scenarios and economic factors, enhances the robustness of climate projections, and provides better support for climate policy (Yao et al., 2021). However, current research is widely based on projections from the CMIP5 model (Chen et al., 2018; Chowdhury et al., 2018; Yan et al., 2022). Owing to the unique climate and economic environment in China, using the latest climate scenarios to assess health risks will help policymakers more accurately understand the future risk of death from air pollution.

Many studies on the health impacts of $PM_{2.5}$ and O_3 in the future only consider changes in concentration and population size and not population aging in the scenarios (Chowdhury et al., 2018; Wang et al., 2021a). Older populations are particularly vulnerable to air pollution because of their higher likelihood of chronic diseases and the decline in physiological protection mechanisms (Di et al., 2017; Shumake et al., 2013). Therefore, population aging may exacerbate health effects under changing climate conditions, especially in China, where the age structure of the population tends to be aging (Mao et al., 2020). No study has evaluated the health burden by considering the interaction of the three aforementioned drivers using the latest CMIP6 models.

To fill these research gaps, this study estimated $PM_{2.5}$- and O_3-related premature death changes from 2015 to 2100 under different SSP scenarios in China. We used air pollution data from the newly developed CMIP6 models and assessed the contribution of three key drivers–climate and emission changes, population size, and population age structure–to the change in the number of pollutant-related deaths. Our study provides a reference for China and other developing countries to formulate long-term clean air policies under different climate change conditions.

2. Materials and methods

2.1. $PM_{2.5}$ and O_3 data

We obtained annual average $PM_{2.5}$, and annual average daily maximum 8 h mean O_3 concentrations from the CMIP6 models in China every-five years from 2015 to 2100 and set 2015 as the base year under various socioeconomic climate scenarios. Four scenarios of a CMIP6 model were used to project the annual average concentration of $PM_{2.5}$, and 12 CMIP6 models were used to project the annual average of daily maximum 8 h mean O_3 concentrations. Details of the individual models are listed in Table S1. The simulation domain was nested over Asia (11°S–55°N, 70°–150°E), and the resolution of each model was statistically downscaled to $1^\circ \times 1^\circ$.

The $PM_{2.5}$ and O_3 exposures were estimated in the SSP1-2.6, 2–4.5, 3–7.0, and 5–8.5 scenarios of CMIP6 models. For scenarios SSP1-2.6 and SSP5-8.5, we assume that the human development trend is relatively optimistic, large sums of money have been invested in education and health, the economy is overgrowing, and organization is functioning well. The difference is that SSP1-2.6 is increasingly turning into sustainable development-related measures, and CO_2 emissions will generate a forcing level of 2.6 Wm^{-2} in 2100. Scenario SSP5-8.5 is assumed to be driven by an energy-intensive, fossil-fuel-based economy, and CO_2 emissions will cause a forcing level of 8.5 Wm^{-2} in 2100 (O'Neill et al., 2016). The SSP2-4.5 scenario represents a "middle way" scenario, which will continue the historical development pattern throughout the 21st century. The CO_2 emissions will generate a forcing level of 4.5 Wm^{-2} in 2100. The SSP3-7.0 scenario assumes a more pessimistic outlook on future socioeconomic development. With rapid population growth and increasing inequality, emerging countries have little investment in education and health. The CO_2 emissions will generate a forcing level of 7.0 Wm^{-2} in 2100 (Riahi et al., 2017).

Population-weighted concentrations (PWE) were used to estimate mean $PM_{2.5}$ and O_3 exposure. PWE $= \frac{\sum C_i * pop_i}{\sum pop_i}$, where C_i is the annual average $PM_{2.5}$ or O_3 concentration in grid *i*. pop_i *isthe* population of grid *i*.

2.2. Population data

Population trends in China were estimated by age groups every-five years from 2015 to 2100 under the five SSPs from the SSP Public Database Version 2.0 (https://tntcat.iiasa.ac.at/SspDb/dsd?Action = htmlpage&page = 30). This trend was subsequently incorporated into the population grid cells (1 km resolution) of the 2010 population census data obtained from the LandScan database of the Oak Ridge National Laboratory (https://landscan.ornl.gov/downloads/2008) to fit the CMIP6 model output.

2.3. Health burden assessment

Different age groups have different levels of immunity and susceptibility to air pollution (Wang et al., 2018). According to the studied population characteristics, we decided to assess air pollution-related deaths by specific age groups for $PM_{2.5}$ (25–65 and 65 + years-old) and for O_3 (30–50, 50–65, and 65 + years-old). The death toll was the sum of the number of deaths in a specific age group.

Cause-specific deaths, including chronic obstructive pulmonary disease (COPD; J40-J47), ischemic heart disease (IHD); I20-I25), stroke (I60-I69), and lung cancer (LC; C34), were obtained from the 10th revised International Classification of Disease Statistics (ICD-10) and summed up for assessing the premature deaths caused by $PM_{2.5}$ (Linares et al., 2018). Respiratory disease (J00-J99) deaths were used to estimate premature deaths caused by O_3 (U.S. Environmental Protection Agency, 2020). As shown in Eq (1), the premature deaths of $PM_{2.5}$ and O_3 associated with different disease categories were estimated every-five years, from 2015 to 2100.

$$\Delta Mort = \sum_{i=1}^{n} pop_{i,m,n,s} {}^{*} y_{j,m} {}^{*} \left[\frac{RR_{i,j,m,n,s} - 1}{RR_{i,j,m,n,s}} \right] \quad (1)$$

where $\Delta Mort$ is the premature mortality caused by $PM_{2.5}$ or O_3; $pop_{i,m,n,s}$ is the population of a specific age group *m* for grid *i* in years *n* under scenario *s*; $y_{j,m}$ is the baseline mortality with disease category *j* of specific age groups *m* obtained from the China Health Statistics Yearbook (Ministry of Health, 2011) (Table S2). $RR_{i,j,m,n,s}$ is the relative risk for disease category *j* of a specific age group *m* at a grid *i* in years *n* under scenario *s* caused by $PM_{2.5}$ or O_3, and *(RR-1)/RR* is the attributable fraction (AF).

We applied a newly developed global exposure mortality model (GEMM) by Burnett et al. (2018) to estimate the RR attributable to $PM_{2.5}$ exposure.

$$RR_{i,j,m,n,s}(\Delta Z_{i,m,n,s}) = exp\left\{ \frac{\theta_{j,m} \times ln\left(\frac{\Delta Z_{i,m,n,s}}{\alpha_{j,m}} + 1\right)}{1 + exp\left\{ - \frac{(\Delta Z_{i,m,n,s} - \mu_{j,m})}{\vartheta_{j,m}} \right\}} \right\},$$

$$\Delta Z_{i,m,n,s} = max\left(0, C_{i,m,n,s} - C_0\right) \quad (2)$$

where $C_{i,m,n,s}$ is the annual average $PM_{2.5}$ concentration of specific age group m at a grid i in years n under scenario s. C_0 is the theoretical minimum-risk concentrations of 2.4 μg/m^3; and $\theta_{j,m}$, $\alpha_{j,m}$,$\mu_{j,m}$ and $\vartheta_{j,m}$ are parameters that determine the shape of the concentration–response relationships (Table S3).

The RR of O_3 exposure for disease category j of a specific age group m at a grid i in years n under scenario s used the log-linear exposure–response function by Jerrett et al. (2009).

$$RR_{i,j,m,n,s} = exp^{\beta_{j,m} \times C_{i,m,n,s}} \quad (3)$$

where,$\beta_{j,m}$ is a coefficient of specific age groups estimated from ozone concentrations and respiratory mortality. The mortality risk coefficient for O_3 exposure used in the analysis is based on Jerrett et al. (2009), and the data were analyzed from 448,850 subjects, with 118,777 deaths during an 18-year follow-up period. This study is one of the several available studies on the long-term effects of O_3 exposure and is one of the few studies that consider risk values for age-stratified groups (30–50 yr-old, 50–65 yr-old, and 65 + years- old).

2.4. Driving factors decomposition

Premature mortality depends on the joint effects of climate and emission changes (pollutant concentrations driven by climate and emission changes), population size, and population age structure. Age-dependent mortality is one of the determinants of overall (all age) mortality, however we ignore age-specific changes in mortality due to data limitations. To evaluate the contribution of each factor to premature death, we projected the future changes in mortality due to individual factors. The impact of climate and emission changes (ICE) under the climate change scenarios was calculated by controlling the population size and adults groups as those in 2015 with projected future concentrations (Eqs. (4)–(5)).

$$A(Mor_{n,s}) = pop_{age-free,s,2015} \times y_{age-free} \times AF_{age-free,s,n} \quad (4)$$

$$\text{ICE}\,(\%) = \frac{A(Mor_{n,s}) - A(Mor_{2015,s})}{A(Mor_{2015})} \quad (5)$$

The adults group death was counted for $PM_{2.5}$-related deaths among people aged ≥ 25 years and for O_3-related deaths among people aged ≥ 30 years. The $pop_{age-free,s,2015}, y_{age-free} and RR_{age-free}$ data corresponding to the age in the equation are listed in Tables S2-S4. The impact of population size (IPS) was calculated by considering the population size change and pollutant concentration effect, and then subtracting (ICE) (Eqs. (6)–(7)).

$$B(Mor_{n,s}) = pop_{age-free,s,n} \times y_{age-free} \times AF_{age-free,s,n} \quad (6)$$

$$\text{IPS}\,(\%) = \frac{B(Mor_{n,s}) - B(Mor_{2015,s})}{B(Mor_{2015})} - ICE \quad (7)$$

The impact of population age structure (IPA) was calculated by considering the effect of population size change, population age structure, and pollutant concentrations and then subtracting IPS and ICE (Eqs. (8)–(9)).

$$C\left(Mor_{n,s}\right) = \sum_{age-group} pop_{age-group,s,n} \times y_{age-group} \times AF_{age-group,s,n} \quad (8)$$

$$\text{IPA}\,(\%) = \frac{C(Mor_{n,s}) - C(Mor_{2015,s})}{C(Mor_{2015})} - IPS - ICE \quad (9)$$

3. Results

3.1. Changes in $PM_{2.5}$ and O_3 concentrations

Both $PM_{2.5}$ and O_3 concentrations declined from 2015 to 2100 in all scenarios, except for SSP3-7.0 (Fig. 1). Compared with the other scenarios, SSP1-2.6 adopted the fastest implementation of air pollution controls and the lowest exposure level until the end of 2100. These changes are driven by massive emissions of anthropogenic aerosols and their precursors such as sulfur dioxide (SO_2), organic carbon (OC) and black carbon (BC) (Wang et al., 2021a). In contrast, the weakly controlled scenario, SSP3-7.0, showed an increased and a persistent trend of $PM_{2.5}$ and O_3 concentrations throughout the entire period. In the SSP5-8.5 scenario, $PM_{2.5}$ concentrations continued to decline until 2100, but high methane concentrations would hinder the decline in O_3 concentrations until 2080 (Liao Hong 2021). The concentration ranges of $PM_{2.5}$ and O_3 in each scenario are shown in the shaded parts of Figs. S1 and S2, respectively. Simulations were carried out in 'historical' mode by CMIP6 models and the observed $PM_{2.5}$ data were available for validation in two historical time periods, the baseline period 2013 to 2014, and 2015 to 2021 under SSPs (Figs. S3-S7). The CMIP6 model-derived $PM_{2.5}$ showed good agreement with the observed spatial distribution of $PM_{2.5}$. In terms of bias, compared with the observed $PM_{2.5}$ and O_3, the CMIP6 model overestimated the average $PM_{2.5}$ concentration and underestimated the average O_3 concentration. Fig. 1c and d showed that population-weighted concentrations of $PM_{2.5}$ are much higher than the average $PM_{2.5}$ levels. After 2030, the PWE of O_3 is also higher than the average concentration and showing an overall trend of first rising and then falling.

The overall population size of China decreased from 1,367.6–1,371.4 million to 562.6–776.5 million during the study period, of which the declines in the SSP1-2.6, 2–4.5, 3–7.0, and 5–8.5 scenarios are 52.4, 43.4, 58.9, and 52.3 %, respectively (Fig. 2a). Simultaneously, the population is aging rapidly from 2015 to 2100, with the smallest increase of 15.1 % (from 9.4 to 24.6 %) and the largest increase of 52.8 % (from 9.6 to 62.4 %) in the SSP 3–7.0 and SSP5-8.5 scenarios, respectively.

3.2. Premature deaths attributable to $PM_{2.5}$ and O_3 exposure

The nationwide premature deaths attributable to $PM_{2.5}$ exposure are shown in Fig. 3(a). In the SSP3-7.0 and SSP5-8 scenarios, $PM_{2.5}$-related deaths increase from 1.4 to 3.2 million (129 % increase relative to 2015) until 2060 (the targeted Chinese carbon–neutral year) and then drop slowly to 2.1 million (a 50 % increase from 2015) by the end of 2100. In contrast, the $PM_{2.5}$-related deaths in the SSP1-2.6 and SSP2-4.5 scenarios are less variable, resulting in 1.8 (a 28 % increase from 2015) and 1.9 (a 36 % increase from 2015) million deaths by 2100. Among the four specific diseases that cause $PM_{2.5}$-related deaths, IHD causes the highest number of deaths annually and is more concentrated in the elderly population (Fig. S8).

From a long-term perspective (2015–2100), the O_3-related mortality changed by 94.6 % to 171.6 % under all SSPs. The patterns of the O_3-related respiratory deaths are similar in the SSP1-2.6, 2–4.5, 3–7.0 scenarios, in which a peak number of deaths (around 0.31 million) occur in 2060. For scenario SSP5-8.5, O_3-related respiratory deaths continue climbing to 0.46 million by 2075. Overall, the death toll is maintained at a low level in the SSP3-7.0 scenario. For every year in SSPs, high levels of $PM_{2.5}$- and O_3-related deaths were observed in northern and central China, especially in the Beijing–Tianjin–Hebei and the surrounding regions (Fig. S9).

3.3. Drivers of changes in premature deaths

In this study, we estimated the changes in the premature mortality burden attributable to $PM_{2.5}$ and O_3 exposure driven by the climate and

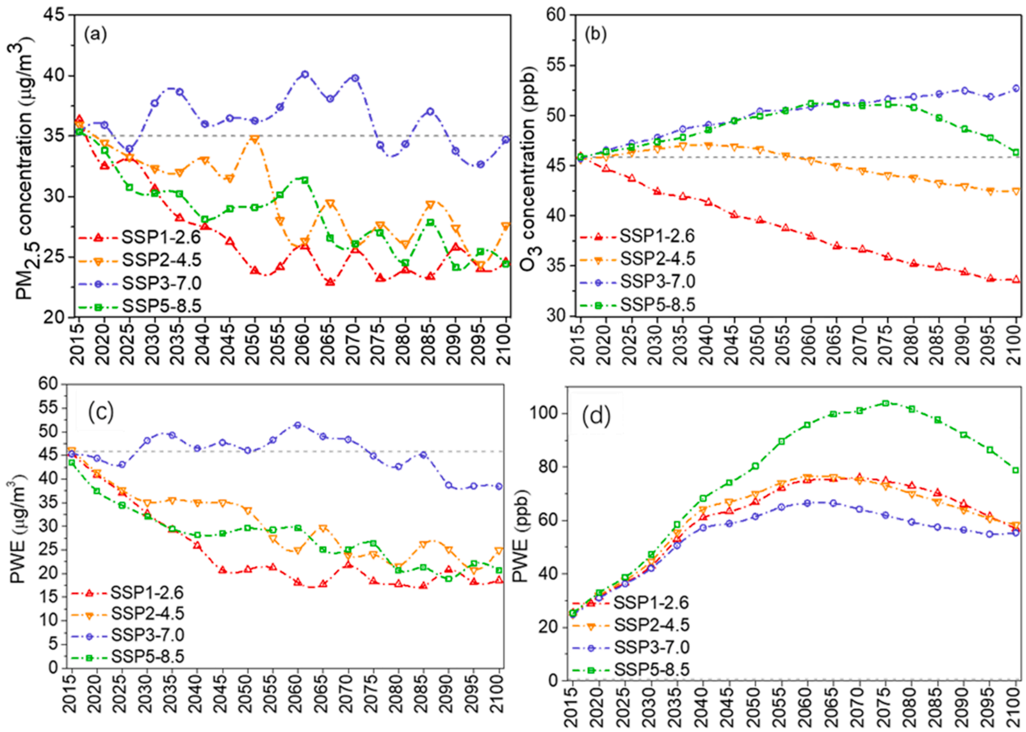

Fig. 1. The mean concentration and PWE of (a,c) $PM_{2.5}$ and (b,d) O_3 of multiple models from 2015 to 2100 in SSP1-2.6, 2–4.5, 3–7.0, and 5–8.5 scenarios.

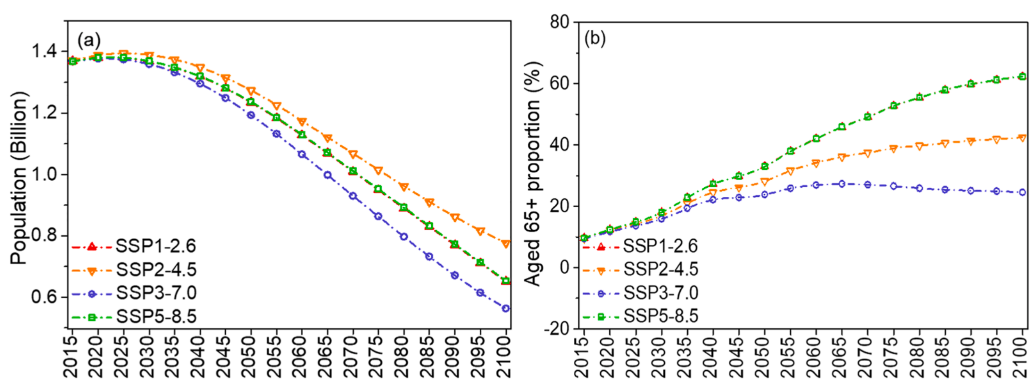

Fig. 2. (a) Projected exposed population size of all ages in SSPs (SSP1-2.6, 2–4.5, 3–7.0, and 5–8.5) in China from 2015 to 2100. (b) The proportion of the population aged above 65 years in four SSP scenarios in China from 2015 to 2100.

emission changes ($PM_{2.5}$ and O_3 concentrations driven by climate and emission change), population size, and population age structure, respectively. The changes in age-specific mortality were omitted here. The temporal change of the individual drivers on the deaths over time as compared to the deaths at baseline in 2015 is shown in Fig. 4. A positive value indicates an increase in premature mortality compared with that of the mortality in 2015. Overall, the increases in the number of deaths attributed to PM and O_3 due to age structure changes are greater than the decreases in these numbers due to the changes in population size and exposure levels. This impact contributed by the age structure was the greatest in the SSP5-8.5 scenario. The impact of population size on $PM_{2.5}$ and O_3-related deaths is small and positive before 2060–2080 (depending on the scenarios and the pollutants) but negative thereafter. The impacts of pollution exposure from global climate and emission changes on $PM_{2.5}$ and O_3 related deaths are notably different for $PM_{2.5}$ and O_3. For example, we observed an elevated negative contribution of the $PM_{2.5}$ concentrations driven by climate and emission changes over time (except in the SSP3-3.7 scenario), and a mixed situation for the impacts of the O_3 concentrations driven by climate and emission changes (positive impact in the SSP3-3.7 and SSP5-8.5 scenarios; negative impact in the SSP1-2.6 scenario).

We calculated the contribution of climate and emission changes, population size, and population age structure to the $PM_{2.5}$-related and O_3-related mortality in eight temperature zones in China (see Fig. S10 for the zone map) arranged in descending order of the temperature (Fig. 5). Overall, $PM_{2.5}$-related deaths decreased in all regions relative to the baseline because of the benefits of the decline in $PM_{2.5}$. Population aging remains the major driver of $PM_{2.5}$-related mortality in all temperature zones, except in the cold temperature zone where the adverse population aging effects are rather small and significantly offset by the tremendous $PM_{2.5}$ decline (100 %) in the SSP1-2.6 scenario. O_3-related mortality is closely related to temperature zones relative to cold temperate zone, the contribution of O_3 concentrations driven by climate and emission changes to mortality is higher in warm temperate zone (SSPs: 86.5–153.9 % vs 116.3–201.1 %). A spatial distribution map of the impact of climate and emission changes, population size, and population age structure on $PM_{2.5}$- and O_3-related mortality is shown in Fig. S11.

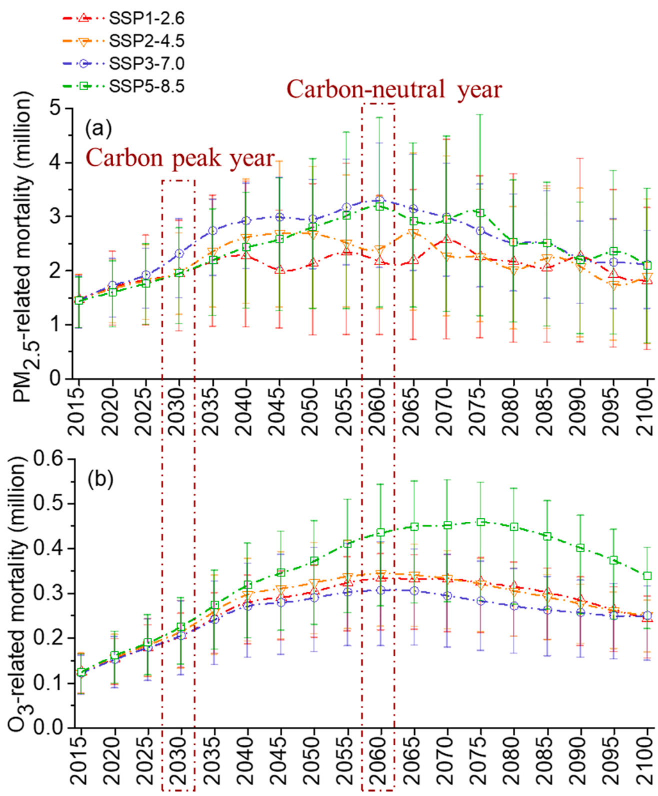

Fig. 3. The mortality caused by (a) $PM_{2.5}$ and (b) O_3 from 2015 to 2100 in SSP1-2.6, 2–4.5, 3–7.0, and 5–8.5 scenarios. The bar represents the range of $PM_{2.5}$- and O_3-related mortality in SSP1-2.6, 2–4.5,3–7.0 and 5–8.5.

4. Discussion

In this study, we estimated premature deaths attributable to ambient $PM_{2.5}$ and O_3 in SSPs from 2015 to 2100 in China and provided insight into the impact of the individual driving factors that induce a change in mortality, including pollutant concentrations, population size, and population age structure. In the coming decades, until 2070, the burden of premature death caused by $PM_{2.5}$ and O_3 will continue to rise, mainly due to the gradual aging of the population, which greatly offsets the positive impact of air pollution decline and population shrinkage. With a greater decline in air pollution and population size after 2070, the adverse impact of population aging on premature deaths related to $PM_{2.5}$ and O_3 is decreasing.

We applied GEMM model to estimate the RR attributable to $PM_{2.5}$ exposure. The most widely used coefficients are derived from the Integrated Exposure-Response (IER) model developed by Burnett et al. (2014), which provide better predictions of RR in more polluted regions. However, a fundamental limitation of the IER model is that it assumes equivalent exposure and toxicity of $PM_{2.5}$ from multiple sources. Recently, Burnett et al. (2018) constructed a GEMM model that constructed that relaxed the contentious assumption in the IER model to avoid the estimation bias and covered a comprehensive range of $PM_{2.5}$ concentrations (2.4 $\mu g/m^3$–84 $\mu g/m^3$) by including new cohort data from China. Thus, more suitable to provide accurate estimates than previous models (Burnett et al., 2018). We observed the optimal pathway in the SSP1-2.6 scenario from 2015 to 2100, which showed the lowest sums of $PM_{2.5}$- and O_3-related premature deaths. The SSP1-2.6 scenario follows the path of achieving the radiation-forcing target at the lowest cost. To achieve the expected radiation forcing (2.6 W/m^2) in the future, greenhouse gas emissions must be limited by controlling coal consumption-intensive industries, improving coal efficiency, and switching to clean fuels, etc. (YanRan Lü, 2020). The Lancet Commission (Watts et al., 2015) pointed out that greenhouse gas emissions, pollutants, and changes in demographic characteristics will accelerate the

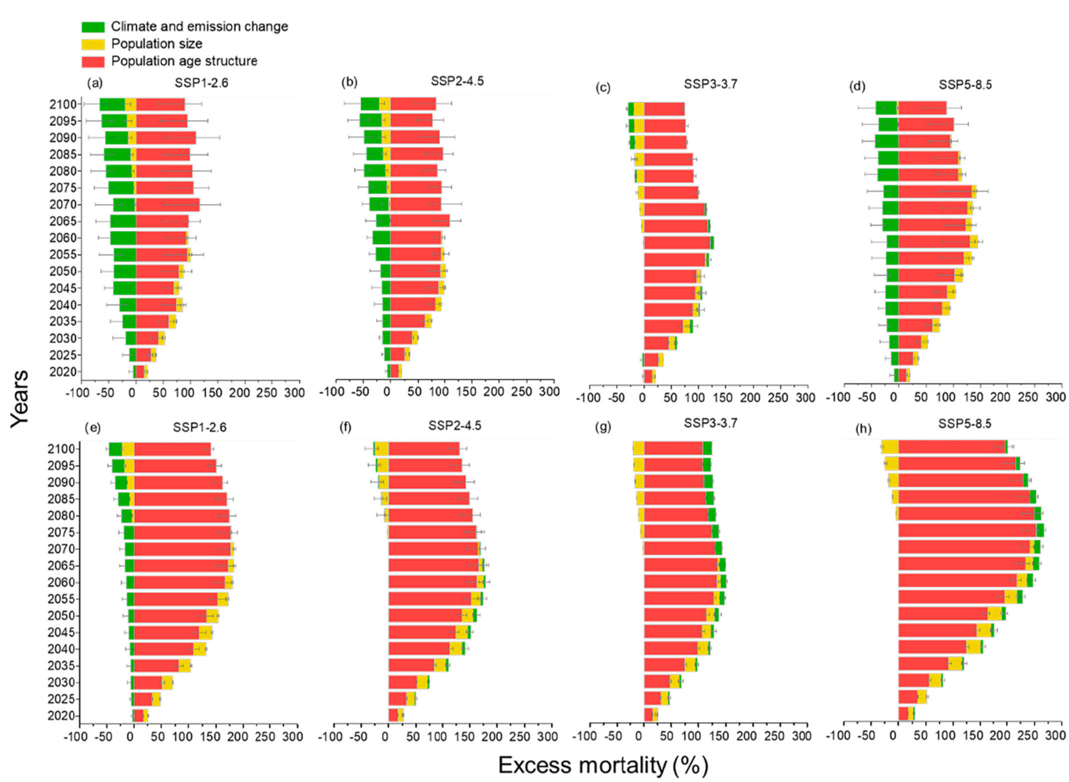

Fig. 4. The sensitivity of climate and emission changes, population size, and population age structure on (a-d) $PM_{2.5}$-related and (e-h) O_3-related premature death from 2015 to 2100 in SSP1-2.6, 2–4.5, 3–7.0, and 5–8.5 scenarios.

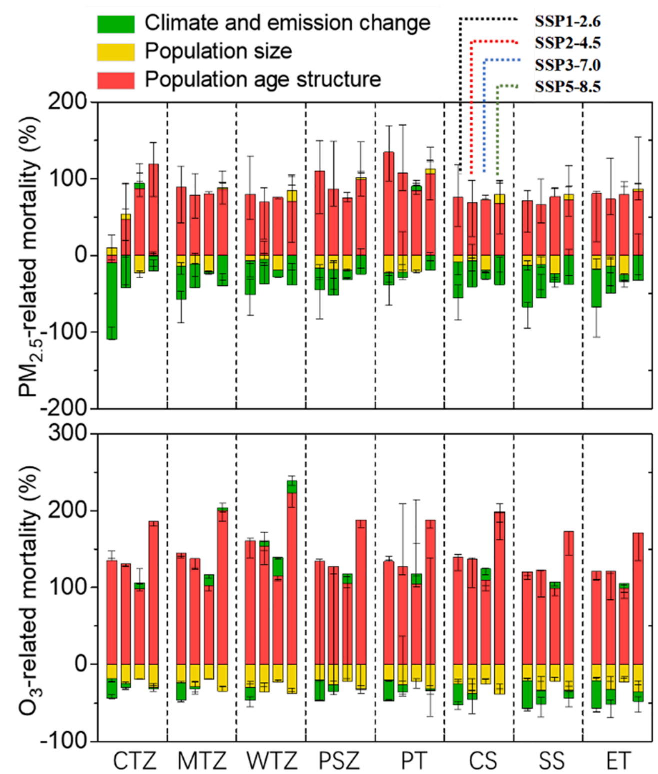

Fig. 5. The sensitivity of climate and emission changes, population size, and population age structure on (a) $PM_{2.5}$-related and (b) O_3-related premature deaths from 2015 to 2100 in different temperature zones in SSP1-2.6, 2–4.5, 3–7.0, and 5–8.5 scenarios. CTZ: cold temperate zone, MTZ: middle temperate zone, WTZ: warm temperate zone, PSZ: plateau subarctic zone, PT: plateau temperate, CS: central subtropical, SS: south subtropical, ET: edge tropical.

threat to human health in the context of climate change. Implementing measures to reduce greenhouse gas emissions and pollutants can avoid more premature deaths and the loss of related benefits. Greenhouse gas emissions of CO_2 and air pollutants have the same root and relationship, and their anthropogenic emissions originate from the burning of fossil fuels. The reduction of CO_2 and air pollutants as a whole was considered and combined various external factors such as energy endowment, economic development, environmental changes, and policy orientation were considered to research the optimized combination of emission reduction measures from the perspective of coordinated emission reduction (Xu et al., 2020).

We found that age structure had significant impacts on $PM_{2.5}$ and O_3 related deaths, mainly due to the increased aging population and the higher risks of cause-specific mortality among the elderly population at baseline. The effect of population aging will far offset the benefits of reduced O_3 and $PM_{2.5}$ concentrations in the future. Recent studies have shown that elderly adults are more susceptible to environmental exposure owing to their slow metabolism (Hahad et al., 2021). Although the O_3 concentration remained the lowest in the SSP1-2.6 scenario, the number of deaths caused by O_3 was the lowest in the SSP3-7.0 scenario, in which the elderly people over 65 years old were the lowest among the four scenarios. Our findings agree with a study by Chen et al. (2018), which suggests that ignoring the age structure of the population may underestimate the future premature mortality related to $PM_{2.5}$ and O_3. In the future, the burden of disease, and economic costs associated with high pollution levels and aging populations will increase rapidly. This will place a heavy burden on the national healthcare system. The reasonable allocation of public medical resources can reduce mortality in response to differences caused by diseases. Strategies to improve the health of the elderly and reduce their exposure may help to reduce the health costs of environmental air pollution. The significance of our research emphasizes the need to take action in the future to control ambient air pollution in an aging population.

Our study has several advantages. First, we use $PM_{2.5}$ and O_3 concentrations from extensive CMIP6 modeling outputs instead of relying on single model output, and accounted for multiple factors, including climate change and socioeconomics, in these scenarios. Thus, it provides reliable estimates for the health impact analyses. Second, a series of integrated SSPs were used to construct future air pollution exposure under dynamic climate change. Previous studies relied on the projections from the CMIP5 model, which did not account for the socioeconomic impact. For example, Liu et al. (2021) projected the deaths related to $PM_{2.5}$ in 2050 from the RCP8.5 scenario with different emissions (including the constant 2015 emissions, the 2050 current legislation emissions, and the 2050 maximum technically feasible reduction emissions). Chen et al. (2018) evaluated the future annual excess mortality related to short-term exposure to O_3 in 104 cities across China under two climate and emission change scenarios (RCP4.5 and RCP8.5). Our assessment of the burden of deaths under multiple scenarios will be useful in guiding future generations to achieve a green and sustainable environment. Finally, we estimated the impact of age structure when calculating the death toll of $PM_{2.5}$ and O_3 because different age groups have different susceptibilities to air pollutants, and the corresponding baseline mortality and exposure–response coefficients are also inconsistent. Many studies have not considered age stratifications, especially the impact of aging populations, which may underestimate the number of premature deaths (Chowdhury et al., 2018).

Our study had a few limitations. First, although it is argued that by accounting for different age groups and by incorporating changes in population size this would be considered "ageing", the mortality rates tend to vary largely by age group and scenario as discussed by Kc et al. (2018). It is worth noting that the future baseline mortality rate was related to many factors, and there is no way to accurately project the future improvement in living conditions and health services. In fact, because we consider age-specific mortality rates, when we consider age-structure changes, the effect of mortality rates should be reflected. In addition, the analysis of the trends in burden of disease due to particulate matter, conducted in the framework of Global Burden of Disease project (Cohen et al., 2017) indicates that changes (decline) in age-standardized mortality in the period 1990–2015 compensated, to a large extent, effects of growing population, its ageing and increase in exposure in China. Our results might be overestimated if the age-standardized mortality further decreases in China in the future. Second, we acknowledge that the relative risk coefficient β of O_3 and $PM_{2.5}$, which was mainly based on studies in the United States and European countries, which increases the uncertainty of our estimates. Although there is some evidence for the effect of O_3 on cardiovascular mortality (Kazemiparkouhi et al., 2020; Lim et al., 2019), the Global Burden of Disease (GBD) (https://vizhub.healthdata.org/gbd-compare/) only considers O_3 to be associated with respiratory mortality, and to avoid controversy, we only considered respiratory diseases. Ignoring the effects of O_3 on other diseases, our results may underestimate the health risks of O_3. In addition, Jerrett et al. (2009) used O_3 exposure data from April to September to calculate RR. We only obtained O_3 annual average concentrations from the CMIP6 models. The annual averages are lower than the warm season averages, which may also lead to underestimation of O_3 risk in this study. Third, the central values of the risk coefficients were used in the mortality assessment, ignoring their confidence intervals, resulting in statistical uncertainty of the risk coefficients. We calculated the range of associated deaths using confidence intervals for the RR of O_3 in Fig. S12 and found that the range of variation was around 0.9–37 %. The risk coefficient for O_3 used in this study is based on Jerrett et al. (2019) as it provides values for various age groups. Recently, several studies focused on the populations in the older age group (65 + yr-old) and provided more precise risk coefficients for the elder group in the United States and European countries (Liu et al., 2022; Shi et al., 2021). Using these coefficients might decrease uncertainty in RR and mortality estimates. In the future, more studies including subjects in various age groups are needed. Moreover, such studies from other regions than Europe and North America are highly recommended. Fourth, in this study, we calculated the health effects of $PM_{2.5}$ and O_3 separately, and their sum is not meant to be the combined effects of $PM_{2.5}$ and O_3. Due to the lack of coefficients for the synergistic exposure–response relationship between $PM_{2.5}$ and O_3, we did not consider the synergistic effect of the two. Fifth, Jerrett et al. (2009) demonstrated differences in sensitivity to O_3 by sex, with women at higher risk of death than men (RR:1.04 (1.03–1.07) vs 1.01(0.99–1.04)). Our study did not account for gender, which adds to the uncertainty. Finally, this study did not consider factors such as individual differences, personal exposure changes in age-specific mortality and indoor air exposure, which also increased uncertainty.

5. Conclusion

In this study, we projected the health burdens attributed to ambient $PM_{2.5}$ and O_3 from 2015 to 2100 under four SSP scenarios in China. The results indicate that in all SSP scenarios, the future death burden due to long-term exposure to $PM_{2.5}$ will decrease by 2100 in China. In the SSP1-2.6 and 2–4.5 scenarios, the future burden of death in China caused by O_3 will decrease by 2100. The decrease in deaths due to air pollution reduction and population change will be largely offset by rapid population aging from 2015 to 2100. Therefore, more aggressive air pollution reduction and medical measures for the elderly are required to prevent premature deaths and related economic impacts more effectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2022.107542.

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