Atmospheric Environment 322 (2024) 120363

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Historical and future health burden attributable to $PM_{2.5}$ exposure in China

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HIGHLIGHTS

- Changes in $PM_{2.5}$-mortality in history and future and the respective leading factor are quantified.
- Improvement in $PM_{2.5}$ air quality drives the decrease in $PM_{2.5}$-mortality in China during 2013–2019.
- The aging population will dominate the increase in $PM_{2.5}$-mortality in China in future.

ARTICLE INFO

Keywords:
$PM_{2.5}$ exposure
Health burden
Contribution factor
Population aging

ABSTRACT

$PM_{2.5}$ is one of the major pollutants in China and poses threats to human health. To better estimate the health burden caused by long-term $PM_{2.5}$ exposure, we use $PM_{2.5}$ data from high-resolution TAP (Tracking Air Pollution in China) database and CMIP6 (Coupled Model Intercomparison Project Phase 6) models to quantify premature mortalities attributed to $PM_{2.5}$ pollution in China during the historical (2001–2019) and future (2030, 2045 and 2060) periods. Sensitivity experiments are also designed to explore the respective impacts of baseline mortality, population size, age structure, and $PM_{2.5}$ concentration on health burden. Results show that population-weighted $PM_{2.5}$ concentration in China over the last 19 years is 57.5 $\mu g\ m^{-3}$, significantly higher than the unweighted value of 33.4 $\mu g\ m^{-3}$. The national average premature mortalities attributable to long-term exposure to $PM_{2.5}$ during 2001–2019 are 2363 (95%CI: 1991–2712) thousand, with severe health damage over Central China (454 (95%CI: 384–519) thousand), North China Plain (442 (95%CI: 375–503) thousand), and Yangtze River Delta (406 (95%CI: 343–465) thousand). The significant increase in premature mortalities in China during 2001–2005 (+213 thousand yr^{-1}) is attributed to the growth in population size and the exacerbation of $PM_{2.5}$ pollution, while the decrease in premature mortalities during 2013–2019 (−59 thousand yr^{-1}) is primarily owing to the improvement in $PM_{2.5}$ air quality. Future improvements in medical care and decreases in $PM_{2.5}$ concentrations will help to alleviate the health burden in China. However, compared to 2019, national premature mortalities are projected to increase, especially during 2030–2060 with significant trends of +116~+181 thousand yr^{-1} under different scenarios. The severe aging population in the future is the primary factor contributing to the increased health risks. In conclusion, severe $PM_{2.5}$ pollution in China during the last 19 years has resulted in a large number of premature deaths, which will be further aggravated by population aging in the future. Therefore, it is imperative to implement more stringent air quality control measures to mitigate future health hazards associated with $PM_{2.5}$ pollution.

1. Introduction

The rapid development of economy, along with the advancement of industrialization and urbanization, has led to severe air pollution in China. In recent decades, $PM_{2.5}$ (fine particulate matter with an aerodynamic diameter of 2.5 μg or less) has been one of the most important air pollutants in China (Badaloni et al., 2017; Hu et al., 2017). Many studies have demonstrated that long-term exposure to high

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https://doi.org/10.1016/j.atmosenv.2024.120363
Received 30 August 2023; Received in revised form 27 November 2023; Accepted 18 January 2024
Available online 20 January 2024

concentrations of $PM_{2.5}$ can harm various human systems, including respiratory, cardiovascular, reproductive, blood and immune systems, which can ultimately result in diseases such as heart disease, stroke, lung cancer, and even premature death from chronic or acute diseases (Apte et al., 2015; Li et al., 2017; Lin et al., 2021; Lu et al., 2015); Global Burden of Disease (GBD) study recently revealed that 4.2 million premature mortalities were attributed to long-term exposure to $PM_{2.5}$ pollution globally in 2015 (Cohen et al., 2017). In order to mitigate the health hazards caused by $PM_{2.5}$ pollution, the Chinese government has implemented the "Action Plan on Prevention and Control of Air Pollution" in 2013 and the "Three-Year Action Plan for Winning the Blue Sky Defense Battle" in 2018 to improve air quality (Xue et al., 2017). These measures have significantly improved the air quality nationwide, with a general decrease of 2.7–9.3 μg m^{-3} yr^{-1} in $PM_{2.5}$ concentrations during 2013–2018 (Zhai et al., 2019), and a reduction of 7.8–33.9% from 2018 to 2020 (Li et al., 2022; Xu et al., 2023). However, the concentration of $PM_{2.5}$ is still high in China compared to other countries (L. Chen et al., 2023; Turnock et al., 2020). As stated in the Bulletin on the State of China's Ecological Environment in 2019 issued by the Ministry of Ecology and Environment, only 157 out of 337 cities in China met the air quality standards, accounting for just 46.6% of the total number of cities in 2019 (Feng et al., 2017). Additionally, some areas are also affected by haze pollution (Gao et al., 2017). It is evident that the issue of $PM_{2.5}$ pollution and its health impact in China requires more attention.

In order to accurately evaluate the health damage caused by $PM_{2.5}$ exposure, a comprehensive and high-quality $PM_{2.5}$ dataset is essential. At present, $PM_{2.5}$ concentrations can be mainly obtained through ground-based station observations, satellite remote sensing retrievals and numerical model simulations. The national-scale $PM_{2.5}$ concentration ground monitoring network in China was built in 2012 (Liu et al., 2017). Observed $PM_{2.5}$ concentrations downloaded from China National Environmental Monitoring Centre can be used to analyze nationwide health impact attributed to long-term $PM_{2.5}$ exposure. However, more than 90% of the monitoring sites are located in urban areas (W. Chen et al., 2023; Kong et al., 2021). Therefore, when analyzing the health burden of $PM_{2.5}$ exposure on the whole country, the dominance of urban-based observation concentrations may introduce bias into the final results (Dang and Liao, 2019). Satellite remote sensing can estimate the national-scale $PM_{2.5}$ concentration by retrieving aerosol optical thickness. Compared with station observations, the retrieval results are more spatially comprehensive but can be influenced by cloud and precipitation, resulting in data gaps (He and Huang, 2018; Jung et al., 2021). Numerical simulation, which encompasses simple statistical models and complex chemical transport models, enables the calculation of $PM_{2.5}$ concentration with high temporal and spatial resolutions (Jang et al., 2022). However, the accuracy of predictions from chemical transport models can be uncertain due to the inaccurate emission inventories and incomplete physical/chemical parameterizations (Carmichael et al., 2008; Jang et al., 2022). Tsinghua University along with other institutions has recently developed an algorithm that combines ground station observations, satellite remote sensing retrievals and numerical model simulations to estimate $PM_{2.5}$ concentrations in China. The released Tracking Air Pollution in China (TAP) dataset can provide near-real-time spatial-temporal continuous gridded daily average $PM_{2.5}$ concentration since 2000. TAP dataset provides comprehensive coverage of $PM_{2.5}$ pollution in terms of both space and time, allowing for high accuracy, long-term coverage, and complete representation (Geng et al., 2021a; Xiao et al., 2021a, 2021b). These advantages make the TAP dataset valuable for analyzing the health impacts of $PM_{2.5}$ exposure.

The health damage caused by $PM_{2.5}$ exposure is not only influenced by pollutant concentration but also by factors such as population size, age structure, and baseline mortality rate (BMR) (Zheng et al., 2019). However, most recent studies mainly focus on the final number of premature mortalities (Feng et al., 2017; Huo et al., 2022; Li et al., 2020; Liu et al., 2016; Xiao et al., 2022b; Xue et al., 2019; Zheng et al., 2021), little attention has been given to quantify the impacts of these factors on health burden. Additionally, these influencing factors have significantly changed over the past few decades (Geng et al., 2021b; Mathers and Loncar, 2006; Tu et al., 2022);. Quantitatively exploring the impact of these factors on premature mortalities will be beneficial for the development of more targeted air pollution prevention and control policies in China. With the improvement of China's economic and healthcare standards, the strengthening of government regulations, and the increasing focus of the public on health, the BMR of most diseases has shown a significant decline during recent years (Mathers and Loncar, 2006; Zhou et al., 2016). In the past few years, the population in China has continued to increase, but the growth rate has slowed in recent years. According to the data from the Chinese Seventh National Population Census (CSNPC) in 2020, the total population was 1.27 billion in 2000, which increased to 1.34 billion in 2010 (an increase of 5.5%), and further grew to 1.41 billion in 2020 (an increase of 5.2%) (Akimov et al., 2021). Meanwhile, the total number and proportion of elderly population showed a significant rising trend. In 2000, China's aging index was only 7%, indicating that China entered to an aging society (Wu et al., 2019). According to the data from CSNPC, the proportion of the elderly population aged 60 and above has increased from 13.32% in 2010 to 18.73% in 2020 (China's National Bureau of Statistics, 2020;2020). Many studies have pointed out that ignoring the evolution of age structure when exploring the health effects of pollutant exposure can cause a significant underestimation of premature deaths (Liu et al., 2023; Xie et al., 2016; Yang et al., 2021).

In order to better explore the effectiveness of air pollution control policies on the improvement of $PM_{2.5}$ air quality in China in recent decades, this study provides a detailed assessment of the spatiotemporal evolution characteristics of $PM_{2.5}$ concentrations from 2001 to 2019 at the national level and several key regions (i.e. Central China, North China Plain, Sichuan-Chongqing region, Yangtze River Delta, and Pearl River Delta), as well as the premature deaths caused by long-term exposure to $PM_{2.5}$ and the impacts of several influencing factors (i.e. $PM_{2.5}$ concentration, population size, age structure, and BMR) on health burden, with the aim to fully ensure public health and provide evidence for differentiated control of air pollution. Furthermore, simulation results from Coupled Model Intercomparison Project (CMIP6) are also used to estimate the future health impacts of $PM_{2.5}$ exposure under different scenarios (i.e. SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5), with the purpose to provide better recommendations for current policies and inform future air quality target policy development in China.

2. Data and method

2.1. $PM_{2.5}$ concentration

The national $PM_{2.5}$ concentration from 2001 to 2019 is sourced from TAP (http://tapdata.org.cn/). The dataset integrates site observation data, satellite remote sensing retrievals and model simulation results through machine learning methods. More details can be found in (Geng et al., 2021a; Xiao et al., 2021a, 2021b, 2022a). The temporal resolution is daily mean and the spatial resolution is $0.1^{\circ} \times 0.1^{\circ}$.

Future $PM_{2.5}$ concentrations in years of 2030, 2045 and 2060 are taken from CMIP6 (https://esgf-index1.ceda.ac.uk/search/cmip6-ceda/). In this study, we select four different SSP (Shared Socioeconomic Pathways) scenarios (i.e., SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) to explore the variation characteristics of $PM_{2.5}$ concentrations and premature deaths caused by particle exposure in China under different development pathways in future. SSP1 represents low challenges for mitigation (resource efficiency) and adaptation (rapid development), which is the sustainable development path. SSP2 describes a middle-of-the-road development in the mitigation and adaptation challenges space, which is the medium emission scenario. SSP3 characterizes high challenges for mitigation (regionalized energy/land policies) and adaptation (slow development), which is the regional competition path. SSP5 means high challenges for mitigation (resource/

fossil fuel intensive) and low for adapt (rapid development), which is the high emission scenario. The numbers of 2.6/4.5/7.0/8.5 are labelled after a possible range of radiative forcing values in the year 2100 with the unit of W m^{-2}. Simulation results of $PM_{2.5}$ concentrations of each scenario are taken from GFDL-ESM4, MIROC6, MIROC-ES2L and NorESM2-LM models, respectively. Detailed information about the four CMIP6 models and the four SSP scenarios are listed in Table S1 and Table S2, respectively.

2.2. Population and age structure

We use a combination of gridded population data from LandScan (https://landscan.ornl.gov/) and provincial population data from China Statistical Yearbook (CSY, http://www.stats.gov.cn/tjsj/ndsj/) to obtain gridded and age-specific (30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79 and over 80 years old) population data over China for years 2001–2019. We revise the grid population data including: (1) updating the LandScan dataset for each year by using the provincial population data from CSY; (2) according to the proportion of the population in each age group in each province from CSY, the population of each age group in each grid in the LandScan dataset is calculated.

The future population data of all age groups in China are derived from the population pyramid (https://www.populationpyramid.net/china/). The grid population ratio from the 2019 LandScan dataset (the proportion of the population in each age group in each grid relative to the total population of all age groups in the country) is used to determine the spatial distribution of population in 2030, 2045 and 2060 with the three age structures of 30~49, 50–69 and over 70 (these future age structures are consistent with the divisions in future BMR described in Section 2.3).

2.3. Baseline mortality rate

The yearly baseline mortality rate (BMR) of noncommunicable diseases (NCDs) and lower respiratory infections (LRIs) in China from 2001 to 2019 are collected from the Global Burden of Disease (GBD) (https://vizhub.healthdata.org/gbd-results/). According to the age structure described in Section 2.2, the age structures of BMR during 2001–2019 are also divided into the same segments (30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79 and over 80 years old).

The future BMRs of the two diseases in years of 2030, 2045 and 2060 are derived from the data published by World Health Organization (WHO) (https://colinmathers.com/2022/05/10/projections-of-global-deaths-from-2016-to-2060/). The age group of this data is only divided into three sections, namely 30–49 years old, 50–69 years old and over 70 years old. Therefore, when calculating the total number of premature deaths in future years, we only quantify the health hazards in these three age groups.

Due to the discrepancy in data sources between the two BMR datasets (historical BMRs are from GBD, while future BMRs are from WHO), we select the commonly used GBD data as a benchmark to modify the BMR provided by WHO with the major aim to get the more reasonable future BMR data. Specific steps are as follows: (1) GBD provides yearly BMRs of NCDs + LRIs from 2001 to 2019, while WHO only provides the dataset in years of 2016, 2030, 2045 and 2060. So we first download the BMRs of GBD and WHO in year 2016, and calculate the age-specific proportions of BMR between GBD and WHO (Table S3). (2) Then we apply the age-specific ratios to update the future age-specific BMRs provided by WHO in years 2030, 2045, and 2060 (assuming the ratio coefficients remain constant in future).

2.4. Health impact assessment model

Global Exposure Mortality Model (GEMM) developed by Burnett et al. (2018) is applied to calculate the health burden attributed to long-term $PM_{2.5}$ exposure. This model can address many limitations associated with the widely used Integrated Exposure-Response (IER) model and can provide better estimates for highly polluted areas such as China (Burnett et al., 2018; Dang et al., 2019; Chen et al., 2020). We select the diseases of NCD and LRI as health endpoints, and the specific expression of premature deaths can be calculated as follows:

$$Mort_{y,a,g} = BMR_{y,a} \times Pop_{y,a,g} \times \left(1 - \frac{1}{RR_{y,g}}\right) \tag{1}$$

where $Mort_{y,a,g}$ is the number of premature deaths from NCD and LRI caused by long-term exposure to $PM_{2.5}$ at the year y, the age group a and the grid point g. $BMR_{y,a}$ represents the total baseline mortality rate of NCD and LRI at the year y and the age group a; $Pop_{y,a,g}$ means the number of people at the year y, the age group a and the grid point g; $RR_{y,g}$ refers to relative risk, and the calculation formula is as follows:

$$RR_{y,g} = exp\left[\frac{\theta \times \ln\left(1 + \frac{C_{y,g} - C_0}{\alpha}\right)}{1 + exp\left(-\frac{C_{y,g} - C_0 - \mu}{v}\right)}\right] \tag{2}$$

where $C_{y,g}$ is the annual average $PM_{2.5}$ concentration at the year y and the grid point g; C_0 is the lowest concentration, which means that when the concentration is less than this value, $PM_{2.5}$ long-term exposure is not harmful to human health. We use the value of 2.4 μg m^{-3} according to Burnett et al. (2018); Parameters of θ、 α、 μ and v are also taken from Burnett et al. (2018) (Table S4). Sum of premature deaths at each age group (eleven age groups for the historical period and three age groups for the future period) are finally used as the total $PM_{2.5}$-related mortalities (i.e., $Mort_{y,g} = \sum_a Mort_{y,a,g}$) at the year y and the grid point g. We conduct 1000 Monte Carlo simulations that randomly sampled from normal distributions of these parameters (i.e., θ、 α、 μ and v) to estimate the 95% confidence interval (CI) of premature deaths, following Silva et al. (2016), Dang et al. (2019) and Hao et al. (2021).

2.5. Driving factor decomposition for historical and future $PM_{2.5}$-mortality

According to formula (1), the number of premature deaths caused by long-term exposure to $PM_{2.5}$ is affected by factors such as baseline mortality rate (BMR), population size (Pop), age structure (AgeStru) and exposure concentration (Conc). Therefore, we carry out sensitivity experiments to assess the individual contribution of each factor to $PM_{2.5}$-mortality variations during 2001–2019 (Table 1). The control experiment $Mort_{Ctl}$ represents a normal scenario in which all factors change over time from 2001 to 2019. The sensitivity test $Mort_{BMR}$ ($Mort_{Pop}$, $Mort_{AgeStru}$, $Mort_{Conc}$) represents the change in the number of premature deaths caused by the changes in BMR (Pop, AgeStru, Conc) alone over 2001–2019, while other factors were fixed in 2001. Similar experimental designs are also applied to future $PM_{2.5}$-mortality changes. For each SSP scenario, we carry out five experiments: one control experiment (all factors change with time), four sensitivity experiments (only one factor changes with time, while the other three factors are fixed in 2019).

3. Results

3.1. Spatiotemporal characteristics of $PM_{2.5}$ concentration

Fig. 1 shows the spatial and temporal distribution characteristics of $PM_{2.5}$ concentrations in China from 2001 to 2019. High $PM_{2.5}$ concentrations are mainly concentrated in densely populated areas of North China Plain, Central China and Yangtze River Delta. These areas are characterized by numerous urban clusters and robust economic

Table 1
Experimental design for examining individual contribution of each factor to $PM_{2.5}$-mortality variations during 2001–2019.

Experiment	Baseline mortality rate (BMR)	Population (Pop)	Age structure (AgeStru)	Concentration (Conc)	Purpose
$Mort_{Ctl}$	2001–2019	2001–2019	2001–2019	2001–2019	Mortality variation during 2001–2019
MortBMR	2001–2019	Fixed at 2001	Fixed at 2001	Fixed at 2001	Mortality variation owing to BMR variation alone
MortPop	Fixed at 2001	2001–2019	Fixed at 2001	Fixed at 2001	Mortality variation owing to Pop variation alone
MortAgeStru	Fixed at 2001	Fixed at 2001	2001–2019	Fixed at 2001	Mortality variation owing to AgeStru variation alone
MortConc	Fixed at 2001	Fixed at 2001	Fixed at 2001	2001–2019	Mortality variation owing to Conc variation alone

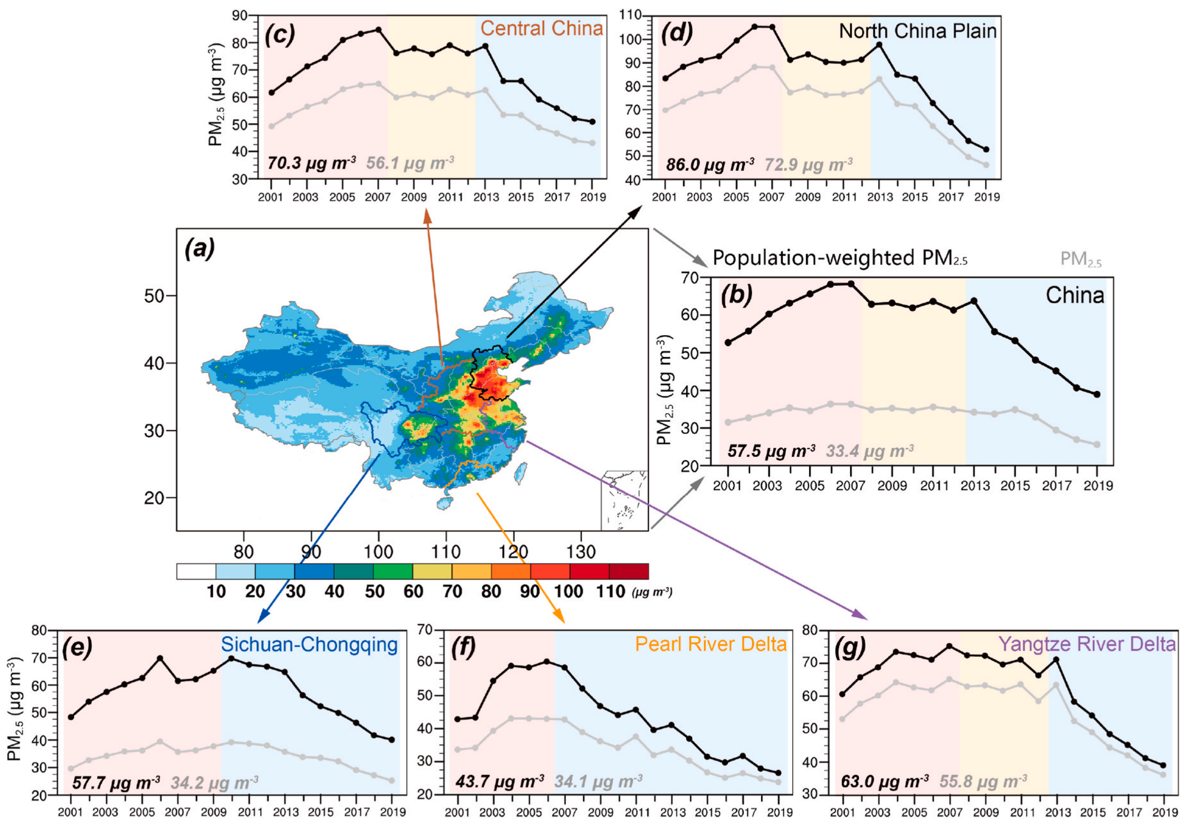

Fig. 1. Spatial-temporal distribution characteristics of $PM_{2.5}$ concentration in China during 2001–2019. (a) Spatial distribution of 19-year-mean $PM_{2.5}$ concentration. (b–g) Annual mean $PM_{2.5}$ concentration (gray dotted line) and population-weighted $PM_{2.5}$ concentration (black dotted line) averaged over China and the five key regions (Central China, North China Plain, Sichuan-Chongqing region, Pearl River Delta, and Yangtze River Delta) during 2001–2019. The light red (yellow, blue) background indicates a phase of continuous increase (fluctuating, decrease) in $PM_{2.5}$ concentration. Mean concentrations averaged over 2001–2019 are also shown at the bottom of each panel.

development, which contribute to significant primary anthropogenic emissions of $PM_{2.5}$, sulfur dioxide (SO_2), and nitrogen oxide (NO_x) (Huang et al., 2017), as shown in Fig. S1. According to the national average time series (Fig. 1(b)), $PM_{2.5}$ concentrations exhibit a continuous increasing trend from 2001 to 2007 with the rate of +0.8 μg m^{-3} yr^{-1}. In 2007, it reaches the peak of 36.3 μg m^{-3}, followed by a period of relatively stable fluctuations. Since the implementation of "Action Plan on Prevention and Control of Air Pollution" in 2013, there has been a significant decrease in anthropogenic emissions (Fig. S2), resulting in the improved $PM_{2.5}$ air quality, with an annual mean concentration decrease of 5.1% from 2013 to 2019. In 2019, the concentration drops to 25.6 μg m^{-3}, which is lower than the second-grade air quality standard (35 μg m^{-3}). Over the past 19 years, the average $PM_{2.5}$ concentration in China is 33.4 μg m^{-3}.

According to the analysis of $PM_{2.5}$ concentrations in the five key regions of China, it can be found that the heavily polluted regions of Central China (Fig. 1(c)), North China Plain (Fig. 1(d)) and Yangtze River Delta (Fig. 1(g)) exhibit similar multi-year variation characteristics to the national level (Fig. 1(b)). Specifically, from 2001 to 2007, the $PM_{2.5}$ concentration continues to increase, followed by a period of stable fluctuation from 2008 to 2012. During 2013–2019, there is a significant decrease in $PM_{2.5}$. Although the concentration has shown a downward trend since 2013, the $PM_{2.5}$ concentration over Central China (43.1 μg m^{-3}), North China Plain (46.2 μg m^{-3}) and Yangtze River Delta (36.2 μg m^{-3}) all exceed 35 μg m^{-3} in 2019. This indicates that the task of future air pollution control remains challenging. In the less polluted areas of Sichuan-Chongqing (Fig. 1(e)) and Pearl River Delta (Fig. 1(f)), the concentrations of $PM_{2.5}$ mainly exhibit an initial increase (2001–2009 for Sichuan-Chongqing, 2001–2006 for Pearl River Delta) followed by a decrease (2010–2019 for Sichuan-Chongqing, 2007–2019 for Pearl River Delta). Over the past 19 years, the average $PM_{2.5}$ concentrations in each region are 56.1 (Central China), 72.9 (North China Plain), 34.2 (Sichuan-Chongqing), 34.1 (Pearl River Delta) and 55.8 (Yangtze River Delta) μg m^{-3}, respectively.

Compared to ordinary average $PM_{2.5}$ concentration, the population-weighted $PM_{2.5}$ concentration is more capable of reflecting the impacts of $PM_{2.5}$ pollution on the exposed population (Fang et al., 2022; Nyhan et al., 2016). This means that the same level of $PM_{2.5}$ pollution poses a much greater public health risk in densely populated areas compared to sparsely populated regions. According to Fig. 1(b), the average population-weighted $PM_{2.5}$ concentration in China from 2001 to 2019 is 57.5 μg m^{-3}, which is much higher than the unweighted concentration of 33.4 μg m^{-3}. This further demonstrates that heavy pollution mainly occurs in densely populated areas. Similarly, the population-weighted $PM_{2.5}$ concentrations in Central China (Fig. 1(c)), North China Plain (Fig. 1(d)), Sichuan-Chongqing region (Fig. 1(e)), Pearl River Delta (Fig. 1(f)), and Yangtze River Delta (Fig. 1(g)) are also higher than the unweighted $PM_{2.5}$ concentrations. Over the past 19 years, the population-weighted $PM_{2.5}$ concentrations in Central China, North China Plain, Sichuan-Chongqing region, Pearl River Delta and Yangtze River Delta are 70.3, 86.0, 57.7, 43.7 and 63.0 μg m^{-3}, respectively.

Fig. 2 shows the changes of predicted $PM_{2.5}$ concentrations in years of 2030, 2045 and 2060 relative to 2019 under different scenarios in China. Compared to the values in 2019, the concentrations of $PM_{2.5}$ are projected to decrease in the scenarios of SSP1-2.6 (Fig. 2(a)), SSP2-4.5 (Fig. 2(b)) and SSP5-8.5 (Fig. 2(d)) in 2030, 2045 and 2060. As a sustainable development route, SSP2-1.6 shows the most significant improvement in $PM_{2.5}$ concentration. In 2060, there is a reduction of 34.7 % (−5.4 μg m^{-3}) in $PM_{2.5}$ concentration. However, in the scenario of SSP3-7.0 (Fig. 2(c)), which represents a lack of climate policies, the projected future $PM_{2.5}$ pollution will become more severe. The average $PM_{2.5}$ concentration in 2030, 2045 and 2060 will increase by 5.4% (+0.9 μg m^{-3}), 11.7% (+2.0 μg m^{-3}) and 6.1% (+1.0 μg m^{-3}), respectively.

3.2. Variation characteristics of population and age structure

From 2001 to 2019, the population over 30 years old in China shows an increasing trend (Fig. 3(a)). It increased from 660 million in 2001 to 910 million in 2019 with a growth of 39.2%. The proportion of elderly people (those aged 65 and above) increased from 13.7 % in 2001 to 19.3 % in 2019, highlighting the severe aging situation in China.

Fig. 3(b) presents the changes in future population and age structures in China. Compared with the total population over the age of 30 in 2019, there will be an increase of 70 million people (+8.0%), 90 million people (+9.8%) and 40 million people (+4.0%) in 2030, 2045 and 2060, respectively. Although the growth rate of the population aged 30 and above will slow down in 2060, the proportion of elderly people aged 70 and above will continue to increase. It will rise from 11.6% in 2019 to 16.1% in 2030, 27.1% in 2045, and 32.8% in 2060.

3.3. Variation characteristics of BMR

From 2001 to 2019, there has been a downward trend in BMR (total mortality rates of NCD and LRI) for each age group above 30 years old in China (Fig. 4(a)). The older the age group, the higher the mortality rates, but the greater the decline in BMR over time. From Fig. 4(a) we can quantify that the BMR for the population aged 30–44 (45–64) is less than 2.5 (14) individuals per thousand. However, the BMR for the population aged 80 and above can reach 146.7 individuals per thousand in 2001, but by 2019, it decreases to 118.8 individuals per thousand, with the decrease of 19.1%. Fig. 4(b) shows the changes in age-specific BMRs in 2030, 2045, and 2060 relative to 2019. Similar to the variation characteristics during 2001–2019, age-specific BMRs for the three age groups also present a downward trend in future, especially for elderly people over 70 years old. Compared to the values in 2019, BMRs for individuals aged 70 and above decreased by 9.1 people per thousand (−15.5%), 14.0 people per thousand (−23.8%), and 14.4 people per thousand (−24.4%) in 2030, 2045, and 2060, respectively.

3.4. $PM_{2.5}$-related mortality

Long-term exposure to $PM_{2.5}$ pollution can have an impact on human health. Fig. 5 detailedly shows the spatial-temporal distribution characteristics of premature deaths caused by long-term exposure to $PM_{2.5}$ in China from 2001 to 2019. From the spatial distribution perspective (Fig. 5(a)), health damage of $PM_{2.5}$ is mainly concentrated over the densely populated central and eastern regions of China, and the higher the $PM_{2.5}$ concentration, the more the premature deaths. From the perspective of temporal changes in Fig. 5(b), the variation in premature deaths in China over the past 19 years is consistent with the evolution of $PM_{2.5}$ concentration, showing a significant increase at first, followed by a stable fluctuation, and finally a gradual decrease. The significant increase in premature mortalities (+213 thousand yr^{-1}) during 2001–2005 is mainly due to the increases in population and $PM_{2.5}$ concentration. However, the rapid decline in premature deaths (−59 thousand yr^{-1}) during 2013–2019 is mainly attributed to the improvement in $PM_{2.5}$ air quality. Over the past 19 years, the mean premature

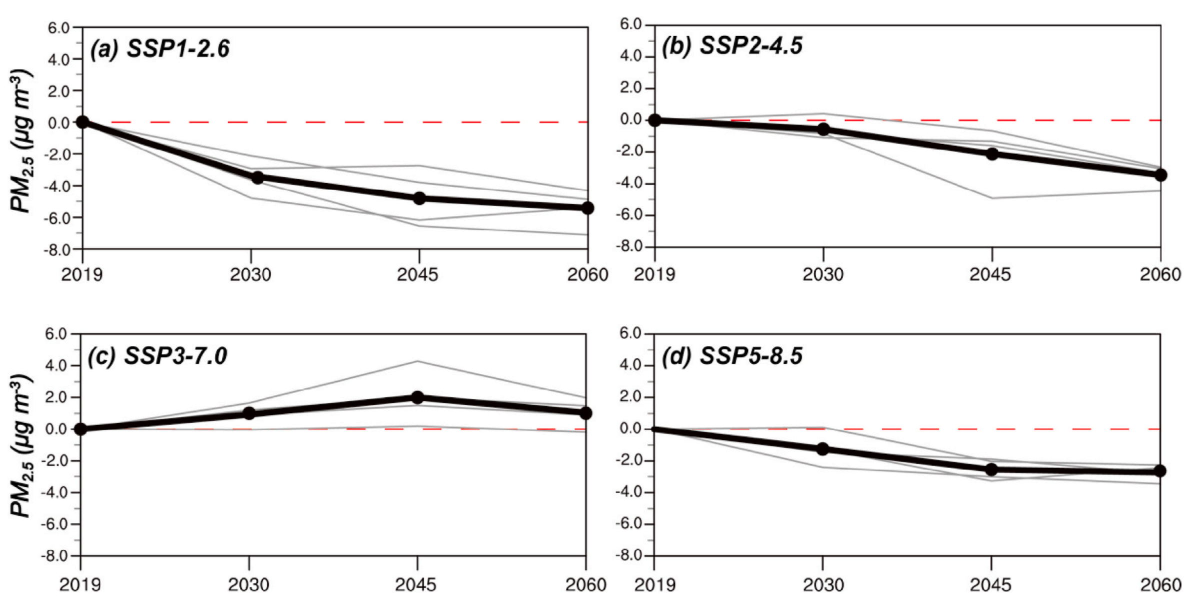

Fig. 2. Future changes in $PM_{2.5}$ concentrations in years of 2030, 2045 and 2060 relative to 2019 under different SSP scenarios: (a) SSP1-2.6, (b) SSP2-4.5, (c) SSP2-7.0, and (d) SSP5-8.5. The gray lines represent the simulated values from the four CMIP6 models, and the black dotted line is the ensemble mean. SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 represent sustainable development scenario, middle of the road scenario, regional rivalry scenario, and fossil fuel-driven development scenario, respectively.

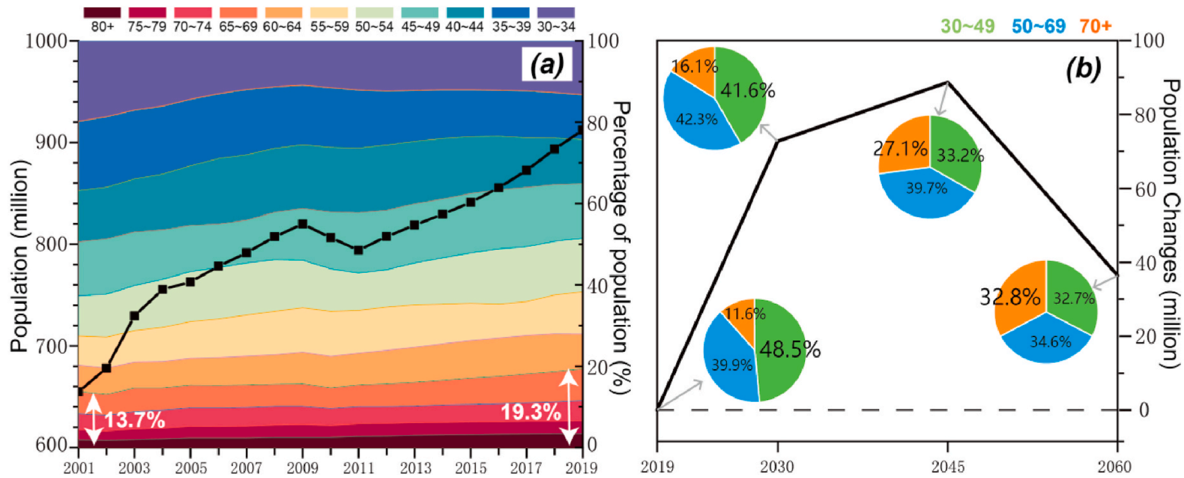

Fig. 3. (a) National population over 30 years old (black dotted line, left y-axis) and the proportion of each age group (colored stacked chart, right y-axis) from 2001 to 2019. (b) Future changes in population over 30 years old in years of 2030, 2045 and 2060 relative to 2019. Proportions of the three age structures (30–49, green; 50–69, blue; over 70, orange) are also shown in pie charts.

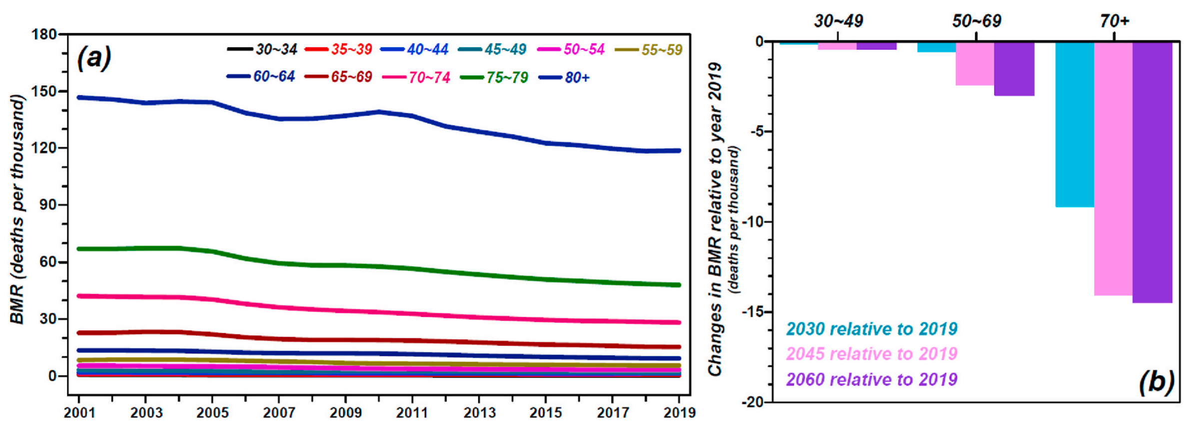

Fig. 4. (a) Age-specific baseline mortality rates (BMRs) of noncommunicable diseases (NCDs) and lower respiratory infections (LRIs) during 2001–2019. (b) Future changes in age-specific BMRs in years of 2030, 2045 and 2060 relative to 2019. The unit of BMR is deaths per thousand.

deaths caused by long-term exposure to $PM_{2.5}$ in China is 2363 thousand (95 % CI: 1991–2712 thousand). Compared to the values calculated by previous studies and observations from CNEMC (China National Environmental Monitoring Centre), the national mortalities attributed to long-term $PM_{2.5}$ exposure in this study seem reasonable (Table 2). For regional-scale $PM_{2.5}$-related health burden, the quantified provincial CNEMC and TAP premature mortalities over China averaged during 2014–2019 are also comparable (Table S5).

The analysis of premature deaths in the five key regions reveals that the health burden caused by long-term exposure to $PM_{2.5}$ is more severe in Central China (Fig. 5(c)), North China Plain (Fig. 5(d)) and Yangtze River Delta (Fig. 5(g)). The average premature deaths over the past 19 years in these regions are 454 (95%CI: 384–519), 442 (95%CI: 375–503) and 406 (95%CI: 343–465) thousand, respectively. Due to lower $PM_{2.5}$ concentrations, Sichuan-Chongqing region (Fig. 5(e)) and Pearl River Delta (Fig. 5(f)) have fewer premature deaths on average over the past 19 years, with the numbers of 201 (95%CI: 169–231) and 154 (95%CI: 129–177) thousand, respectively. Since 2013, the improvement in $PM_{2.5}$ air quality achieved by measures to control air pollution has had the most significant health benefits in Central China, North China Plain and Yangtze River Delta. The trends in premature deaths during 2013–2019 were −9 (95%CI: 10∼-8), −15 (95 %CI: 16∼-13) and −14 (95%CI: 16∼-13) thousand persons yr^{-1} for Central China, North China Plain and Yangtze River Delta, respectively. Although the decrease in $PM_{2.5}$ concentration from 2013 to 2019 in North China Plain (−36.9 μg m^{-3}) is greater than that in Yangtze River Delta (−27.2 μg m^{-3}), the change in premature deaths in North China Plain (decreased by 78 thousand from 466 thousand in 2013 to 388 thousand in 2019) is slightly smaller than that in Yangtze River Delta (decreased by 84 thousand from 425 thousand to 341 thousand). This can be explained by the larger increases in the age-specific population from 2013 to 2019 over Yangtze River Delta than North China Plain (Fig. S3).

Fig. 6 shows the future changes in $PM_{2.5}$-related mortalities in years of 2030, 2045 and 2060 relative to 2019 under different scenarios in China. Under the scenario of SSP3-7.0 (Fig. 6(c)), premature deaths are projected to continue rising in future due to the increases in $PM_{2.5}$ concentration and population. In comparison to the year 2019, premature deaths are estimated to increase by 672 thousand (95%CI: 556–785 thousand) individuals in 2060. Despite a continuous decrease in $PM_{2.5}$ concentration in future (Fig. 2), premature deaths are projected to increase in all scenarios of SSP1-2.6, SSP2-4.5 and SSP5-8.5, primarily driven by population growth and the aging (Fig. 3). This phenomenon is particularly obvious after year 2030. During 2030–2060, the trend of premature deaths under scenario of SSP1-2.6 (SSP2-4.5, SSP5-8.5) is 116 thousand (129, 181 thousand) individuals yr^{-1} (95%CI:111–121 thousand (105–133,152-209 thousand) individuals yr^{-1}).

3.5. Effects of individual factors on $PM_{2.5}$-related mortality

The health effects of long-term exposure to $PM_{2.5}$ are related to BMR,

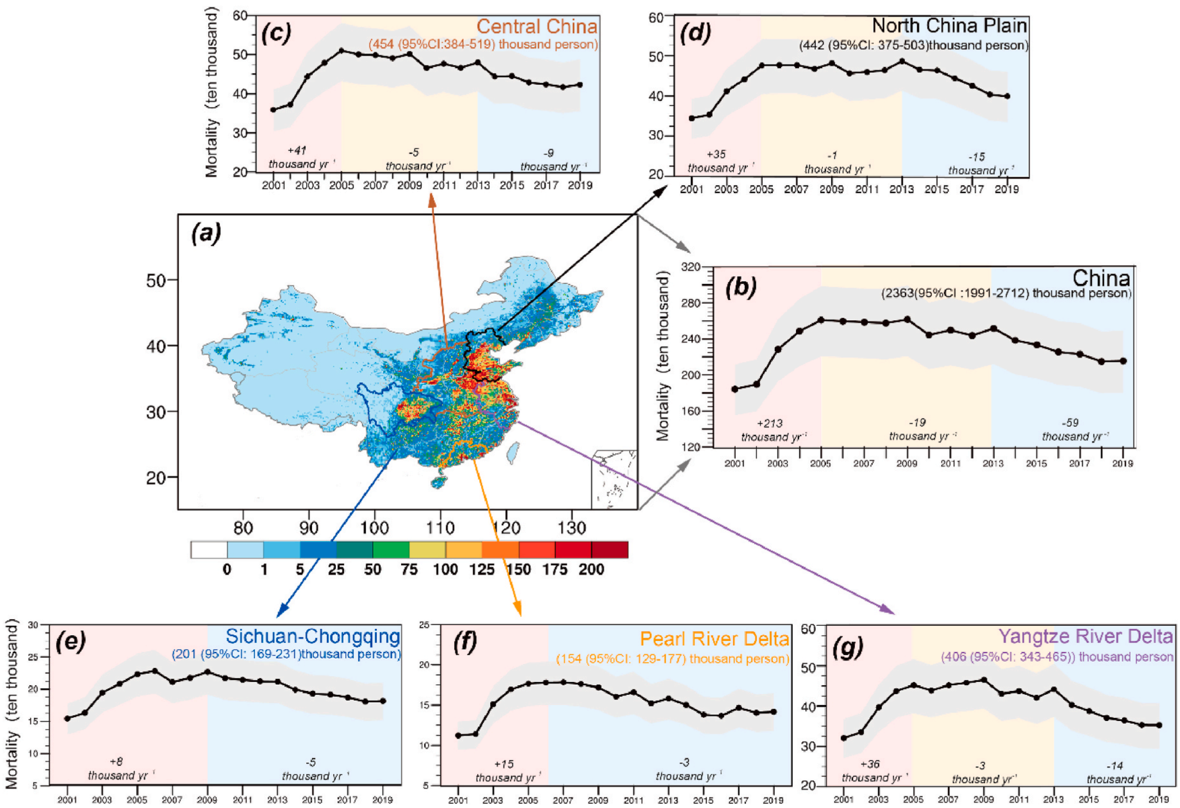

Fig. 5. Spatial-temporal distribution characteristics of premature deaths caused by long-term exposure to $PM_{2.5}$ in China during 2001–2019. (a) Spatial distribution of 19-year-mean premature deaths. (b–g) Annual mean premature deaths (black dotted line) averaged over China and the five key regions (Central China, North China Plain, Sichuan-Chongqing region, Pearl River Delta, and Yangtze River Delta) during 2001–2019. The gray shaded areas represent the 95% confidence interval. The light red (yellow, blue) background indicates a phase of continuous increase (fluctuating, decrease) in premature deaths. Mean premature deaths averaged over 2001–2019 and the trends in each time period are also shown in each panel.

Table 2
Comparisons of premature mortalities attributed to long-term $PM_{2.5}$ exposure over China in this study with values calculated by previous researches and China National Environmental Monitoring Centre (CNEMC).

Reference	Year	Premature mortalities (million)	This study (million)
Geng, et al. (2021b)	2002	1.73	1.89
Liu et al. (2020)	2005	2.10	2.60
Geng, et al. (2021b)	2012	2.26	2.06
Ma et al. (2021)	2014	2.36	2.43
Burnett et al. (2018)	2015	2.47	2.33
Wu et al. (2021)	2015	1.94	2.33
Liu et al. (2020)	2015	2.20	2.33
Zhang et al. (2019)	2017	1.98	2.23
Geng, et al. (2021b)	2017	2.12	2.23
Ma et al. (2021)	2018	1.83	2.14
Maji (2020)	2019	1.76	2.15
CNEMC	2014–2019	2.25	2.26

population size, age structure and exposure concentration. In order to better analyze the premature deaths caused by long-term exposure to $PM_{2.5}$ in China, we carry out several sensitivities to quantify the impacts of various factor changes on premature deaths. Fig. 7 shows the contributions of each factor to premature mortalities in China and the five key regions from 2001 to 2019. Due to the continuous improvement of medical standards, $PM_{2.5}$-related mortalities owing to changes in BMR alone ($Mort_{BMR}$) vary at the rates of −34, −7, −6, −3, −2 and −6 thousand yr^{-1} over the whole China, Central China, North China Plain, Sichuan-Chongqing region, Pearl River Delta and Yangtze River Delta, respectively. Due to the increase in population size and the severe aging, both $Mort_{Pop}$ (premature deaths attributed to changes in population size alone) and $Mort_{AgeStru}$ (premature deaths attributed to changes in age structure alone) show a significant upward trend. Over the past 19 years, the impacts of population size/age structure on health burden at the national level and the five key regions are +34/+38 (China), +5/+8 (Central China), +8/+7 (North China Plain), +2/+3 (Sichuan-Chongqing, +4/+2 (Pearl River Delta), and +6/+6 (Yangtze River Delta) thousand yr^{-1}, respectively. $PM_{2.5}$ concentration has different variation characteristics at different stages (Fig. 1), which determines the multi-year evolution characteristics of premature deaths in $Mort_{Conc}$ (premature deaths attributed to changes in exposure concentration alone). Over the past 19 years, the changes of $Mort_{Conc}$ in the whole country and the five key regions are almost consistent with $Mort_{Ctl}$ (premature deaths attributed to changes in all factors). For example, during the increase stage of $Mort_{Ctl}$, the increased $Mort_{Conc}$ can contribute 27.2% (China), 33.1% (Central China), 19.9% (North China Plain), 39.2% (Sichuan-Chongqing), 24.0% (Pearl River Delta) and

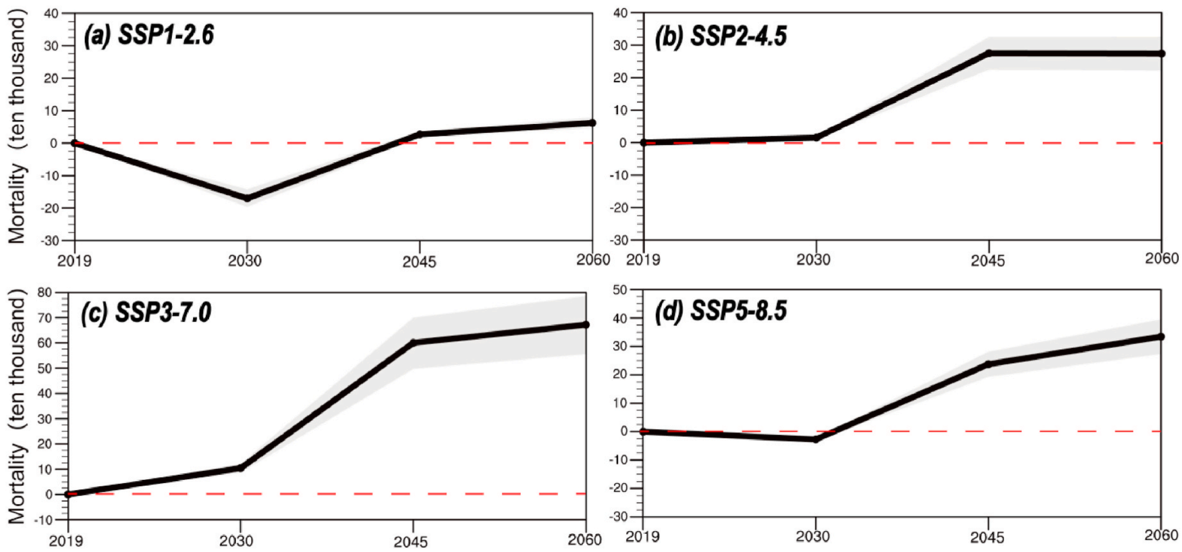

Fig. 6. Future changes in premature mortalities attributable to $PM_{2.5}$ exposure in years of 2030, 2045 and 2060 relative to 2019 under different SSP scenarios: (a) SSP1-2.6, (b) SSP2-4.5, (c) SSP2-7.0, and (d) SSP5-8.5. The black dotted line is the ensemble mean averaged from four CMIP6 models, and the gray shaded areas represent the 95% confidence interval. SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 represent sustainable development scenario, middle of the road scenario, regional rivalry scenario, and fossil fuel-driven development scenario, respectively.

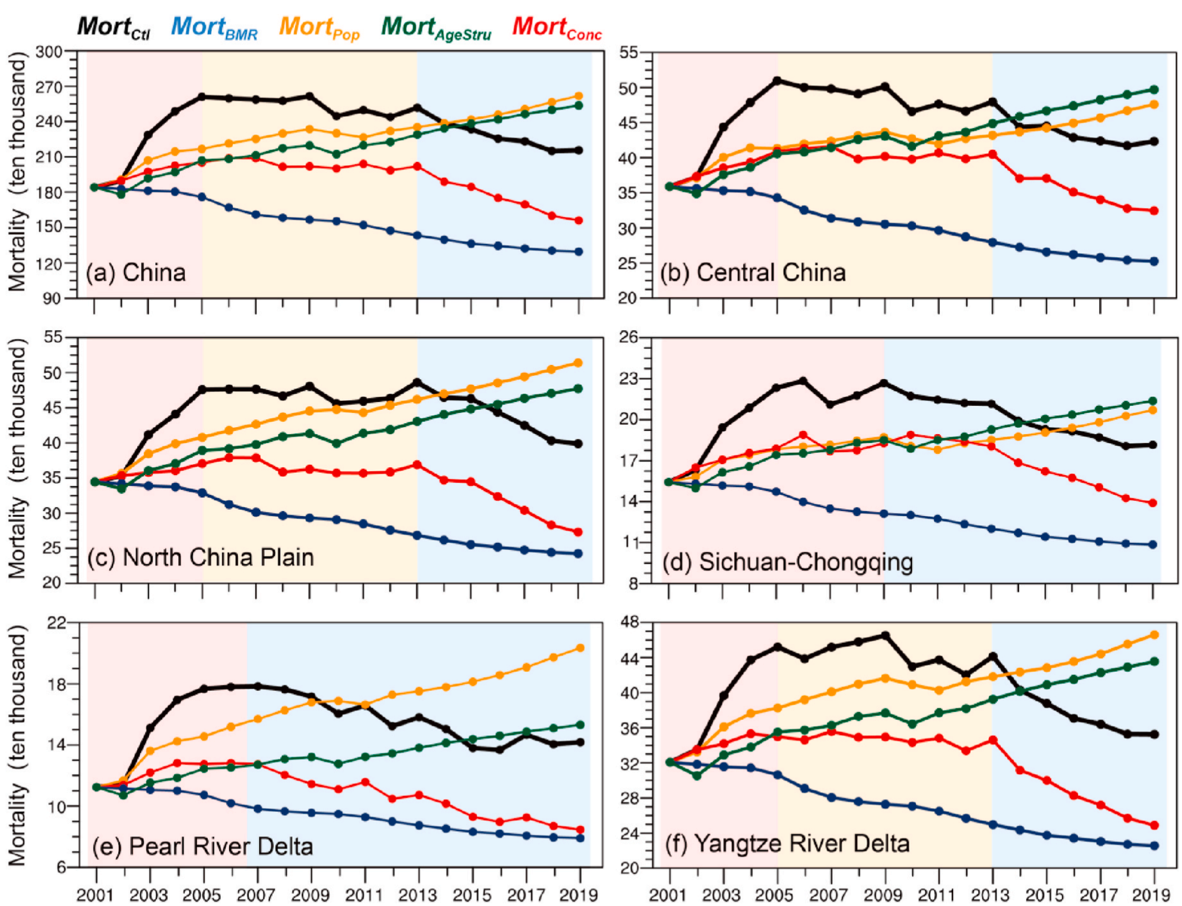

Fig. 7. Yearly premature mortalities attributable to long-term $PM_{2.5}$ exposure during 2001–2019 in normal-condition experiment and the four sensitivity experiments averaged over (a) China, (b) Central China, (c) North China Plain, (d) Sichuan-Chongqing region, (e) Pearl River Delta, and (f) Yangtze River Delta. The light red (yellow, blue) background indicates a phase of continuous increase (fluctuating, decrease) in premature deaths according to the normal-condition experiment.

22.0% (Yangtze River Delta) of the increase in $Mort_{Ctl}$, while the predominant factor drivers the increase in $Mort_{Ctl}$ is $Mort_{Pop}$. During the decreasing stage of $Mort_{Ctl}$, $Mort_{Conc}$ plays a dominant role and contributes 126.7% (China), 142.7% (Central China), 110.3% (North China Plain), 96.5% (Sichuan-Chongqing), 116.9% (Pearl River Delta) and 109.2% (Yangtze River Delta) of the decrease in $Mort_{Ctl}$,

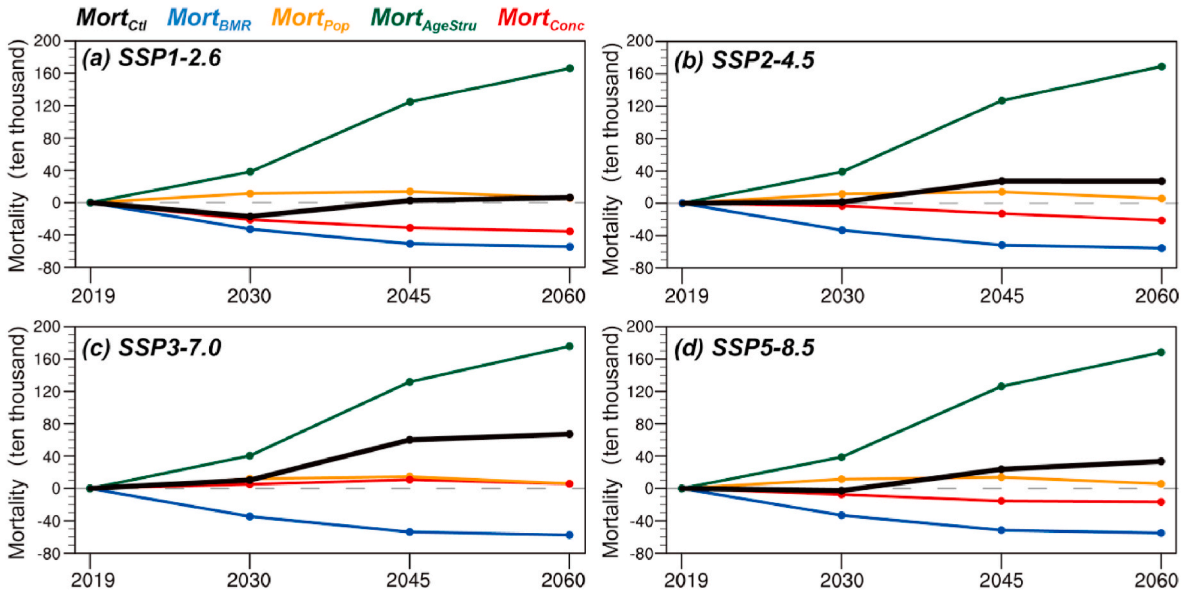

Fig. 8. Future changes in national $PM_{2.5}$-related premature deaths in years of 2030, 2045 and 2060 relative to 2019 in normal-condition experiment and the four sensitivity experiments under different SSP scenarios: (a) SSP1-2.6, (b) SSP2-4.5, (c) SSP2-7.0, and (d) SSP5-8.5. These scenarios represent sustainable development scenario, middle of the road scenario, regional rivalry scenario, and fossil fuel-driven development scenario, respectively.

respectively.

In order to investigate the impacts of future changes in factors on $PM_{2.5}$-related deaths in China under different scenarios, we further conduct sensitivity experiments to analyze the evolution of premature mortalities. According to Fig. 8, we can find that the continuous decreases in future BMR and $PM_{2.5}$ exposure concentration (except for the scenario of SSP3-7.0) can effectively mitigate premature deaths. Relative to the values in year 2019, premature mortalities in year 2030 (2045, 2016) are projected to decrease by −347~-328 thousand (−538~-509 thousand, −311~-127 thousand) and −211~-33 thousand (−576~-545, −356~-166 thousand) due to changes in BMR and $PM_{2.5}$ concentration, respectively. Although the increase in future population will result in more health burdens (premature deaths in 2030, 2045 and 2060 under the four scenarios are projected to increase by 114~120 thousand, 138–146 thousand and 57–60 thousand compared to year 2019), the significant trend of population aging determines the occurrence of more premature deaths in future. Premature mortalities caused by changes in age structure is projected to increase by 382~404 thousand, 1247–1319 thousand and 1662–1757 thousand in year 2030, 2045 and 2060 relative to 2019, respectively.

4. Conclusion and discussion

In this study, we use high-resolution TAP data and different scenarios of CMIP6 data to study spatiotemporal variations in health burden caused by long-term exposure to $PM_{2.5}$ in China at present (from 2001 to 2019) and in future (years of 2030, 2045 and 2060). Sensitivity experiments are also designed to quantify the impacts of baseline mortality rate (BMR), population size, age structure, and $PM_{2.5}$ concentration on premature deaths.

The national population-weighted $PM_{2.5}$ concentration during 2001–2019 is 57.5 μg m^{-3}, significantly higher than the unweighted value of 33.4 μg m^{-3}. The major regions with high $PM_{2.5}$ concentrations are located in densely populated areas of North China Plain, Central China, and Yangtze River Delta. From 2001 to 2007, the national average $PM_{2.5}$ concentration shows a positive trend with the value of +0.8 μg m^{-3} yr^{-1}, and reaches its highest value of 36.3 μg m^{-3} in 2007. It then remains relatively stable with slight fluctuations. After the implement of “Action Plan on Prevention and Control of Air Pollution” in 2013, the national average $PM_{2.5}$ concentration decreases significantly with an annual mean decline of 5.1% from 2013 to 2019. However, $PM_{2.5}$ concentrations in 2019 over many regions still exceed the national first-grade standard (35 μg m^{-3}), which means the task of air pollution prevention and control remains challenging in future.

Over the past 19 years, an average of 2363 (95%CI: 1991–2712) thousand premature deaths are calculated in China due to the long-term exposure to $PM_{2.5}$. The significant increase in premature deaths from 2001 to 2005 (+213 thousand yr^{-1}) is mainly attributed to the growth in population size and the worsening $PM_{2.5}$ pollution. Meanwhile, the rapid decline in premature deaths from 2013 to 2019 (−59 thousand yr^{-1}) is primarily due to the improvement in $PM_{2.5}$ air quality. Focusing on the health burden over key regions in China, the most significant health damage can be found in Central China, North China Plain and Yangtze River Delta. The mean premature mortalities in these regions from 2001 to 2019 are 454 (95%CI: 384–519), 442 (95%CI: 375–503) and 406 (95%CI: 343–465) thousand, respectively.

Compared with 2019, the future $PM_{2.5}$ concentration in China is projected to decrease under the SSP1-2.6, SSP2-4.5 and SSP5-8.5 scenarios. But in SSP3-7.0, $PM_{2.5}$ pollution is expected to worsen. Although the improvement in medical care can contribute to alleviating the burden on public health, the future increase in population size and the prominence of aging will lead to the upward trend in premature mortalities, and it will be especially evident during 2030–2060 with the trend of +116–181 thousand yr^{-1} under the four scenarios. According to the results from sensitivity experiments, it can be further concluded that the aging population will dominate the increase in premature deaths in future. By 2030, 2045 and 2060, premature mortalities due to changes in age structure alone are projected to increase by 382~404, 1247–1319, and 1662–1757 thousand relative to 2019, respectively.

There are also some limitations in this study (1) Eleven age groups (i.e., 0–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79 and 80+). of baseline mortality rates (BMRs) are applied to estimate the historical $PM_{2.5}$-realted health burden, while three age groups (i.e., 30–49, 50–69, 70+) are used to quantify the future premature mortalities attributed to $PM_{2.5}$ exposure. Even though little differences (−0.2%~+1.3%) of historical premature mortalities during 2001–2019 are found among the results calculated by the 3-age-group method and the 11-age-group method (Table S6), the same age structure should be selected in future works. (2) BMRs for noncommunicable diseases (NCDs) and lower respiratory infections (LRIs) provided by the

Global Burden of Disease (GBD) can only be available until 2019. Therefore, the health burden caused by long-term exposure to $PM_{2.5}$ in China after 2019 has not been quantified in this study; (3) Relative risk (RR) is a crucial variable in health impact assessment models (e.g. GEMM) for quantifying premature deaths attributed to long-term exposure to $PM_{2.5}$. Burnett et al. (2018) have taken into account the applicability of RR to highly polluted areas when constructing the calculation formula. However, considering the severe air pollution in China and the spatial non-uniformity of $PM_{2.5}$ concentrations, it is necessary to make more effort to summarize relevant researches on air pollution and human health in China, and conduct a meta-analysis on the relationship between $PM_{2.5}$ pollution and its related premature mortalities, which may provide more scientific evidence for better air pollution prevention and human health protection.

CRediT authorship contribution statement

Yang Bai: Formal analysis, Investigation, Resources, Visualization, Writing – original draft. **Lei Chen:** Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing. **Zijia Feng:** Software, Supervision, Validation, Writing – review & editing. **Jia Zhu:** Conceptualization, Funding acquisition, Supervision. **Yixuan Gu:** Software, Validation. **Ke Li:** Supervision, Writing – review & editing. **Hong Liao:** Conceptualization, Supervision.

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.

Acknowledgments

This work is supported by National Key R&D Program of China (Grant 2022YFE0136100), National Natural Science Foundation of China (Grants 42305121, 42007195), State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex (Grant SCAPC202114), National Key R&D Program of China (Grant 2019YFA0606804), and Natural Science Foundation of Jiangsu Province (Grant BK20220031).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2024.120363.

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