Health Burden and Economic Impacts Attributed to PM_{2.5} and O₃ in China from 2010 to 2050 under Different Representative Concentration Pathway Scenarios

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Research

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Abstract:

Background: Quantifying future health burden attributed to fine particulate matters (PM_{2.5}) and ozone (O₃) in China is challenging when jointly accounting for emissions, climate and population changes. Future health burdens caused by PM_{2.5} and O₃ in China remain largely understudied.

Methods: In this paper, we used the Goddard Earth Observing System chemical transport model (GEOS-Chem) to project PM_{2.5} and O₃ concentrations from 2010 to 2050 under four Representative Concentration Pathway scenarios (RCPs), then projected the PM_{2.5} and O₃-related premature mortality and years of life lost (YLL) in this period. We then estimated 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 O₃.

Results: Compared to the targeted year 2050, we found that PM_{2.5} concentrations changed between -31.5% to 14.5% since 2010, resulted in -13.5% to 9.4% change in PM_{2.5}-related mortality and -25.7% to 0.6% change in YLL across all the RCPs scenarios. For O₃, the concentrations varied -13.3% to 3.7% by 2050, contributing to -26.9% to 13.1% change in O₃-related mortality and -48.8% to 4.0% change in YLL. The lowest health impacts occurred in the RCP4.5 scenario by 2050 for both pollutants. In 2010, the ME caused by PM_{2.5} and O₃ was \$6.3-6.5 billion, and the VSL was \$112.1-114.9 billion, accounting for 2.9-3.0% of the total GDP (\$3874 billion). By 2050, ME and VSL will change from -19.7% to 17.5% and from -65.5% to 136.6%, respectively.

Conclusion: This study suggested that future PM_{2.5} and O₃ under certain RCP scenarios can have large health and economic benefits. However, given that the future population will always be higher than the baseline in 2010, more aggressive air pollution mitigation measures are needed for China.

Keywords: PM_{2.5}; O₃; premature mortality; China; Representative Concentration Pathway scenarios

1. Background

A large number of epidemiological studies had shown that fine particulate matters (PM_{2.5}) and ozone (O₃) contributed to premature mortality from chronic or acute diseases, including respiratory and cardiovascular diseases [1-6]. The Global Burden of Diseases Study found that the PM_{2.5} and O₃ caused 4.2 million and 0.25 million premature deaths globally in 2015, respectively [7], with 39% [8] of PM_{2.5} and 32% [9] of O₃ attributed to China alone. Nearly 86% of the population in China was exposed to PM_{2.5} with a daily concentration higher than 75 µg/m³ of the Grade II Chinese Ambient Air Quality Standards (CAAQS) in 2015 [7]. A recent report demonstrated that O₃ concentrations in all major Chinese metropolitan regions are more than 10% higher than the CAAQS level (160 µg/m³) [10]. The adverse health impacts of PM_{2.5} and O₃ pollution had placed a huge burden on economic development in China [11, 12].

Projecting future pollution changes and their impacts on health is challenging because of uncertainties in the changes of 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) [13] projected the potential health benefits by 2020 according to the concentration of PM_{2.5} in policy scenarios (WHO IT-1: 35 µg/m³, IT-2: 25 µg/m³, IT-3: 15 µg/m³ and AQG: 10 µg/m³ et al.). Wang et al (2019) [14] 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, we used the Goddard Earth Observing System chemical transport model (GEOS-Chem) to projected changes in PM_{2.5} and O₃ concentrations in China under four Representative Concentration Pathway (RCP) from 2010 to 2050 and evaluated the impacts of air quality changes under different RCP scenarios on future premature death burden. RCP scenarios generated a series of future scenarios representing different levels of emission changes. This study primarily focused on health and economic consequences from air pollution emission changes, as a few studies had revealed that the 21st-century air quality forecast range was mainly driven by changes of emissions rather than climate [15, 16].

2. Methods

2.1 PM_{2.5} and O₃ data

Annual average concentrations of PM_{2.5} and O₃ were projected 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 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 $0.5^{\circ} \times 0.667^{\circ}$ (50 × 66.7 km) and 47 vertical layers up to 0.01 hPa. PM_{2.5} was estimated as the total mass of each component of PM_{2.5} from the GEOS-Chem model. Specific

116 details were showed in Li et al (2016) [17]. O₃ concentrations were estimated by
117 emissions of O₃ precursors, aerosol precursors, and aerosols, and the specific details
118 were showed in Zhu et al (2016) [18]. GEOS-Chem model had successfully reproduced
119 the spatial-temporal distribution of O₃ [19] and PM_{2.5} [20] concentrations in China. Li
120 et al (2016) [17] compared PM_{2.5} model predictions with the observational data in five
121 cities in 2010 under four RCP scenarios, and found high agreement between the
122 predictions and observations, i.e. correlation coefficients were 0.50-0.70, and the
123 normalized mean deviations (NMB) were -31%-39%. Similarly, Zhu et al (2016) [18]
124 compared measured and simulated O₃ concentration at ten stations in 2000 under the
125 RCP4.5 scenario. The observed correlation coefficient was 0.76 and the normalized
126 mean deviation (NMB) was +11.6%.

127 Four RCPs warming scenarios (i.e. RCP2.6, RCP4.5, RCP6.0 and RCP8.5) were
128 used to project the PM_{2.5} and O₃ concentrations since the year of 2010 for every decade
129 through 2050. The RCPs is the basis for future climate change projection proposed by
130 the IPCC's fourth assessment report, each of which represents a representative scenario
131 of radiation forcing stabilization at 2.6 W/m², 4.5 W/m², 6.0 W/m² or 8.5 W/m² by 2100,
132 respectively. Among the scenarios, RCP8.5 was considered as a global high greenhouse
133 gas emission scenario without mitigation measures, followed by RCP6.0, RCP4.5, and
134 RCP2.6 [21]. Therefore, it is expected that the consequent global temperature may rise
135 by 4.1 ° C, 2.2 ° C, 1.7 ° C and 0.9 ° C until 2050 by different RCPs, as compared to
136 that in 2000 [5].

137 **2.2 Population data**

Population data with every 5-year intervals between 0 and 100 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>).

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

2.3 Health impact assessment of PM_{2.5} and O₃ exposures

Premature mortality associated with PM_{2.5} and O₃ for different disease categories were estimated for each decade starting from 2010 to 2050 according the equation 1. Premature mortality attributed to PM_{2.5} concentrations was estimated first 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) [22], then summed up to represent the total deaths in each decade. For O₃ concentration, the cardiovascular (CVD, I00-I99) and respiratory (Res, J00-J99) mortality data were used to estimate the premature mortality by O₃, because there is currently no convinced evidence that O₃ is causally or likely to be causally associated with death from other diseases [23]

$$\Delta \text{Mort} = \sum_{i=1}^n pop_i * y_0 [(RR_{i,j} - 1)/RR_{i,j}] \dots \dots \dots (1)$$

Where ΔMort is premature mortality caused by PM_{2.5} or O₃, pop_i is the

population for grid i , $RR_{i,j}$ is relative risk for a disease j at a grid i caused by $PM_{2.5}$ or O_3 , and $(RR-1)/RR$ is the attributable fraction, y_0 is the baseline mortality of particular disease categories, obtained from China Health Statistics Yearbook [24].

The RRs of $PM_{2.5}$ exposure for different disease categories were estimated using an integrated exposure-response (IER) by Burnett et al [25, 26].

$$RR_{i,j} = 1 \quad C \leq C_0$$

$$RR_{i,j} = 1 + \alpha_j \{1 - \exp(-\gamma_j(C - C_0)^{\delta_j})\} \quad C > C_0 \quad (2)$$

Where α_j , γ_j , and δ_j are obtained through the average of 1000 sets of fitting parameters by Burnett et al (2014) [26]. C is the projected $PM_{2.5}$ concentrations under different RCPs scenarios, C_0 is the theoretical minimum-risk concentrations of 5.8 $\mu g/m^3$ as used in GDB 2010 [27].

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) [28]

$$RR_{i,j} = \exp(\beta \times (X - X_0)) \dots \dots \dots (3)$$

Where, β is a coefficient estimated based on the associations of ozone concentration with CVD and respiratory mortality from the estimates of the multi-pollutant model, which simultaneously adjusted for $PM_{2.5}$ and NO_2 [29]. X is the concentration of O_3 , X_0 is a theoretical of 26.7 ppb based on the minimum ozone exposure from the study of Turner et al (2016) [29].

The corresponding YLL was calculated as follows:

$$\Delta YLL = \sum \Delta Mort_t \times LE_t \dots \dots \dots (4)$$

Where ΔYLL is YLL caused by $PM_{2.5}$ or O_3 at a specific age t group, LE_t is the

life expectancy at a specific age t group from 2010 to 2050 the was shown in table S1 (<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, we mutually controlled one factor constant to project the impact of the other determinant on future change in mortality.

2.4 Economic impacts

We estimated economic impact from air pollution changes based on two factors: 1) the total medical expenditure (ME), which refers to any expenses incurred to prevent or treat injuries or diseases; 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 analysis in the United States and Europe to evaluate the benefits of savings [30]. The ME and VSL caused by premature death were calculated for each province in China.

$$ME_{p,s,y} = \sum_1^p \Delta Mort_{p,s,y} \times (GDP_{p,y} \times \beta_p + \delta_p) \dots\dots\dots (5)$$

Where, $ME_{p,s,y}$ is the medical expenses [billion dollar/year] for the province p, scenario s and year y. β_p and δ_p are the parameters of medical service price by Xie et al (2016) [31]. $GDP_{p,y}$ is the per capita GDP for the province p at year y (<https://www.pwc.com.tr/tr/publications/arastirmalar/assets/world-in-2050/2050-de-dunya-raporu.pdf>).

$$VSL_{p,s,y} = \sum_1^p WTP \times \Delta Mort_{p,s,y} \times \left(\frac{GDP_{p,y}}{GDP_{2010,China}} \right)^{0.5} \dots\dots(6)$$

Where, $VSL_{p,s,y}$ is the value of statistical life. $GDP_{2010,China}$ is the national average per capita GDP in 2010. WTP is 250,000 dollars in 2010, which is a willingness to pay for avoiding premature mortality [32]. The assumption of future GDP is consistent with 2010.

3. Results

3.1 Future PM_{2.5} and O₃ Concentrations and Population Projection

Figure 1(a) and Figure 1(b) showed the change of annual average concentrations of PM_{2.5} and O₃ by decades between 2010-2050 under four different RCP scenarios. In Figure 1(a), an inverse U-shape pattern of PM_{2.5} variations were observed under the RCP2.6, 4.5 and 8.0 scenarios across the period with peak level shown in 2020 or 2030 and the lowest level occurred in 2050. For the RCP6.0 scenario, an elevated trend was noted throughout the years. This is consistent to the temporal variations of the major air pollutants' emissions which showed increase trends under the RCP6.0 (e.g. SO₂, NO_x, NH₃, OC and BC) starting the year of 2010-2030 as compared to the declining pattern of the emissions in the other scenarios (Figure S5). Among different scenarios, the RCP4.5 achieved the largest reduction in PM_{2.5} for about 10 µg/m³ as compared to the baseline PM_{2.5} levels. On the contrary, O₃ projections decreased consistently under the RCP2.6 and RCP4.5 scenarios, but increased under the RCP6.0 and RCP8.5. Overall, PM_{2.5} concentrations decreased by 6.3-11.1 µg/m³ under the RCP2.6, 4.5 and 8.5 scenarios until 2050 from baseline, and O₃ concentrations decreased by 3.7-6.1 ppb under RCP2.6 and RCP4.5 scenarios. The magnitude of reduction for PM_{2.5}

concentrations is comparable to a previous study in Eastern China suggesting about 1–8 $\mu\text{g}/\text{m}^3$ lower for $\text{PM}_{2.5}$ in 2050 than that in 2000 under the RCP2.6, 4.5 and 8.5 scenarios [16] and for O_3 concentration, a reduction by 7 to 6 ppb under RCP4.5 scenarios [33].

The projected spatial distributions of $\text{PM}_{2.5}$ and O_3 concentrations by decades were shown in figure S1 and figure S2. By 2050, the largest $\text{PM}_{2.5}$ reduction area ($>40 \mu\text{g}/\text{m}^3$) was mainly the regions used to be highly industrialized or urbanized, such as the Beijing-Tianjin-Hebei region and the Sichuan Basin (Figure S4 (a)). For O_3 , significant O_3 reduction was observed in the south-central areas of China around the Yangtze River Delta region (Figure S4 (b)).

The population size was estimated to reach a peak by 2030 for 1 464 million and then drop down to 1 402 million by 2050 (figure 1 (c)). The population was aging significantly from 2010 to 2050, with increased proportion of the elderly group over 75 years old by decades (figure 1 (d)), suggesting increased susceptibility to $\text{PM}_{2.5}$ and O_3 for the Chinese population in the future.

3.2 Estimated premature Mortality and YLL

Premature mortality for $\text{PM}_{2.5}$ and O_3 exposure generally followed the same pattern as for the concentration changes over the decades under the RCPs (figure 2(a) and figure 2(b)). The largest number of avoided deaths were observed under the RCP4.5 scenario for $\text{PM}_{2.5}$ and the RCP2.6 for O_3 , which resulted in 254 303 and 112 900 less deaths by 2050 as compared to the deaths at baseline. Although the reductions of $\text{PM}_{2.5}$ and O_3 were spatially different, the resulting largest changes in deaths were consistently

shown in the Beijing-Tianjin-Hebei region, the Yangtze River Delta and the Sichuan Basin. (figure S4(c-d)).

There were 1886 650-1933 886 deaths caused by PM_{2.5} in 2010, in which stroke deaths contributed the highest (50.4-50.5%), followed by deaths from IHD (34.6%-34.7%), LC (7.5-7.6%) and COPD (7.3%-7.4%) respectively. By 2050, PM_{2.5} caused a change of -254 333 to 181 652 deaths. Except for the RCP6.0 scenario, the relative contribution of IHD to the total deaths increased by 0.8%-1.7%, whereas the COPD decreased by 0.4%-0.8% (figure S3(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% figure S3(c)).

In 2010, there were 385 971 (201 197, 562 256) to 423,363 (221 046, 615 469) deaths related to O₃, and CVD accounts for 51.7-51.9% and respiratory accounts for 48.0-48.3%. By 2050, O₃ changed -112 900 to 55 670 deaths. The changes in the contributions of the two diseases fluctuate slightly (0.4-0.6%) (figure S3(b)). Under the RCP2.6 and RCP4.5 scenarios, the mortality associate with each disease was reduced. In the RCP6.0 and RCP8.5 scenarios, the results were opposite (figure S3(d)). Figure 2(c) and Figure 2(d) showed the year of loss (YLL), which reflected the number of years lost due to death before life expectancy, caused by PM_{2.5} and O₃. 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 increased slightly, then decreased for the next 30 years. By 2050, the YLL caused by PM_{2.5} had decreased by 25.7% since baseline under the best scenario (i.e. RCP4.5). The trend of YLL caused by O₃ was consistent with that of premature

death from 2010 to 2050, suggesting about 6.7 million reduced by 2050 under the best scenario (i.e. RCP2.6).

3.3 Impact of changes in emission and population size on premature mortality

Figure 3 showed the independent impacts of two factors (emission and population size) on PM_{2.5}- and O₃-related mortality from 2010 to 2050 under four RCP scenarios. The change in PM_{2.5} concentration while holding the population growth caused a 7.8%-17.3% reduction in mortality across all scenarios except the RCP6.0. The population change while maintaining the baseline PM_{2.5} distribution resulted in 3.8%-4.9% increase in excess mortality by 2050 relative to 2010. For O₃, the impact of concentration reduction *per se* contributed to 30.2% avoided O₃-related mortality under the RCP2.6 scenario followed by the 18.0% under the RCP4.5 scenario. In comparison, increase in population size led to a small increase in O₃-related mortality under all scenarios.

3.4 Provincial mortality changes driven by air pollution changes

Figure 4 showed the relationships between percent decline in pollutant-related premature deaths that jointly accounted for the impacts of the concentration changes and population growth, and the changes in air pollution by provinces between 2010 and 2050 under the future scenarios. In general, the scatter plots followed the 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 scenarios. However, there were 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 rate may play an important role in these provinces. Under the RCP4.5 scenario, the number of deaths in Hainan was 0. This result was due to the sparse population and low pollutant concentration. In provinces, such as Xinjiang, Gansu, Qinghai, Neimeng, where the concentration reduction rate is less than 20%, it was difficult to further reduce the concentration due to the low initial concentration.

3.5 Economic impact in four RCP scenarios

Premature mortality caused a GDP loss, including Medical expense (ME) loss and value of statistical life (VSL), which reflected the GDP loss for a family and society, respectively (figure 5). In 2010, PM_{2.5} caused \$5.8-5.9 billion for ME and \$102.6-104.3 billion for VSL, which was 2.7-2.8% of GDP in total (\$3874 billion). This loss continuously increased to the year of 2020-2030. After that, ME and VSL under the RCP6.0 scenario keep this uptrend while ME and VSL under the other three scenarios decrease with time. By the year of 2050, the lowest ME and VSL that can be projected under the RCP4.5 scenario were 4.75\$ billion and \$172.11 billion, respectively. Economic loss caused by ozone was shown in figure 5(b) and figure 5(d). ME and VSL under all scenarios initially increased and reached maximum at different time before they reduce with time. After 2040, RCP2.6 scenario contributed to the lowest ME (\$0.33 billion) and VSL (around \$12.73 billion).

4. Discussion

In this study, we projected China's future PM_{2.5} and O₃-related health burden (premature mortality and YLL) and economic impacts under four RCP scenarios. By 2050, the lowest health burden and smallest economic impacts of PM_{2.5}-related and O₃-related occurred in the RCP4.5 scenario, whereas the worst impacts occurred in the RCP6.0 scenario. The change in population size caused the excess mortality rate in 2050 to increase by 3.9%-4.9%, partially offsetting the benefits of reducing 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 [33] reported that by 2050, O₃-related short-term deaths increased under RCP8.5, but decreased under RCP4.5, which was consistent with our findings. The health impact of ozone was far less than PM_{2.5} pollution. For example, in the RCP4.5 scenario, the death toll caused by O₃ (360 958) was 22.1% of that caused by PM_{2.5} (1 632 196), and O₃ related ME (0.37 billion) was 7.8% of PM_{2.5} related ME (4.75 billion) in 2050 (figure 5(a-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 (mainly COPD) treatment are expensive compared to other diseases related to PM_{2.5} [29, 34, 35]. Moreover, unlike the large reductions in PM_{2.5} over the recent years due to clean air actions [36], ozone pollution has been increasing in China [37]. Therefore, the pollution of O₃ should be taken seriously. Similarly, a previous study [32] found that per capita expenditure (87 yuan) related to O₃ 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. 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 [38]. The Lancet Commission [39] pointed out that emissions of greenhouse gas and pollutants and changes in demographic characteristics will threaten climate change to human health more and more serious. Implementing measures to mitigate air pollutants such as $\text{PM}_{2.5}$ can avoid more premature deaths and loss of related benefits.

The study of the relationship between future deaths and $\text{PM}_{2.5}$ showed that the varied measures should be taken 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 induced 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 [6].

In the scenarios of RCP2.6, RCP4.5 and RCP8.5, the decrease in the concentration of $\text{PM}_{2.5}$ result in a decrease in the number of deaths. However, the effects of a population size partially offset the benefits of reduced $\text{PM}_{2.5}$ concentration. It was suggested that elderly were more susceptible to air pollutants than young adults, and thus resulted in higher risk of pollution related death [40]. 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 the young adults [41]. As of the rapid population aging [42], future research should quantify the health burden of air pollution by jointly accounting for the effects of population aging [43]. Moreover, given the augmented health burden by changes in the total population and age structure, more emission reduction will be expected in the future. A limitation of our study was that we assumed an unchanged baseline mortality rate because high-resolution or subnational baseline mortality rate projection is not available. Thus it was difficult to predict the future improvement for living conditions and health services at a high spatial resolution.

Some studies have suggested that the adverse health consequences of PM_{2.5} and O₃ pollution have placed a huge burden on economic development [12, 44-46]. Li et al (2017) [46] found that the economic loss caused by smoke particulate matter (SPM) in 2012 was US\$8882.4 million (95% CI: 3574.4, 13034.2) and 0.1% of the total GDP in China. The World Bank estimated \$35 billion income losses in China due to premature death by PM_{2.5} in 2010 [44] and \$7.6 billion economic loss caused by O₃ in 2016 [11]. This is consistent with our finding at baseline year. However, few studies investigated dynamic changes of the impact of PM_{2.5} and O₃ on the economic burden. Thus, our results may not be directly comparable with other studies. Our study results may be relatively high due to the use of the WTP method.

We observed that even under RCP8.5, PM_{2.5} showed a decreasing trend by 2050, whereas PM_{2.5} under RCP6.0 showed an increasing trend. This was due to the increased

in SO₂, NO_x, BC and OC emissions under the RCP scenario by 2050, as shown in figure S5. 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 1850-2100 used in Coupled Model Intercomparison Project Phase 5 (CMIP5), which showed in Figure 8.SM.1 in Supplementary Material of Chapter 8 of IPCC (2013) [47].

5. Conclusions

Overall, we found that the future death burden due to long-term exposure to PM_{2.5} and O₃ 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 offset some of the benefits brought by the reduction in air pollution from 2010 to 2050. Our estimates suggested increasing economic burden due to PM_{2.5} and O₃ exposure in 2010 and a 60.91% cost can be avoided in the RCP4.5. 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 were effectively avoided.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

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

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Not applicable

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Figures

Figure 1. The concentration of PM_{2.5} (a) and O₃ (b) change from 2010 to 2050 under RCP scenarios. Projected changes in exposed population size (c) of all ages in China from 2010 to 2050. Demography transition change (d) from 2010 to 2050.

Figure 2. The mortality (a-b) and YLL(c-d) caused by PM_{2.5} and O₃ from 2010 to 2050 under four RCP scenarios.

Figure 3. The impact of concentration and population size changes on PM_{2.5}-related and O₃-related premature death reduction from 2010 to 2050 under four RCP scenarios.

Figure 4. Scatter plots of the ratio of PM_{2.5} concentration difference to baseline concentration and PM_{2.5} death rate difference to baseline ratio in 2050 compared to 2010 for 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, 21- Chongqing, 22- Jiangxi, 23- Hunan, 24- Yunnan, 25- Fujian, 26- Guangxi, 27- Guangdong, 28- Hainan, 29- Tianjin, 30- Liaoning, 31- Shanghai.

Figure 5. The ME (a-b) and VSL (c-d) caused by PM_{2.5} and O₃ from 2010 to 2050 under four RCP scenarios.

Figures

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Figure 5

The ME (a-b) and VSL (c-d) caused by PM_{2.5} and O₃ from 2010 to 2050 under four RCP scenarios.

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