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# Health Burden and economic impacts attributed to $PM_{2.5}$ and $O_3$ in china from 2010 to 2050 under different representative concentration pathway scenarios

Yiyi Wang [a], Jianlin Hu [a,*], Jia Zhu [a], Jingyi Li [a], Momei Qin [a], Hong Liao [a], Kai Chen [b,c], Meng Wang [d,e,f,**]

[a] Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment Technology, Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, Nanjing University of Information Science & Technology, 219 Ningliu Road, Nanjing 210044, China
[b] Department of Environmental Health Sciences, Yale School of Public Health, 60 College Street, New Haven, CT, 06520-8034, United States
[c] Yale Center on Climate Change and Health, Yale School of Public Health, 60 College Street, New Haven, CT, 06520-8034, United States
[d] Department of Epidemiology and Environmental Health, School of Public Health and Health Professions, University at Buffalo, Buffalo, NY, United Sates
[e] RENEW Institute, University at Buffalo, Buffalo, NY, United States
[f] Department of Environmental and Occupational Health Sciences, School of Public Health, University of Washington, Seattle, WA, United States

A R T I C L E I N F O

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A B S T R A C T

Quantifying the future health burden attributed to fine particulate matter ($PM_{2.5}$) and ozone ($O_3$) in China is challenging when jointly accounting for emissions, climate, and population changes. Future health burdens caused by $PM_{2.5}$ and $O_3$ in China remain largely understudied. In this study, the Goddard Earth Observing System chemical transport model (GEOS-Chem) was used to calculate the $PM_{2.5}$ and $O_3$ concentrations from 2010 to 2050 under four Representative Concentration Pathway (RCP) scenarios, including RCP2.6, RCP4.5, RCP6.0, and RCP8.5. Then the $PM_{2.5}$ and $O_3$-related premature mortality and years of life lost (YLL) in this period were projected. The resulting economic burdens, such as medical expenses (ME) and value of statistical life (VSL) in 2010–2050 attributed to the burdens of disease on $PM_{2.5}$ and $O_3$, were estimated. The results show that the $PM_{2.5}$ concentrations by 2050 will change by -31.5% to 14.5% compared to those in 2010 among different RCP scenarios, resulting in -13.5% to 9.4% changes in the $PM_{2.5}$-related mortality and -25.7% to 0.6% changes in the YLL. For $O_3$, the concentration changes will vary from -13.3% to 3.7% by 2050, contributing to -26.9% to 13.1% changes in the $O_3$-related mortality and -48.8% to 4.0% changes in the YLL. The lowest health impacts occur in the RCP4.5 scenario by 2050 for both pollutants. In 2010, the ME caused by $PM_{2.5}$ and $O_3$ is $6.3–6.5 billion, and the VSL is $112.1–114.9 billion, accounting for 2.9–3.0% of the total GDP ($3874 billion). By 2050, the ME and VSL will change -19.7% - 17.5% and -65.5% - 136.6%, respectively. This study suggested that future $PM_{2.5}$ and $O_3$ under RCP4.5 and RCP2.6 scenarios can have significant health and economic benefits. However, given that the future population will be higher than the baseline in 2010, more aggressive air pollution mitigation measures are required for China.

## Background

A large number of epidemiological studies have shown that fine particulate matter ($PM_{2.5}$) and ozone ($O_3$) contributes to premature mortality from chronic or acute diseases, including respiratory and cardiovascular diseases (Basagana et al., 2015; Hu et al., 2017; Monier et al., 2018). In China, the $PM_{2.5}$ and $O_3$ pollution problem is still very serious. The estimated population–weighted annual mean $PM_{2.5}$ concentration was 42.0 μg/m$^3$ (95% CI: 35.7–48.6) in 2017, which was more than four times of the World Health Organization annual mean $PM_{2.5}$ guideline of 10 μg/m$^3$ (Q. Zhang et al., 2019). Recent studies demonstrated that $O_3$ concentrations in Beijing, Chengdu and Shanghai exceeded the World Health Organization $O_3$ guideline value of 100 μg/m$^3$ for more than 30% of the days during 2013 to 2015 (Wang et al.,

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* Corresponding authors: Phone: +86-25-58731504.
** Corresponding author: Phone: +01-716-8292975.
*E-mail addresses:* jianlinhu@nuist.edu.cn (J. Hu), mwang54@buffalo.edu (M. Wang).

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2017). In addition, the daily maximum 8-hour average $O_3$ (8h-$O_3$) concentrations in Beijing, Chengdu, and Shanghai in 2015 increased by 12%, 25% and 22%, respectively, compared to those in 2013. The Global Burden of Diseases Study found that $PM_{2.5}$ and $O_3$ caused 4.2 million and 0.25 million premature deaths globally in 2015, respectively (Cohen et al., 2017), with 39% of $PM_{2.5}$ related premature mortality and 32% of $O_3$ related premature mortality attributed to China. The adverse health impacts of $PM_{2.5}$ and $O_3$ pollution place a huge burden on economic development in China (Chen et al., 2017; Maji et al., 2019). According to estimates by the World Bank, premature deaths due to $PM_{2.5}$ in China caused \$35 billion economic losses in 2010 and $O_3$ caused \$7.6 billion economic loss in 2016 (Maji et al., 2019).

Projecting future pollution changes and their impacts on health is challenging due to the uncertainties of changes in future emissions, climate, and population. A few studies had attempted to quantify the health impacts under specific future policy scenarios. For instance, Maji et al. (2018) projected the potential health benefits by 2020 according to the concentration of $PM_{2.5}$ in policy scenarios (WHO IT-1: 35 μg/m$^3$, IT-2: 25 μg/m$^3$, IT-3: 15 μg/m$^3$, and AQG: 10 μg/m$^3$ et al.). Wang et al. (2019) projected $PM_{2.5}$-related premature mortality in 2010, 2020, and 2030 using the target $PM_{2.5}$ concentration proposed (13th Five-Year Plan for Environmental Conservation). These studies set several future target pollutant concentrations that were not linked to pollutant emissions in the context of climate change.

In this study, the Goddard Earth Observing System chemical transport model (GEOS-Chem) is used to calculate changes in the annual mean $PM_{2.5}$ and 8h-$O_3$ concentrations in China under four representative concentration pathways (RCP) from 2010 to 2050 according to emission projections. Then the impacts of air quality changes under the different RCP scenarios are evaluated for their future premature death burden. The RCP scenarios generated a series of future scenarios representing different levels of concentration changes. This study primarily focuses on health and economic consequences from air pollution concentration changes, as a few studies had revealed that the 21st-century air quality forecast range was primarily driven by changes in concentrations rather than climate (Colette et al., 2013; Jiang et al., 2013).

## Methods

### *$PM_{2.5}$ and $O_3$ data*

The annual average concentrations of $PM_{2.5}$ and 8h-$O_3$ were calculated according to the emission projections in China from 2010 to 2050, with the year 2010 as the baseline period using a nested grid capability of GEOS-Chem 9.1.3 model (http://acmg.seas.harvard.edu/geos/). The model was driven by assimilated meteorological data in 2010 from the Goddard Earth Observation System (GEOS) of NASA's Global Modeling and Assimilation Office. The simulation domain was nested over Asia (11°S–55°N, 70°–150°E), with a horizontal resolution of 0.5° × 0.667° (50 × 66.7 km$^2$) and 47 vertical layers up to 0.01 hPa. The $PM_{2.5}$ was estimated as the total mass of each component of $PM_{2.5}$ from the GEOS-Chem model. The specific details were shown in Li et al. (2016). The $O_3$ concentrations were estimated by emissions of $O_3$ precursors, aerosol precursors, and aerosols, and the specific details were shown in Zhu et al. (2016). The GEOS-Chem model had reproduced the spatial-temporal distribution of $O_3$ and $PM_{2.5}$ concentrations in China. Li et al. (2016) compared the $PM_{2.5}$ model predictions with the observational data in five cities in 2010 under four RCP scenarios and found a general agreement between the predictions and observations, i.e., the correlation coefficients were 0.50–0.70, and the normalized mean deviations (NMB) were −31% to 39%. Similarly, Zhu et al. (2016) compared measured and simulated $O_3$ concentration at ten stations in 2000 under the RCP4.5 scenario. The observed correlation coefficient was 0.76, and the normalized mean deviation (NMB) was +11.6%.

Four RCPs warming scenarios (i.e. RCP2.6, RCP4.5, RCP6.0, and RCP8.5) were used to project the annual average of the $PM_{2.5}$ and the 8h-$O_3$ concentrations since the year 2010 for every decade through 2050. The RCPs were the basis for future climate change projections proposed by the IPCC's fourth assessment report, each of which represented a representative scenario of radiation forcing stabilization at 2.6 W/m$^2$, 4.5 W/m$^2$, 6.0 W/m$^2$, or 8.5 W/m$^2$ by 2100. Among the scenarios, the RCP8.5 was considered as a global high greenhouse gas emission scenario without mitigation measures, followed by RCP6.0, RCP4.5, and RCP2.6 . Therefore, it has been reported that the consequent global temperature may rise by 4.1 °C, 2.2 °C, 1.7 °C, and 0.9 °C until 2050 by different RCPs, as compared to that in 2000 (Monier et al., 2018).

### *Population data*

The population data from 2010 to 2050 were obtained from United Nations, Department of Economic and Social Affairs, Population Division: World Population Prospects: The 2019 Revision. (Medium variant) (https://www.populationpyramid.net/china). The data include population between the ages of 0 and 100, and are available every 5-year from 2010 to 2050.

Gridded population data from the 2010 census at 1 km resolution were obtained from the Oak Ridge Nation Laboratory's LandScan database (https://landscan.ornl.gov/downloads/2008) and grid fit the GEOS-Chem model resolution.

### *Health impact assessment of $PM_{2.5}$ and $O_3$ exposures*

Premature mortality associated with $PM_{2.5}$ and $O_3$ for different disease categories was estimated for each decade beginning from 2010 to 2050 according to Eq. (1). Premature mortality attributed to $PM_{2.5}$ concentrations was first estimated by disease categories, including chronic obstructive pulmonary disease (COPD, J40-J47), ischemic heart disease (IHD, I20-I25), stroke (I60-I69), and lung cancer (LC, C34), then summed to represent the total deaths for each decade. Premature mortality due to $O_3$ was estimated for cardiovascular (CVD, I00-I99) and respiratory (Res, J00-J99) mortality (U.S. Environmental Protection Agency, 2020):

$$\Delta\mathrm{Mort} = \sum_{i=1}^{n} pop_i * y_0 \left[\frac{\mathrm{RR}_{i,j} - 1}{\mathrm{RR}_{i,j}}\right], \tag{1}$$

where ΔMort is premature mortality caused by $PM_{2.5}$ or $O_3$; $pop_i$ is the population for grid i; $\mathrm{RR}_{i,j}$ is the relative risk for disease j at grid i caused by $PM_{2.5}$ or $O_3$; (RR-1)/RR is the attributable fraction; and $y_0$ is the baseline mortality of the particular disease categories obtained from China Health Statistics Yearbook (Ministry of Health, 2011).

The RRs of the $PM_{2.5}$ exposure for the different disease categories were estimated using an integrated exposure-response (IER) by Burnett et al. (2018; Burnett et al., 2014).

$$\mathrm{RR}_{i,j} = 1 \; C \leq C_0$$

$$\mathrm{RR}_{i,j} = 1 + \alpha_j\left\{1 - exp\left(-\gamma_j(C - C_0)\right)^{\delta_j}\right\} C > C_0, \tag{2}$$

where $\alpha_j, \gamma_j,$ *and* $\delta_j$ were obtained using the average of 1000 sets of fitting parameters by Burnett et al. (2014) (Table S1); $C$ is the projected $PM_{2.5}$ concentrations under the different RCPs scenarios; and $C_0$ is the theoretical minimum-risk concentrations of 5.8 μg/m$^3$ as used in the GDB 2010 (Lim et al., 2012).

The RR of $O_3$ related mortality risk by disease categories was calculated using the log-linear exposure-response function by Jerrett et al. (2009):

$$\mathrm{RR}_{i,j} = \exp(\beta \times \; (X - X_0)), \tag{3}$$

where $\beta$ is a coefficient estimated based on the associations of the ozone concentration with CVD and respiratory mortality from the estimates of the multi-pollutant model (Table S1), which were simultaneously adjusted for $PM_{2.5}$ and $NO_2$ (Turner et al., 2016); $X$ is the annual average 8h-$O_3$ concentrations; and $X_0$ is a theoretical of 26.7 ppb based on the minimum ozone exposure from the study of Turner et al. (2016).

The corresponding YLL was calculated as follows:

$$\Delta \text{YLL} = \sum \Delta \text{Mort}_t \times \text{LE}_t, \tag{4}$$

where ΔYLL is the YLL caused by PM2.5 or O3 at a specific age group, t; and $\text{LE}_t$ is the life expectancy at a specific age group, t, from 2010 to 2050, as shown in Table S2 (https://population.un.org/wpp/Download/).

The calculation of premature mortality under future scenarios had jointly accounted for the effects of exposure to pollutant concentrations due to emission changes and population size. To study the independent contribution of premature deaths from each determinant, one factor was mutually controlled as a constant to project the impact of the other determinants on future change in mortality.

### Economic impacts

The economic impact from air pollution changes was estimated based on two factors: 1) the total medical expenditure (ME), which refers to any expenses incurred to prevent or treat injuries or diseases; and 2) the value of a statistical life (VSL), which indicates how much an individual is willing to pay (WTP) for reducing the risk of death. It is widely used in cost-benefit analyses in the United States and Europe to evaluate the benefits of savings . The ME and VSL caused by premature death were calculated for each province in China.

$$ME_{\text{p,s,y}} = \sum\nolimits_1^p \Delta \text{Mort}_{p,s,y} \times \left(\text{GDP}_{p,y} \times \beta_p + \delta_p\right), \tag{5}$$

where $ME_{\text{p,s,y}}$ is the medical expenses [billion dollar/year] for province p, scenario s, and year y; $\beta_p$ and $\delta_p$ are the parameters of the medical service price by Xie et al. (2016); and $\text{GDP}_{p,y}$ is the per capita GDP for the province p at year y (Fig. S5) (Hawksworth, 2017).

$$VSL_{\text{p,s,y}} = \sum\nolimits_1^p \text{WTP} \times \Delta \text{Mort}_{p,s,y} \times \left(\frac{GDP_{p,y}}{GDP_{2010,China}}\right)^{0.5}, \tag{6}$$

where $VSL_{\text{p,s,y}}$ is the value of statistical life; $\text{GDP}_{\text{2010,China}}$ is the national average per capita GDP in 2010; and WTP is 250,000 dollars in 2010, which is a willingness, t, to pay for avoiding premature mortality (Xie et al., 2019). The assumption of future GDP was consistent with that of 2010.

## Results

### Future $PM_{2.5}$ and $O_3$ concentrations and population projections

Fig. 1(a) and Fig. 1(b) show the changes in the annual average concentrations of $PM_{2.5}$ and the 8h-$O_3$ by decades between 2010 and 2050 under the four different RCP scenarios. In Fig. 1(a), an inverse U-shape pattern of the $PM_{2.5}$ variations is shown under the RCP2.6, 4.5, and 8.0 scenarios across the period with the peak level shown in 2020, and the lowest level that occurred in 2050. For the RCP6.0 scenario, an elevated trend is noted throughout the years. This is consistent with the temporal variations of the major air pollutant emissions, which demonstrate an increasing trend under RCP6.0 (e.g. $SO_2$, NOx, $NH_3$, OC, and BC) from 2010 to 2030, as compare to the declining pattern of the emissions in the other scenarios (Fig. S4). Among the different scenarios, the RCP4.5 achieve the largest reduction in $PM_{2.5}$ of approximately 10 $\mu g/m^3$, as compare to the baseline $PM_{2.5}$ levels. By contrast, the $O_3$ projections decrease consistently under the RCP2.6 and RCP4.5 scenarios, but increase under the RCP6.0 and RCP8.5 scenarios. Overall, the $PM_{2.5}$ concentrations decrease from the baseline by 6.3–11.1 $\mu g/m^3$ under the RCP2.6, 4.5, and 8.5 scenarios until 2050, and the $O_3$ concentrations decrease by 3.7–6.1 ppb under the RCP2.6 and RCP4.5 scenarios. The magnitude of reduction for the $PM_{2.5}$ concentrations is comparable to a previous study in eastern China that suggested

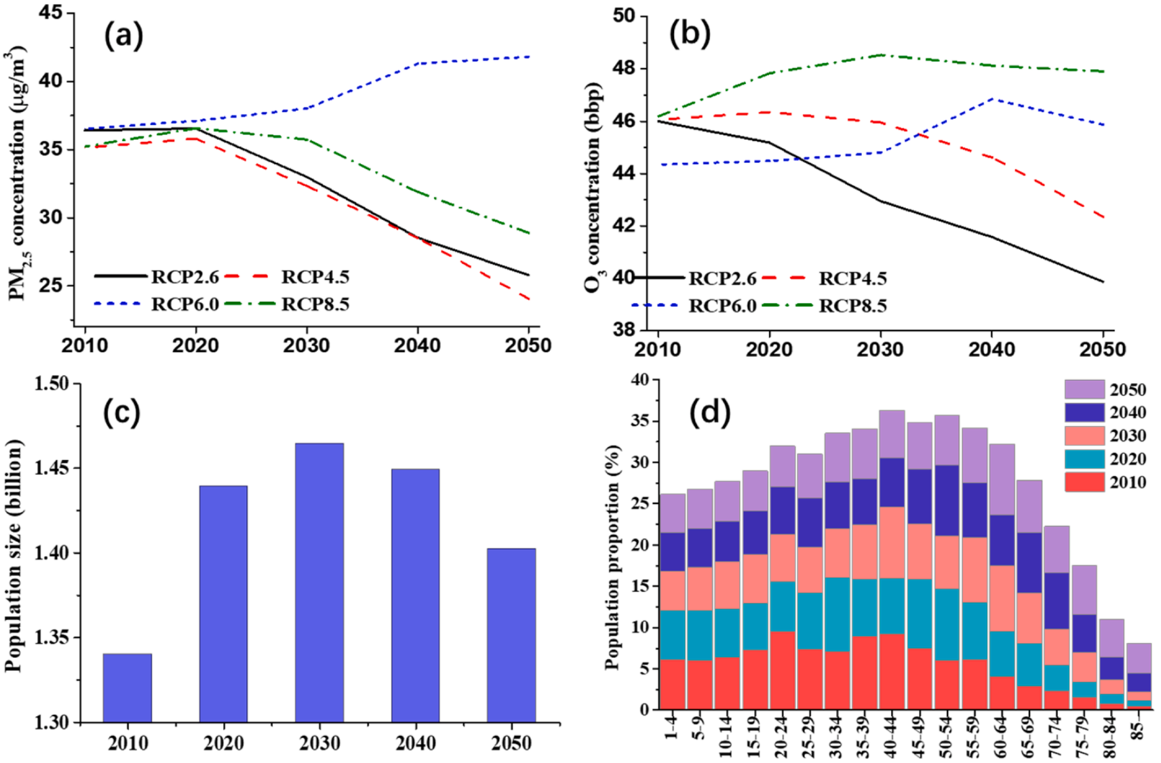

**Fig. 1.** The concentration of $PM_{2.5}$ (a) and $O_3$ (b) from 2010 to 2050 under the RCP scenarios. Projections of the exposed population sizes (c) of all ages in China from 2010 to 2050. Population proportions in each age group (d) from 2010 to 2050.

approximately 1–8 μg/m$^3$ lower $PM_{2.5}$ concentrations in 2050 than that in 2000 under the RCP2.6, 4.5, and 8.5 scenarios (Jiang et al., 2013). In addition, for the $O_3$ concentration, a reduction of 7–6 ppb under the RCP4.5 scenarios is demonstrated (Chen et al., 2018).

The population size is estimated to reach a peak by 2030 of 1464 million and then drop to 1402 million by 2050 (Fig. 1(c)). The population will be aging significantly from 2010 to 2050, with an increase proportion of the elderly over 75 years old (Fig. 1(d)); the decadal changes suggest an increased susceptibility to $PM_{2.5}$ and $O_3$ for the Chinese population in the future.

The projected spatial distributions of the $PM_{2.5}$ and $O_3$ concentrations by decades are shown in Fig. S1 and Fig. S2. By 2050, the largest $PM_{2.5}$ reduction area (>40 μg/m$^3$) is primarily the regions that are highly industrialized or urbanized, such as the Beijing-Tianjin-Hebei region and the Sichuan Basin (Fig. S3 (a)). For $O_3$, a significant $O_3$ reduction is observed in the south-central areas of China near the Yangtze River Delta region (Fig. S3 (b)).

### *Estimated premature mortality and the YLL*

Premature mortality for $PM_{2.5}$ and $O_3$ exposure generally follows the same pattern as the concentration changes over the decades under the RCPs (Fig. 2(a) and Fig. 2(b)). The largest number of avoided deaths is observed under the RCP4.5 scenario for $PM_{2.5}$ and the RCP2.6 for $O_3$, which resulted in 0.25 million and 0.11 million less deaths by 2050 as compare to the deaths at baseline. Although the reductions of $PM_{2.5}$ and $O_3$ are spatially different, the resulting largest changes in deaths are consistently shown in the Beijing-Tianjin-Hebei region, the Yangtze River Delta, and the Sichuan Basin (Fig. S3(c and d)).

There are 1.88–1.93 million deaths caused by $PM_{2.5}$ in 2010, in which stroke deaths contribute the highest percentage (50.4–50.5%), followed by deaths from IHD (34.6%–34.7%), LC (7.5–7.6%), and COPD (7.3%–7.4%). By 2050, $PM_{2.5}$ cause a change of −0.25 million to 0.18 million deaths. Except in the RCP6.0 scenario, the relative contribution of IHD to the total deaths increased by 0.8%–1.7%, whereas deaths from COPD decreased by 0.4%–0.8% (Fig. 3(a)). Under the RCP 4.5 scenarios, the mortality caused by COPD, stroke, IHD, and LC decreased by 22.9%, 9.2%, 13.8%, and 22.2%, respectively (Fig. 3(c)).

In 2010, there are 0.38 million (0.20 million, 0.56 million) to 0.42 million (0.22 million, 0.61 million) deaths related to $O_3$, and CVD accounted for 51.7–51.9%, and respiratory illnesses accounted for 48.0–48.3%. By 2050, $O_3$ changed the figures from −0.11 million to 0.05 million deaths. The changes in the contributions of the two diseases fluctuated slightly (0.4–0.6%) (Fig. 3(b)). Under the RCP2.6 and RCP4.5 scenarios, the mortality associated with each disease was reduced. In the RCP6.0 and RCP8.5 scenarios, the results were opposite (Fig. 3(d)). Fig. 2(c) and Fig. 2(d) show the year of loss (YLL), which reflects the number of years lost due to death before life expectancy, caused by $PM_{2.5}$ and $O_3$. In 2010, the YLL caused by $PM_{2.5}$ exposure is 92.4–94.8 million. From 2010 to 2020, the number of early death years increase slightly, then decreased for the next 30 years. By 2050, the YLL caused by $PM_{2.5}$ will have decreased by 25.7% since baseline under the best scenario (i.e. RCP4.5). The trend of YLL caused by $O_3$ is consistent with that of premature death from 2010 to 2050, suggesting an approximate reduction of 6.7 million by 2050 under the best scenario (i.e. RCP2.6).

### *Impact of changes in the emissions and population size on premature mortality*

Fig. 4 shows the independent impacts of two factors (emissions and population size) on $PM_{2.5}$- and $O_3$-related mortalities from 2010 to 2050 under the four RCP scenarios. The change in the $PM_{2.5}$ concentration while holding the population growth caused a 7.8%–17.3% reduction in mortality across all the scenarios, except the RCP6.0. The population change while maintaining the baseline $PM_{2.5}$ distribution resulted in a 3.8%–4.9% increase in excess mortality by 2050 relative to 2010. For $O_3$, the impact of the concentration reduction *per se* contributed to a total of 30.2% avoided $O_3$-related mortalities under the RCP2.6

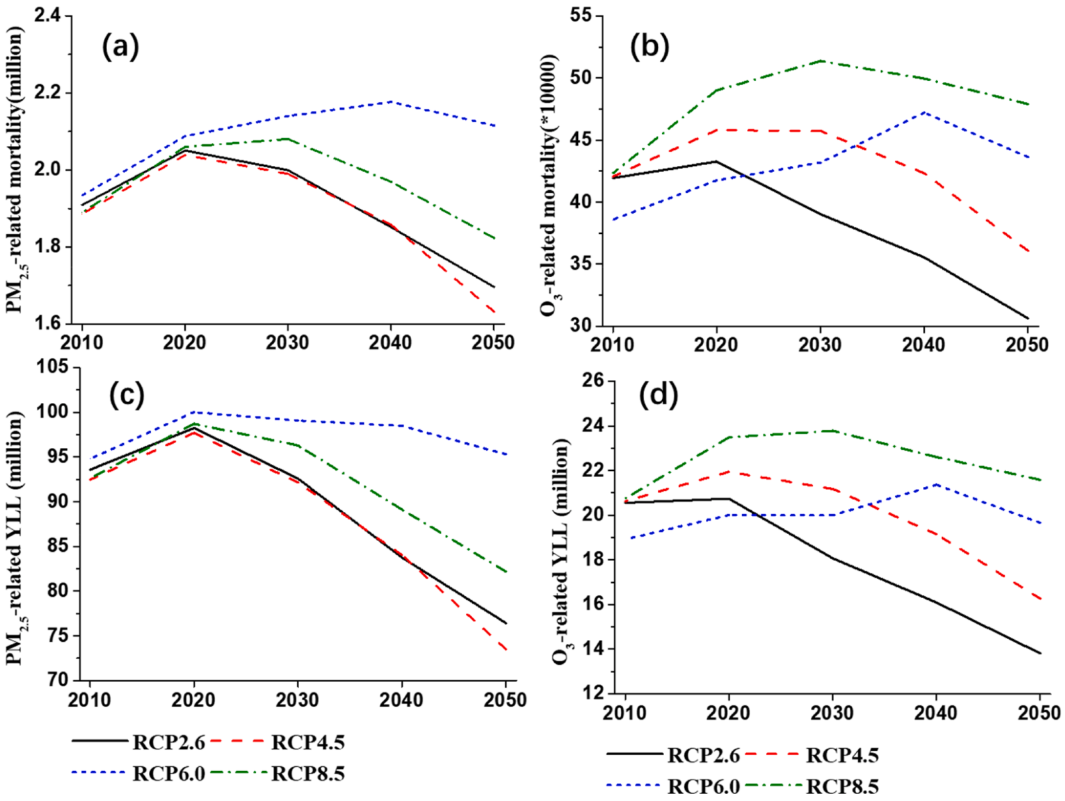

**Fig. 2.** The mortality (a, b) and YLL (c, d) caused by $PM_{2.5}$ and $O_3$ from 2010 to 2050 under the four RCP scenarios.

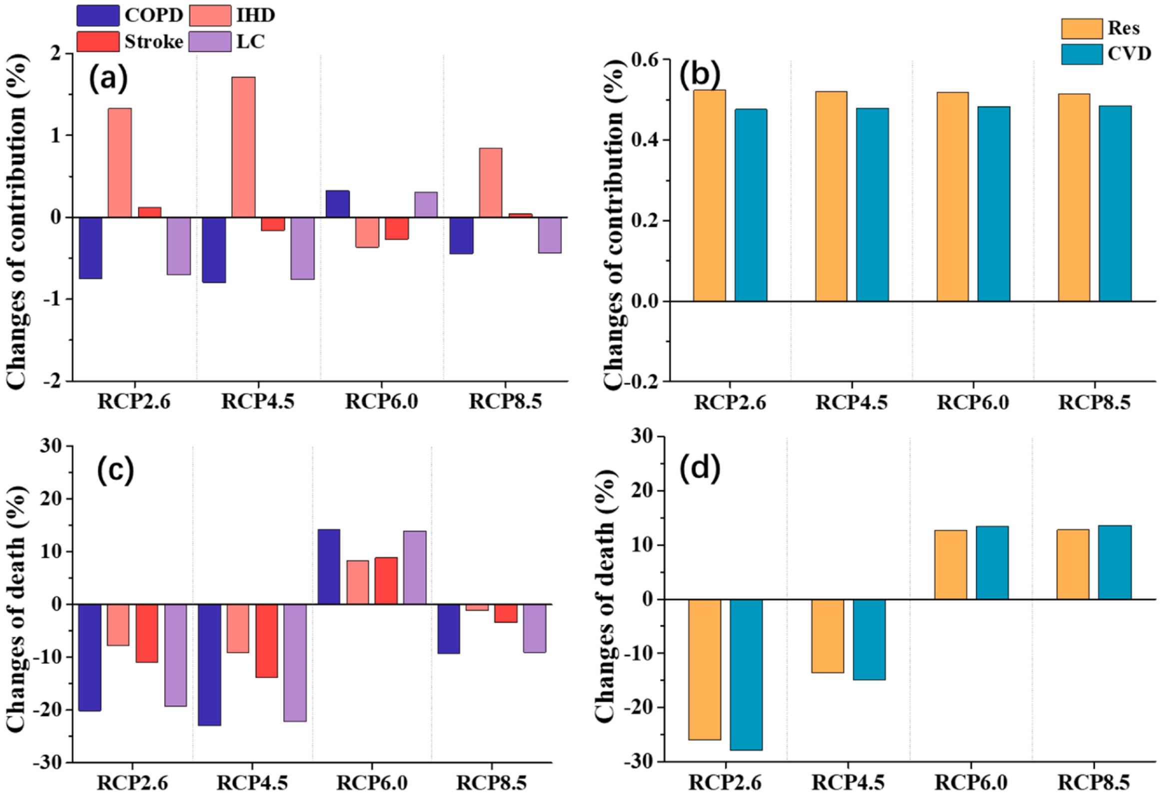

**Fig. 3.** Changes in contribution (a) and mortality (c) of specific diseases (Chronic obstructive pulmonary disease (COPD), Ischemic heart disease (IHD), stroke and Lung cancer (LC)) related to $PM_{2.5}$. Changes in contribution (b) and mortality (d) of Cardiovascular (CVD) and respiratory related to $O_3$.

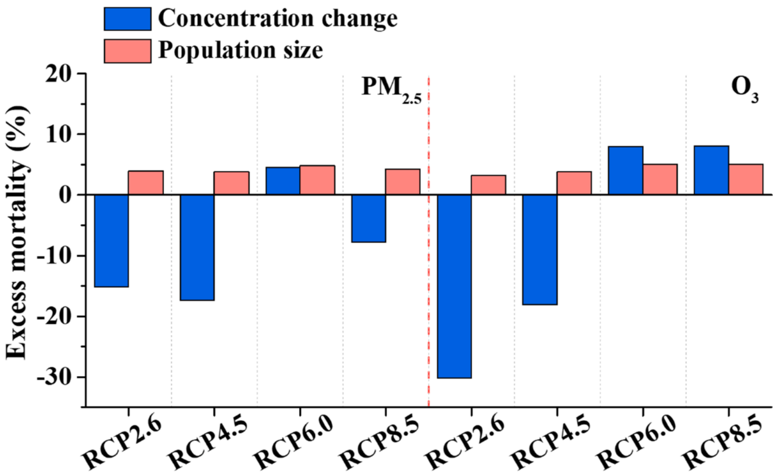

**Fig. 4.** The impact of concentration and population size changes on the $PM_{2.5}$-related and $O_3$-related premature death reductions from 2010 to 2050 under the four RCP scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scenario. This is followed by 18.0% under the RCP4.5 scenario. In comparison, an increase in the population size led to a small increase in the $O_3$-related mortality under all the scenarios.

### *Provincial mortality changes driven by air pollution changes*

Fig. 5 shows the relationships between the percent decline in pollutant-related premature deaths that jointly accounted for the impacts of the concentration changes and population growth. Fig. 5 also shows the changes in air pollution in the provinces between 2010 and 2050 under the future scenarios. In general, the scatter plots display a positive relationship pattern for air pollution and mortality in most of the provinces, confirming the major impact of concentration changes on the mortality reductions for all the scenarios. However, there are also some provinces far beyond the regression line, such as Tibet, Hainan, and Yunnan, which suggested that additional factors, such as population changes and baseline mortality rates, may play important roles in these provinces. Under the RCP4.5 scenario, the number of deaths in Hainan is zero. This result is due to the sparse population and low pollutant concentration. In provinces, such as Xinjiang, Gansu, Qinghai, and Neimeng, where the concentration reduction rate was less than 20%, it is difficult to further reduce the concentration due to the low initial concentration.

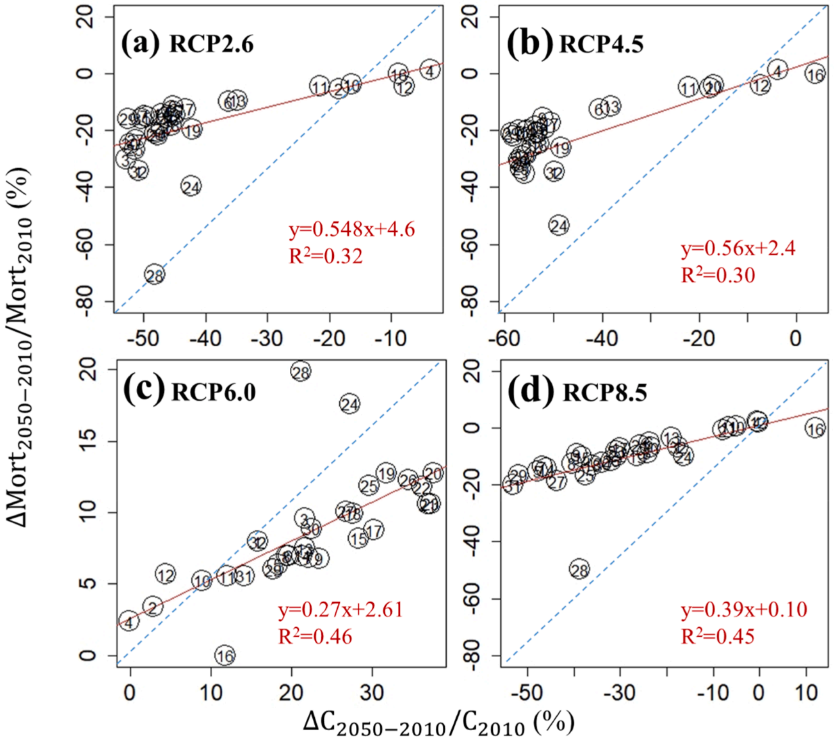

**Fig. 5.** Scatter plots of the ratio of the $PM_{2.5}$ concentration difference to the baseline concentration and $PM_{2.5}$ death rate difference to baseline ratio in 2050 compared to 2010 for the different provinces under RCP2.6 (a), RCP4.5 (b), RCP6.0 (c), and RCP8.5 (d). The provinces are numerically coded as 1- Heilongjiang, 2- Neimeng, 3- Jilin, 4- Xinjiang, 5- Beijing, 6- Shanxi, 7- Shandong, 8- Hebei, 9- Henan, 10- Gansu, 11- Ningxia, 12- Qinghai, 13- Shaanxi, 14- Jiangsu, 15- Anhui, 16- Tibet, 17- Hubei, 18- Zhejiang, 19- Sichuan, 20- Guizhou, 1- Chongqing, 22- Jiangxi, 23- Hunan, 24- Yunnan, 25- Fujian, 26- Guangxi, 27- Guangdong, 28- Hainan, 29- Tianjin, 30- Liaoning, and 31- Shanghai. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### *Economic impact in the four rcp scenarios*

Premature mortality caused a GDP loss, including medical expense (ME) loss and value of statistical life (VSL), which reflect the GDP loss for a family and society, respectively (Fig. 6). In 2010, $PM_{2.5}$ caused \$5.8–5.9 billion for ME and \$102.6–104.3 billion for VSL, which is 2.7–2.8% of the GDP in total (\$3874 billion). This loss continuously increased during the years of 2020–2030. After that, the ME and VSL under the RCP6.0 scenario maintain an uptrend, while the ME and VSL under the other three scenarios decrease with time. By the year 2050, the lowest ME and VSL that can be projected under the RCP4.5 scenario is 4.75\$ billion and \$172.11 billion, respectively. The economic losses

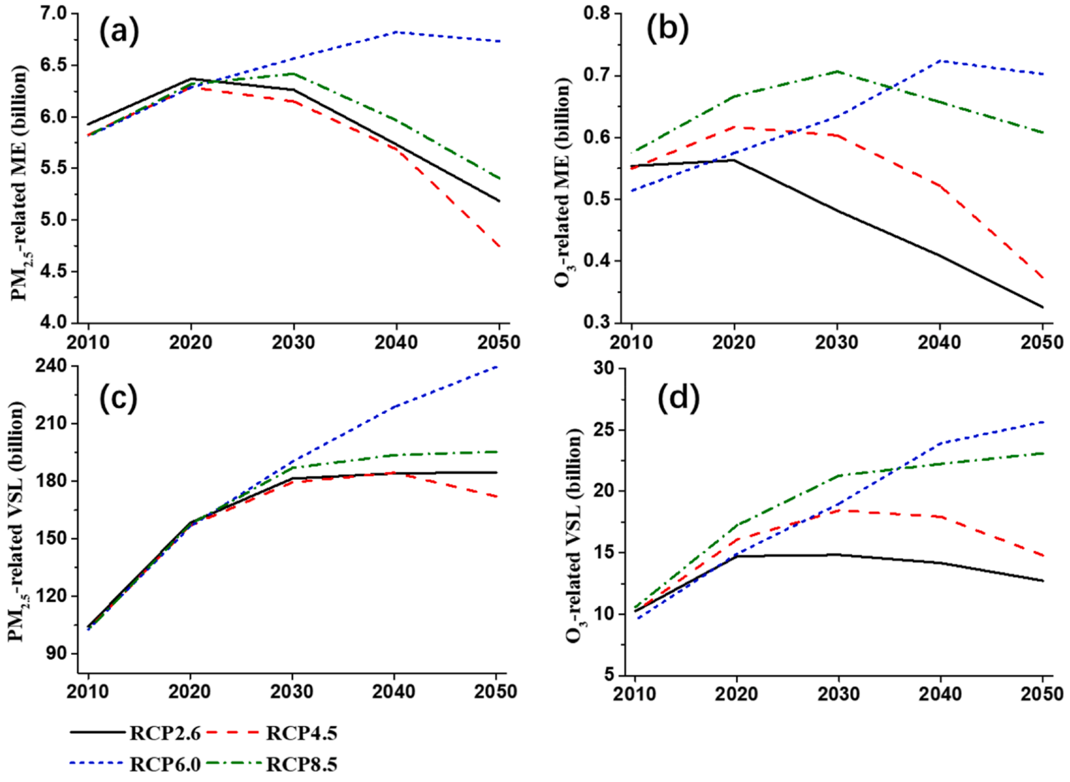

**Fig. 6.** The ME (a, b) and VSL (c, d) caused by $PM_{2.5}$ and $O_3$ from 2010 to 2050 under the four RCP scenarios.

caused by ozone are shown in Fig. 6(b) and Fig. 6(d). The ME and VSL under all the scenarios initially increase and reach a maximum at different times before they reduce with time. After 2040, the RCP2.6 scenario contributed to the lowest ME ($0.33 billion) and VSL (approximately $12.73 billion).

## Discussion

In this study, China's future $PM_{2.5}$ and $O_3$-related health burden (premature mortality and YLL) and economic impacts under four RCP scenarios are projected. By 2050, the lowest health burden and smallest economic impacts of $PM_{2.5}$-related and $O_3$-related illnesses occurred in the RCP4.5 scenario, whereas the worst impacts occurred in the RCP6.0 scenario. The change in population size cause an excess mortality rate in 2050 to increase by 3.9%–4.9%, partially offsetting the benefits of reducing the $PM_{2.5}$ concentration under emission reduction scenarios.

Few studies had evaluated future changes in $PM_{2.5}$-related mortality under different climate and emission change scenarios in China. A recent study (Chen et al., 2018) reported that by 2050, $O_3$-related short-term deaths increased under RCP8.5, but decreased under RCP4.5, which was consistent with these findings. The health impact of ozone was far less than that of $PM_{2.5}$ pollution. For example, in the RCP4.5 scenario, the death toll caused by $O_3$ (0.36 million) was 22.1% of that caused by $PM_{2.5}$ was 1.63 million, and $O_3$-related ME (0.37 billion) was 7.8% of the $PM_{2.5}$-related ME (4.75 billion) in 2050 (Fig. 6(a and b)). However, the per capita expenditure caused by ozone pollution was $102.5, which was 35.2% of the per capita expenditure caused by $PM_{2.5}$ ($291.0). This was because bronchodilators used for ozone-related respiratory diseases (primarily COPD) treatment are expensive compared to other diseases related to $PM_{2.5}$ (Kazemiparkouhi et al., 2020; Lim et al., 2019; Turner et al., 2016). Moreover, unlike the large reductions in $PM_{2.5}$ over the recent years due to clean air actions (Q. Zhang, Q. et al., 2019), ozone pollution has been increasing in China (Liu and Wang, 2020). Therefore, the pollution of $O_3$ should be seriously considered. Similarly, a previous study (Xie et al., 2019) found that the per capita expenditure (87 yuan) related to $O_3$ was higher than that of $PM_{2.5}$ (40 yuan).

The number of premature deaths in the RCP4.5 scenario by 2050 was the lowest. The RCP4.5 scenario follows the path of achieving the radiation forcing target at the lowest cost. To achieve the expected radiation forcing (4.5 $W/m^2$) in the future, greenhouse gas emissions need to be limited by changing the energy system, utilizing multi-energy and low-emission energy technologies, and developing carbon capture and geological storage technologies . The Lancet Commission (Watts et al., 2015) pointed out that emissions of greenhouse gas and pollutants and changes in demographic characteristics will threaten climate change and cause more serious harm to human health. Implementing measures to mitigate air pollutants, such as $PM_{2.5,}$ can avoid more premature deaths and the loss of related benefits.

The study of the relationship between future deaths and $PM_{2.5}$ show that varied measures should be pursued depending on the areas. In some provinces, such as Ningxia, Gansu, Heilongjiang, Qinghai, and Xinjiang, air pollution control technology might not help reduce the impact of pollutants, but induce a large economic burden, leading to a negative economic impact. Premature deaths can be reduced more efficiently by reducing pollutant concentrations in Jiangsu, Shandong, and Sichuan due to the high population-weighted exposure (Hu et al., 2017).

In the scenarios of RCP2.6, RCP4.5, and RCP8.5, the decrease in the concentration of $PM_{2.5}$ resulted in a decrease in the number of deaths. However, the effects of the population size practically offset the benefits of the reduced $PM_{2.5}$ concentration. It has been suggested that elderly are more susceptible to air pollutants than young adults, and thus this results in a higher risk of pollution-related death . According to the 2019 China Health Statistics Yearbook, the cause-specific deaths, including COPD, IHD, stroke, and LC in adults above 60 years old, were 98%, 92%, 97%, and 86% higher than those of young adults (Ministry of Health of the People's Republic of China, 2014). Due to rapid population aging, future research should quantify the health burden of air pollution by jointly accounting for the effects of population aging (Chen et al., 2020). Moreover, given the augmented health burden by changes in the total population and age structure, increased emission reductions will be expected in the future. A limitation of this study was that an unchanged baseline mortality rate was assumed because a high-resolution or sub-national baseline mortality rate projection was not available. Thus it was difficult to predict the future improvements in living conditions and health services at a high spatial resolution.

Some studies have suggested that the adverse health consequences of $PM_{2.5}$ and $O_3$ pollution have placed a huge burden on economic development (World Bank, 2016; Chen et al., 2017; Li et al., 2017; Nansai et al., 2020). Li et al. (2017) found that the economic loss caused by smoke particulate matter (SPM) in 2012 was $8882.4 million US (95% CI: 3574.4, 13,034.2) and 0.1% of the total GDP in China. The World Bank estimated $35 billion in income losses in China due to premature deaths by $PM_{2.5}$ in 2010 (World Bank, 2016), and $7.6 billion in economic losses caused by $O_3$ in 2016 (Maji et al., 2019). This was consistent with the finding of this study at the baseline year. However, few studies have investigated dynamic changes in the impact of $PM_{2.5}$ and $O_3$ on the economic burden. Thus, these results may not be directly comparable with other studies. The results of this study may be relatively high due to the use of the WTP method.

It is observed that even under RCP8.5, $PM_{2.5}$ show a decreasing trend by 2050, whereas $PM_{2.5}$ under RCP6.0 showed an increasing trend. This is due to the increases in $SO_2$, NOx, BC, and OC emissions under the RCP scenario by 2050, as shown in Fig. S4. It should be noted that although the $PM_{2.5}$ concentration in the RCP6.0 scenario did not ease from 2010 to 2050, its concentration began to decline sharply after 2050. This is consistent with the time evolution of the regional anthropogenic and biomass combustion emissions from 1850 to 2100 used in the Coupled Model Intercomparison Project Phase 5 (CMIP5), which is shown in Fig. 8.SM.1 in the supplementary material of Chapter 8 of the IPCC (2013).

It is worth to note that air quality changes in the future also have significant environmental costs. Studies indicate that some environmental costs related to dealing with pollution could outweigh the health costs in some regions, especially those adjacent to industrial areas or sensitive ecosystems (Landrigan, 2018). Future studies could consider to utilize our method to estimate the air quality changes in different climate scenarios and assess the environmental costs in different countries and regions.

## Conclusions

In summary, it is found that the future death burden due to long-term exposure to $PM_{2.5}$ and $O_3$ pollution in China will decrease by 2050 under RCP2.6, RCP4.5, and RCP8.5. The increase in the number of deaths caused by the change in population size will offset some of the benefits brought about by the reduction in air pollution from 2010 to 2050. The estimates calculated in this study suggest an increasing economic burden due to $PM_{2.5}$ and $O_3$ exposure in 2010, and a 60.91% cost can be avoided in the RCP4.5 scenario. According to the difference in the future trend and the magnitude of the death toll under the RCP scenarios, it is necessary to adopt more active air pollution emission mitigation measures to ensure that more premature deaths and the associated economic impacts are effectively avoided.

## Author contributions

J.H., Y.W., and M.W. who designed the research and developed the methodology; Y.W. conducted the data analysis and led the writing; J.H. provided supervision and acquired the funding; J.Z. and H.L. assisted in the data collection; and J.L., M.Q., K.C. contributed through significant comments and editing of the manuscript.

## 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.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105731.

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