Global PM2.5 prediction and associated mortality to 2100 under different climate change scenarios

Journal:	*Environmental Science & Technology*
Manuscript ID	es-2023-00967y
Manuscript Type:	Article
Date Submitted by the Author:	04-Feb-2023

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Global $PM_{2.5}$ prediction and associated mortality to 2100 under different climate change scenarios

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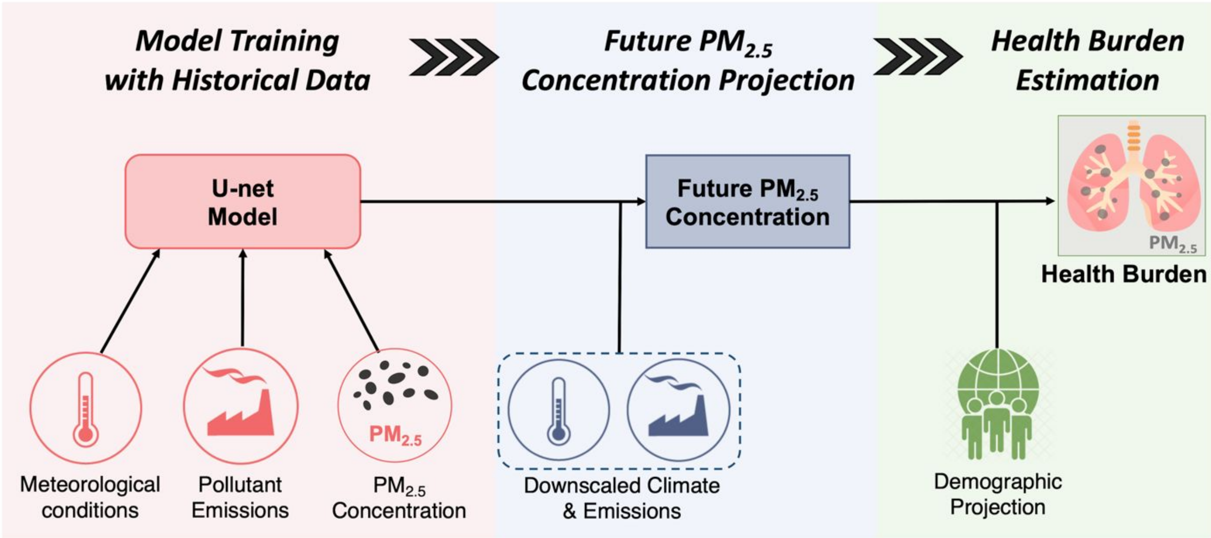
Abstract

Ambient fine particulate matter ($PM_{2.5}$) can cause severe adverse health impacts in humans. Thus, reducing $PM_{2.5}$ exposure is an important public health focus. Meteorological and emissions factors, which considerably affect the $PM_{2.5}$ concentrations in air, vary significantly under different climate change scenarios. However, $PM_{2.5}$ concentrations and their associated disease burden under future climate scenarios are not well clarified. In this work, the global $PM_{2.5}$ concentrations from 2021 to 2100 were estimated by combining the U-Net convolutional neural network deep learning technique, reanalysis data, emissions data, and bias-corrected Coupled Model Intercomparison Project Phase 6 future climate scenario data. Based on the estimated $PM_{2.5}$ concentrations, the future premature mortality burden associated with $PM_{2.5}$ exposure was assessed using the Global Exposure Mortality Model. Ambient $PM_{2.5}$ exposure is expected to be highest in the SSP3-7.0 scenario and lowest in the SSP1-2.6 scenario in the major representative regions of the world. The global mortality rate (per 100,000 exposed population) associated with $PM_{2.5}$ under the four different scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, ranging from 84.6 (95% Confidence Interval (CI): 59.6–107.0) to 150.0 (95% CI: 106.2–185.0)) at the end of this century is expected to be lower than the baseline (the 2010s, 161.1 (95% CI: 113.3–199.9)). Among all four scenarios, the sustainable development scenario (SSP1-2.6) results in the lowest $PM_{2.5}$ concentrations and the lowest premature mortality burden, which indicates that this is the pathway that countries should strive for. Our work helps to advance the scientific understanding of the global geo-climatic system and provides suggestions for scientists and policymakers.

Keywords: Climate change; Global; $PM_{2.5}$; Mortality; Deep learning

Synopsis: Future $PM_{2.5}$ pollution and its associated health burden have not been well clarified. In this study, a new set of global-scale, spatially explicit $PM_{2.5}$ concentration from 2021 to 2100 with a spatial resolution of 0.1° × 0.1° was estimated, and associated $PM_{2.5}$ exposure and premature mortality burden was calculated.



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1. Introduction

Ambient particulate matter ($PM_{2.5}$) poses a considerable global threat to human health. Exposure to outdoor $PM_{2.5}$ caused 4.14 million deaths in 2019, accounting for 62% of all global deaths attributable to air pollution estimated by the Global Burden of Disease Project.[1-4] Unmitigated climate change is projected to exacerbate inevitable challenges and threats to global air quality and increase its attributable adverse health impacts.[5-7] Therefore, it is necessary to understand how future climate change scenarios will influence surface $PM_{2.5}$ concentrations and propose appropriate climate mitigation measures.

Most studies[7, 8] on $PM_{2.5}$ concentration estimation under different climate scenarios have been based on the Coupled Model Intercomparison Project 5 (CMIP5) Representative Concentration Pathways scenarios. However, with the release of the CMIP6 simulation results, the Scenario Model Intercomparison Project provides new alternative scenarios that are intimately connected with societal concerns regarding climate change mitigation, adaptation, and impacts.[9, 10] Some studies have estimated future air quality based on CMIP6 climate projections;[11, 12] however, these studies either investigated the $PM_{2.5}$ exposure in only one country or region,[11-13] or the predicted periods were shorter than 50 years.[14, 15] Although future global-scale $PM_{2.5}$ simulations are available,[12, 16] the low model spatial resolution (e.g., 1.875° × 1.25°) prevents a clear understanding of how this pollutant will evolve over the next several decades and hampers reliable estimations of how this pollutant will influence human health in the future. As yet, no comprehensive study has estimated the global mortality burden associated with ambient $PM_{2.5}$ based on high-resolution (e.g., 0.1° × 0.1°) and bias-corrected future climate projections that incorporate demographic and emissions data. Such a study is urgently needed to understand how the $PM_{2.5}$ concentration and the associated health burden in each country will vary under different climate scenarios.

In this study, we estimated $PM_{2.5}$ exposure and its associated mortality burden over the 2021–2100 period under the SSP1-2.6[17], SSP2-4.5[18], SSP3-7.0,[19] and SSP5-8.5[20] scenarios (SSP: Shared Socioeconomic Pathway). The relationships between critical meteorological variables and $PM_{2.5}$ concentrations were constructed using a U-Net convolutional neural network[21] based on Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2)[22], CMIP6 global emissions data,[23] and satellite-retrieved $PM_{2.5}$ data.[24] $PM_{2.5}$ exposure and the associated premature mortality over the 2021–2100 period were estimated based on the constructed relationships between the $PM_{2.5}$ concentrations, meteorological variables, emissions, the high-resolution and bias-corrected CMIP6 future climate SSP scenario data (adjusted using the delta downscaling method), and future SSP demographic projections. Our work endeavored to elucidate how and through what pathways $PM_{2.5}$ exposure would influence the premature mortality burden in 184 countries and regions worldwide over the forthcoming 80 years, spanning the space of challenges to mitigation and adaptation to climate change, which can exhibit a more expansive and comprehensive blueprint to air quality projection.

2. Methods

2.1. Data acquisition

2.1.1. Surface $PM_{2.5}$ data for training

High-resolution and highly accurate global surface $PM_{2.5}$ data are required to examine the relationships between $PM_{2.5}$ concentrations and meteorological and emissions conditions. Therefore, global surface $PM_{2.5}$ data at 0.1° × 0.1° combining AOD retrievals from the NASA MODIS, MISR, and SeaWIFS instrument, GEOS-Chem chemical transport model, and ground-based observations calibrated by geographically weighted regression were selected for the study.[24] Compared with previous global surface $PM_{2.5}$ concentration datasets,[25-27] this set of $PM_{2.5}$ values contained finer resolution data and compensated for missing or limited monthly measurements. This $PM_{2.5}$ dataset was highly consistent with collocated ground-based observations from monitoring networks $PM_{2.5}$ ($R^2 = 0.84$), with a root mean square error (RMSE) of 8.4 μg m^{-3}, and thus can accurately represent the surface $PM_{2.5}$ concentrations.

2.1.2. Meteorological and emissions data for model input

To train the deep learning model, the following monthly average meteorological data were taken from the MERRA-2 dataset:[28] surface temperature, wind speed, specific humidity, planetary boundary layer height, and sea level pressure; these parameters can strongly influence the $PM_{2.5}$ concentration.[29] Several studies have contrasted the MERRA-2 dataset with ground-based observations and other reanalysis datasets and have shown that the MERRA-2 data better represent the surface meteorological conditions.[22, 30-33] For example, when compared with the ground observation data from China, the RMSE, MB (mean bias), and R value for temperature were 3.62 K, −2.14 K, and 0.95, respectively.[33] These three statistical metrics for humidity were 5%, 0.63%, and 0.89.[34]

Since the deficiency in the emissions of primary $PM_{2.5}$ components (except organic carbon (OC) and black carbon (BC)) in the CMIP6 datasets, future $PM_{2.5}$ concentrations are driven by changes to precursor emissions (ammonia (NH_3), nitrogen oxides (NOx), and sulfur dioxide (SO_2)), BC, OC and climate in this study. Global emission amounts and percentages of the five species are presented in Table S1 and S2. Based on existing global emission inventory, 92 such as PKU-FUEL, primary $PM_{2.5}$ emission has high correlation with the emissions of these five pollutants.[35, 36] Covering the period of 1750–2100 (historical dataset: 1750–2014, future emissions dataset: 2015–2100), CMIP6 gridded emissions dataset includes aviation emissions, all other anthropogenic emissions sectors, and total open burning emissions. This gridded dataset has previously been used for global model simulation and for emission scenario comparisons.[13, 37, 38] CMIP6 dataset contains historical emissions (1750 to 2014) and future emission data for SSP scenarios (2015-2100). CMIP6 emissions data were utilized in both the training and prediction processes. CMIP6 historical emissions data (1998–2014, the historical emissions data are available till 2014) were used to build the deep learning model, and the emission data of SSP scenarios for 2015 to 2019 were used in the deep learning model verification process. Future emission data for 2021–2100 were input into the trained deep learning model for prediction. The detailed narratives of emission inventory used in this study are summarized in Table S3.

The monthly MERRA-2 meteorological data and CMIP6 emissions data from 1998 to 2019 were input into the deep learning model for training and validation. The frequency distribution of meteorological and emission data is presented in Figure S1–S2 and discussed in Text S1. Before training the deep learning model, all meteorological and emissions data were re-interpolated from their original spatial resolutions (meteorological data with 0.625° × 0.500° and emission data with 0.5° × 0.5°) into the same grid as the surface $PM_{2.5}$ data with a resolution of 0.1° × 0.1°. The bilinear interpolation technique was applied in this work, which has been widely used to interpolate climate data into different resolutions in previous studies.[39,40]

2.2. U-Net convolutional neural networks

Tremendous advances in computer vision have led to convolutional neural networks (CNNs) being widely used for 2D data analysis.[41] We built a CNN-based U-Net framework to construct relationships between $PM_{2.5}$ concentrations and predictor variables.[21] First proposed for medical segmentation,[21] U-Net assumes that local information and global information are both essential, which is also apposite for $PM_{2.5}$ prediction. Equipped with flexible global aggregation blocks, U-Net can sufficiently consider non-local influences from other grid cells to local $PM_{2.5}$ concentration. In addition, multiple layers of U-Net CNNs make it possible to elucidate nonlinear relationships among critical meteorological variables, ambient pollutant emissions, and surface $PM_{2.5}$ concentrations; these relationships can be too complex to be delineated through traditional regression methods.[42-44]

All of the predictor variables (meteorological and emission data) and the $PM_{2.5}$ concentrations were treated as 2D images. The detailed architecture of our U-Net model, including the number of channels for each convolution layer, the size of the convolution kernel, the activation function of the convolution layer, and the image size are provided in Figure 1. The description of the U-Net model can be found in Text S2. The data augmentation and dropout regularization have been applied to improve the model generalization ability, as discussed in Text S3. And the monotonic decreases in training and validation loss (Figure S4) have proved that no overfitting was detected.

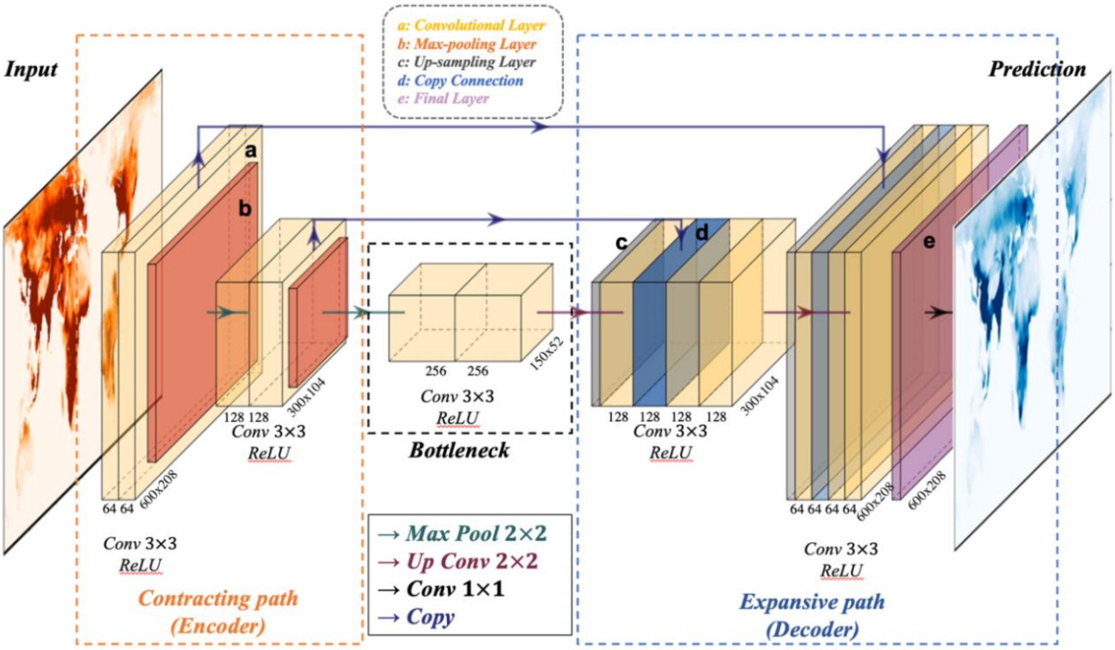

Figure 1. Architecture of the U-Net model

2.3. Future climate data under different Shared Socioeconomic Pathway (SSP) scenarios

The trained model was used to predict the 2021–2100 $PM_{2.5}$ concentrations using the meteorological variables from the CMIP6 future climate scenarios dataset. As shown in Table S4, historical simulations (1981–2010) and future projections (2021–2100) of global climate multiple-model ensemble results from 28 global climate models (GCMs) and four SSPs (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) were utilized. The four SSPs are classified by socioeconomic, land use, and environmental development assumptions and represent conceivable future scenarios that capture distinctive climate mitigation and adaptation challenges. SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 represent low, medium, medium to high, and high radiative forcing by the end of the century, respectively.[45-47] Changes in greenhouse gas concentrations in the atmosphere affect radiative forcing; thus, 'radiative forcing' mentioned in this work corresponds to different greenhouse gas (GHG) emission scenarios and the resulting climate change. Both SSP1-2.6 and SSP5-8.5 represent strong climate mitigation scenarios,[17, 48] with the distinction that the anthropogenic radiative forcings by 2100 are 2.6 Watt/m^2 and 8.5 Watt/m^2, respectively.[20, 49] SSP2-4.5 represents a moderate mitigation scenario and the radiative forcing is stabilized at 4.5 Watt/m^2 until 2100 by implementing moderately restrictive emission reduction measures and strategies.[18] SSP3-7.0 is the weakest climate mitigation scenario with an anthropogenic radiative forcing of 7.0 Watt/m^2 by 2100.[19] The critical elements relevant to air pollution among four SSP scenarios are summarized in Table S5. Further information and the assumptions used in the future scenarios are provided in Eyring et al. (2016)[50] and Gidden et al. (2019).[51] The SSPs explored in this study cover a wide range of plausible socioeconomic trends for this century.

2.4. Bias correction and downscaling

Before being fed into the trained U-Net model, the meteorological variables from CMIP6 were corrected and downscaled to achieve reliable climate change impact metrics. To produce high-resolution and bias-corrected future climate information, we used the delta change (DC) method, which applies a change factor (i.e., delta) derived from GCMs to historical observations.[52, 53] Studies have found the DC method to be robust for downscaling climate data.[54, 55] Our implementation of the DC method was intended to correct the simulated climate data while providing results at high spatial resolution. The details of the DC method are described in the Text S4.

2.5. Mortality calculation

The Global Exposure Mortality Model (GEMM) proposed by Burnett et al. (2018)[56] was used as a hazard ratio model to estimate the premature mortality burden associated with $PM_{2.5}$ exposure (i.e., population-weighted $PM_{2.5}$ concentration, Text S5). GEMM has relieved some of the contentious assumptions that are stipulated by other disease-specific hazard ratio models, such as the Integrated Exposure Response Model.[56] The detailed of the GEMM model are provided in the Text S6.

The baseline mortality rates for different countries in 2015 obtained from the Global Health Data Exchange data catalog were used for estimating premature mortality. The gridded population projections for all SSPs during 2021–2100 at a resolution of 1 km × 1 km are available from the Spatial Population Scenario database. This demographic projection dataset has been previously verified[57] and has been used to project heat-related excess mortality[58, 59] and to model future patterns of urbanization.[60] In this work, we calculated the $PM_{2.5}$-associated premature mortality in accordance with the projected population, but the baseline mortality rate was assumed to be that of 2015 owing to a lack of credible alternatives. Constant baseline mortality has been applied in other works that have projected the future environmental burdens of disease[61, 62].

3. Results

3.1. Performance evaluation

To verify that the trained U-Net model could generate accurate $PM_{2.5}$ concentration predictions, we validated the model performance from the spatial, scatter point, and statistical matrix perspectives. CMIP6 historical emissions data are available through 2014, while the data from 2015 to 2019 were from the CMIP6 future scenario emissions dataset. In the CMIP6 future scenario emissions dataset, the different scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) have their own emissions datasets, but the differences are very limited throughout the 2015–2019 period. Because of this, we separated the verification by (1) implementing 8-fold cross-validation to verify the performance for the estimations from 1998 to 2014 and (2) inputting the future emissions datasets (2015–2019) of the four scenarios together with other independent variables into the trained model to output the $PM_{2.5}$ estimation for the comparison. For the 8-fold cross-validation, 15 years of data were used for training and 2 years of data were used for comparison in each fold. The calculation of 8-fold cross-validation is further described in Text S7.

Figure S5 shows a spatial comparison between the satellite-retrieved $PM_{2.5}$ data and the values predicted by the U-Net CNN using 8-fold validation. The results show that the model produced good fits in the areas with both low ($\leq$ 35 μg/m^3) and high (> 35 μg/m^3) $PM_{2.5}$ concentration. As demonstrated in Figures S6 and S7, the errors between the simulated and target monthly average $PM_{2.5}$ concentrations for all grid cells were within $\pm$ 12 μg/m^3 for 1998-2014. The monthly average relative errors specific to each country were within $\pm$ 10%.

Figure 2 shows the scatter plots of the satellite-retrieved $PM_{2.5}$ concentrations and the 8-fold average predicted concentrations. The strong correlation coefficient (R, 0.987) was better than that of previous studies[63-65] and indicates that the model could accurately predict all of the 8-fold cross-validation data. The statistical evaluation metrics (A1–A6 in the supplemental material) shown in Table 1 were further used to verify the model performance. The relatively small standard deviation of error indicates that our trained model has considerable stability. From these statistical matrix perspectives, the $PM_{2.5}$ concentrations estimated by our proposed deep learning model were also better than those of previous studies.[29, 66, 67] In addition to the comparison with the satellite-retrieved $PM_{2.5}$ data, we compared the annual model-predicted $PM_{2.5}$ concentrations with the monitor-based observations in China, the United States, and Europe because these regions have well-established ground-based observation networks (Table S6). The R values for China, the United States, and Europe were 0.91, 0.80, and 0.81, respectively. These results show that the $PM_{2.5}$ estimates from our method were also in general agreement with the ground-based observations in these regions.

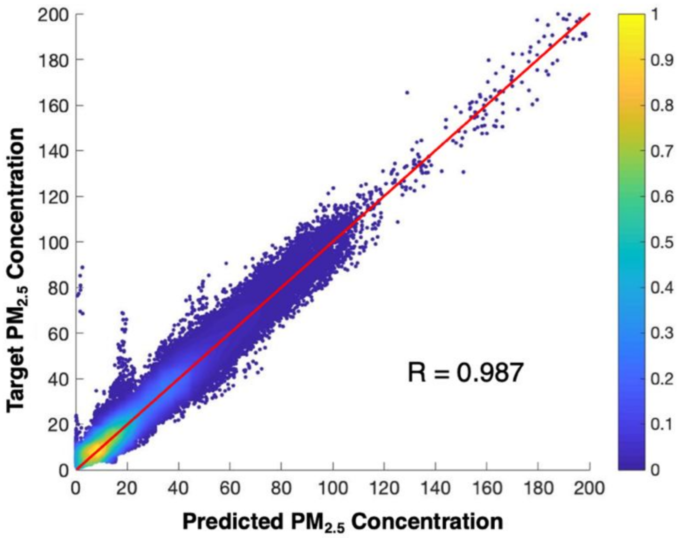

Figure 2. 8-fold cross-validation of the global $PM_{2.5}$ concentrations predicted by the U-Net CNN model during 1998-2014. The color represents the sample density.

Table 1. 8-fold cross-validation of U-Net CNN model performance

	NMB*	NME*	MB* (μg/m^3)	MAGE* (μg/m^3)	RMSE* (μg/m^3)	R
Average	−0.01	0.22	−0.05	1.36	4.02	0.987
Standard error	0.01	0.03	0.08	0.11	0.39	0.010

***NMB:** normalized mean bias; **NME:** normalized mean error; **MB:** mean bias; **MAGE:** mean absolute gross error; **RMSE:** Root Mean Squared Error

As mentioned above, the CMIP6 emissions from 2015–2019 under the four SSP scenarios together with other input data were fed into the trained deep learning model to estimate the $PM_{2.5}$ concentrations for these 5 years, as shown in Table S7. These metrics indicate the good feasibility and generalizability of our model in predicting the $PM_{2.5}$ concentrations. In summary, the satisfactory performance indicated that the trained U-Net model was able to identify the relationships between $PM_{2.5}$ and the influencing factors, which demonstrates that this model could be used for future $PM_{2.5}$ pollution estimation in the 2021–2100 period under different climate scenarios.

3.2. Projection of future ambient $PM_{2.5}$ concentrations

The built U-Net deep learning model was used to project future $PM_{2.5}$ concentrations under the SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios. Changes in the downscaled multi-model ensembles of critical meteorological variables are shown in Figures S8–S12. Emissions (SO_2, NH_3, OC, BC, NOx) for the four SSP scenarios up to 2100 are shown in Figures S13-S17. The projected $PM_{2.5}$ concentrations were compared with the baseline concentration (the average $PM_{2.5}$ concentration from 2010 to 2019), as shown in Figure 3. The $PM_{2.5}$ decadal average concentrations for the different SSP scenarios are shown in Figures S18–S21.

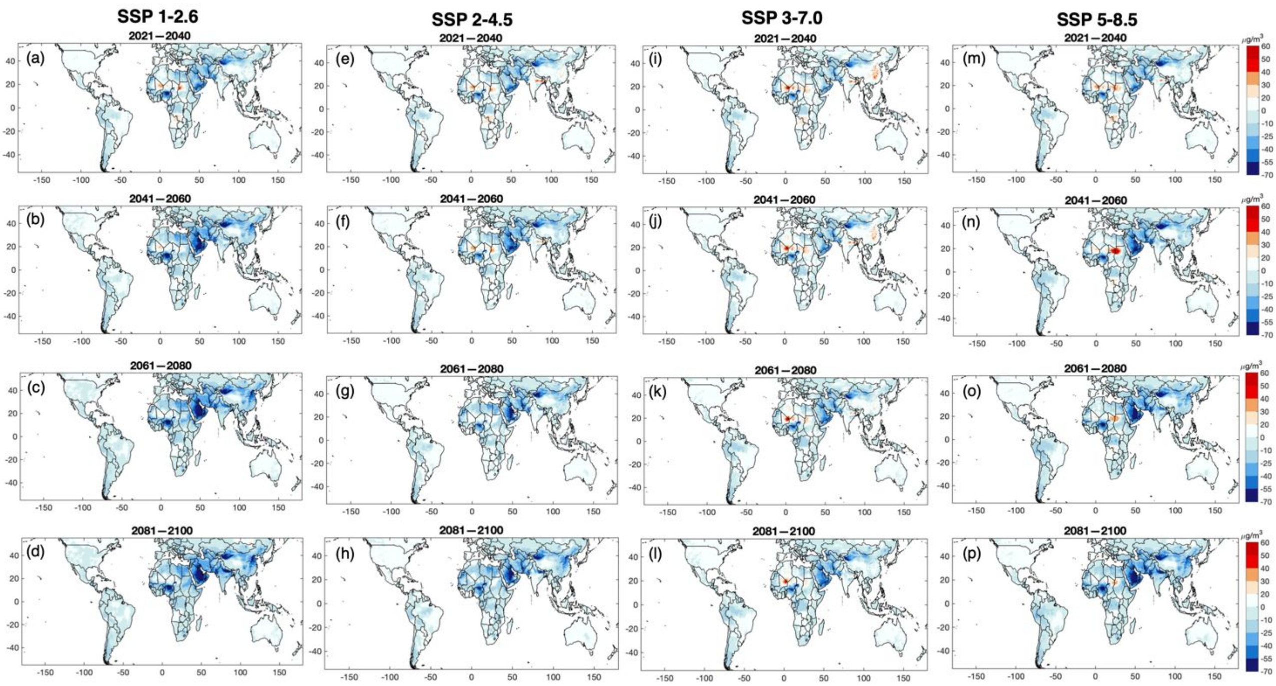

Figure 3. Spatial distribution of changes in projected global $PM_{2.5}$ concentrations relative to the baseline period (2010–2019) under different climate change scenarios. Panels (a)-(d) represent the changes in $PM_{2.5}$ concentration for 2030s (2021-2050 average), 2050s (2041-2070 average), 2070s (2061-2090 average), and 2080s (2071-2100 average) under SSP1-2.6 scenarios compared to the baseline condition. Panels (e)-(h) represent that of the same period but under SSP2-4.5. Panels (i)-(l) represent that of the same period but under SSP3-7.0. Panels (m)-(p) represent that of the same period but under SSP5-8.5.

Based on the deep learning model estimations, the $PM_{2.5}$ concentrations are projected to decrease in almost all regions in all scenarios; however, there are some notable differences among the projections. In SSP1-2.6, the projected $PM_{2.5}$ concentration will decrease consistently from 2030 to 2100. Among the investigated regions, the Middle East, Eastern

China, and India will undergo the most significant decline in $PM_{2.5}$ concentrations under this scenario. SSP2-4.5 represents the middle range of plausible future pathways. In this scenario, although the furthest projection into the 2090s showed a decline compared with the baseline level (that of the 2010s), this reduction was much smaller than the corresponding changes under SSP1-2.6. The projections are different for SSP3-7.0, which assumes more pessimistic development strategies, such as less investment in the environment and health care and a fast-growing population.[17, 19, 68] This would lead to an apparent increase in $PM_{2.5}$ concentrations in Asia and Africa before the 2050s. After meeting economic development needs and implementing environmental control measures, the $PM_{2.5}$ concentrations would decrease to a level similar to the baseline period. In SSP5-8.5, fossil fuels are heavily relied on to achieve rapid economic growth. Thus, in the middle of the 21st century, climate and emission change would considerably increase $PM_{2.5}$ concentrations and cause considerable damage to human health in central Africa. Nevertheless, with the rapid development of society and pollution mitigation policies, the overall $PM_{2.5}$ concentrations will undergo a sharper reduction after the 2050s. $PM_{2.5}$ concentrations continued to exceed baseline values in central Africa under SSP3-7.0 and SSP5-8.5, which is quite consistent with the emission-increasing trends in the region as shown in Figure S22 and S23, implying that the emission change should be the major driver for the $PM_{2.5}$ concentration increase in Central Africa.

3.3. Projection of future ambient $PM_{2.5}$ exposure

SSPs narratives gave rise to spatial and temporal differences in the demographic projections. Figures S24 and S25 show the demographic projections for the four SSPs scenarios for the world and for different regions, respectively. The projected population density (persons/km^2) and the corresponding variations (compared to the situation in the 2010s) in four SSP scenarios are shown in Figure S26. Combined with demographic projections, the exposure concentration can be estimated and used to assess the $PM_{2.5}$ exposure associated health impacts.[69, 70]

Figure 4 shows the projected $PM_{2.5}$ exposure concentrations in several representative regions (North America, South America, Europe, Africa, the Middle East, Russia and Economies in Transition [EIT], Asia, and the rest of the world) under the various SSP scenarios. The region boundaries are shown in Figure S27. Overall, $PM_{2.5}$ exposure is highest in the SSP3-7.0 scenario and lowest in the SSP1-2.6 scenario for the major representative regions of the world, although the main drivers for the projected outcomes differ.

In Europe and North America, where $PM_{2.5}$ concentrations will be relatively low, the population distribution is the main determinant of $PM_{2.5}$ exposure. Spatially-averaged $PM_{2.5}$ concentrations will be lower in the SSP5-8.5 scenario owing to the stronger pollution control measures than in the “middle of the road” SSP2-4.5 scenario, but the population-weighted $PM_{2.5}$ concentrations in SSP5-8.5 will slightly exceed those of SSP2-4.5 and even surpass those of SSP3-7.0 after the 2060s. These trends will be caused by the higher birthrate in Europe and North America in SSP5-8.5 driven by economic optimism and international migration, leading to accelerated population growth in these two regions (Figures S25 and S28).[71] This implies that a greater share of the population will be concentrated in areas with higher levels of social development and education. Therefore, compared with SSP2-4.5, the SSP5-8.5 scenario will result in a higher population-weighted $PM_{2.5}$ exposure in North America and Europe after the 2060s.

In both Asia and Africa, $PM_{2.5}$ exposure will decline steadily over time, reaching −58.2% (−47.3%) and −52.5% (−32.0%) for Asia (Africa) by the end of the century under the SSP1-2.6 and SSP5-8.5 scenarios, respectively, compared with the baseline period. However, there will be no significant decline under the SSP3-7.0 scenario, and before the 2060s, the exposure levels will be even higher than in the baseline period. Two explanations can be offered for the persistently high exposure concentrations in Asia and Africa under the SSP3-7.0 scenario. The emissions and unfavorable meteorological factors will lead to increased $PM_{2.5}$ pollution under this scenario before the 2030s. Meanwhile, population increase due to high fertility accompanied by slow urbanization in these regions will intensify the density of urban and rural settlement patterns, thereby increasing $PM_{2.5}$ exposure.[71]

The proportion of the population that would be exposed to the $PM_{2.5}$ concentration below previous and current Air Quality Guideline (AQG) values is also estimated under future climate change scenarios. As shown in Figure S29, the differences between SSP1-2.6 scenario and the other three scenarios are considerable. Compared with the other three scenarios, SSP1-2.6 would result in the largest fraction of the population exposed to the $PM_{2.5}$ level that is lower than 5 μg/m³. In the SSP1-2.6 scenario, 3.5% of the world’s population will live in areas that have $PM_{2.5}$ concentrations lower than 5 μg/m³ by 2100, which is well above the baseline (2.0%). The other scenarios are comparable in terms of the proportion of the population exposed to the $PM_{2.5}$ concentration that is below the current AQG values.

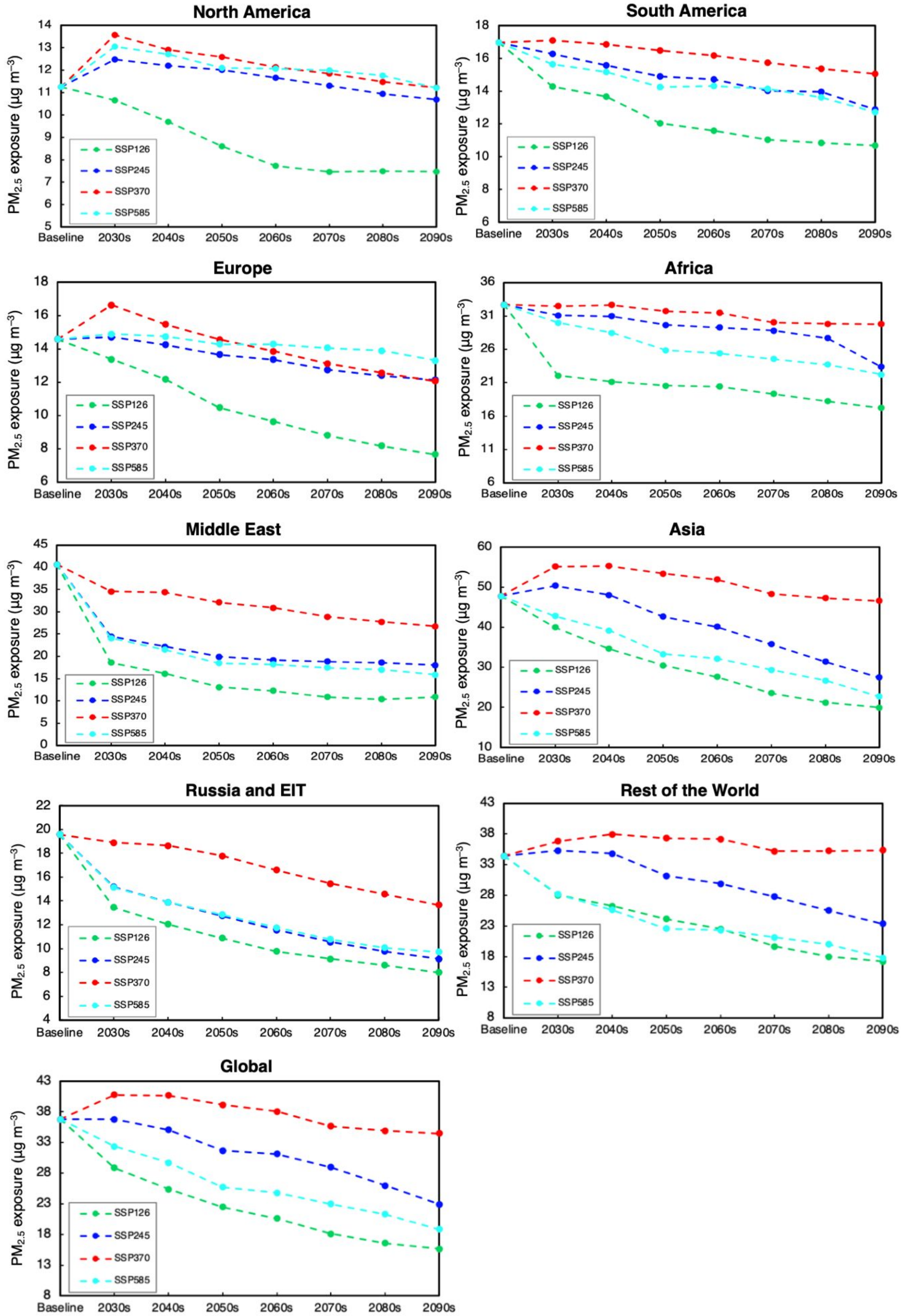

Figure 4. Projected ambient $PM_{2.5}$ exposure concentrations for 2030–2100 under different climate change scenarios.

3.4. Projection of premature mortality burden

The global premature mortality burden associated with future $PM_{2.5}$ concentrations under the different SSP scenarios was also analyzed. Figure 5 shows the $PM_{2.5}$-associated premature deaths for the baseline (2010–2019) and future (2030–2100) periods in several representative regions. The green growth and sustainable development assumptions in the SSP1-2.6 scenario would lead to a rapid reduction in air pollution emissions globally. Therefore, the number of $PM_{2.5}$-associated premature deaths worldwide would start to decline in the near future (2031–2040) before the population growth turning point (2071–2080). Given the middle-road development pattern of SSP2-4.5, premature deaths in this scenario would peak at 9,024,000 (95% Confidence Interval (CI): 6,352,000–11,236,000) in the 2060s and then steadily decline to 7,394,000 (95% CI: 5,202,000–9,291,000) in the final decade of the century, which is a less rapid decline than in the SSP1-2.6 scenario. SSP3-7.0 assumes weak pollution control in which the implementation of pollution mitigation measures is delayed and less ambitious in the long term. In this scenario, premature deaths would spike dramatically in all regions except North America, Europe, and Russia and would not decrease until the end of the century. The global number of $PM_{2.5}$-associated premature deaths would reach 11,149,000 (95% CI: 7,877,000–13,800,000) in 2091–2100, an increase of 63% from the baseline period. In the SSP5-8.5 scenario, which emphasizes technological progress and rapid economic growth through human capital development, environmental issues become a priority health concern, and ambitious air quality goals result in pollutant levels well below current levels in the medium to long term.[16, 72] Therefore, in SSP5-8.5, global premature deaths would peak at 8,509,000 (95% CI: 5,981,000–10,617,000) in the 2040s and then decline to 6,258,000 (95% CI: 4,410,000–7,887,000) in the second half of the 21st century as high-performance pollution control technologies are developed. This decrease would result in a smaller premature death burden than in the baseline period.

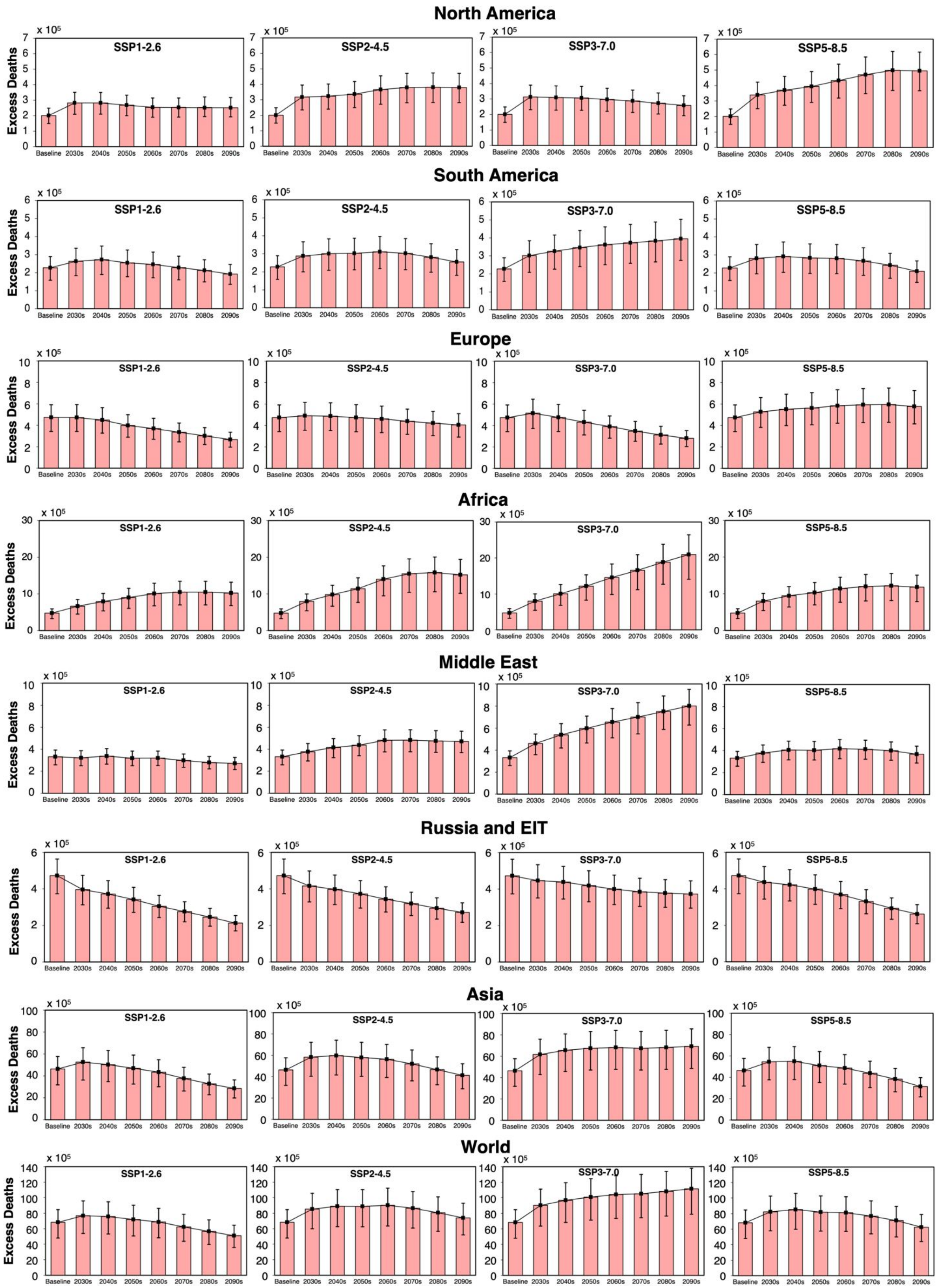

Figure 5. PM$_{2.5}$-associated premature deaths (> 25 years old) in different regions. The red bars represent premature deaths, and the vertical black lines indicate the 95% empirical confidence intervals.

Because the size of the population will determine the absolute number of premature deaths, country-specific mortality rates per 100,000 people were used to describe the $PM_{2.5}$-associated mortality burden. Figure S30 shows the mortality rate per 100,000 people for 184 countries or districts. Overall, countries in North America, Western Europe, and Oceania will have the lowest mortality rates. The mortality rates in Eastern European countries (e.g., Ukraine and Serbia) will be the highest, followed by some countries in Asia, such as China and India.

3.5. Key factors that influence the premature mortality burden

Two sensitivity studies were conducted to explore how future population distributions and $PM_{2.5}$ concentrations would affect the burden of $PM_{2.5}$-associated premature mortality (Table S8). In the first sensitivity experiment (SA1), the only contributor to the difference in the estimated premature deaths from the baseline period is the demographic transition, while the contributor to the difference in the second sensitivity experiment (SA2) is the $PM_{2.5}$ variation.

When considering only the future demographic projections (i.e., demographic changes and changes in total population by age), the changes in the population distribution over the coming decades (2021–2040) will exacerbate the burden of premature deaths in all four scenarios, but the magnitude of the effect differs among the scenarios. These differences are reflected in the demographic assumptions about the birthrate, mortality, and migration.[73] SSP1-2.6 and SSP5-8.5 both envision a development path of increased investment in education and health, thereby accelerating the demographic transition.[71] Therefore, in these two scenarios, the demographic turning point in population decline will be reached earlier, in the medium term (2050s) (Figure S25), after which the impact of demographics on the burden of premature mortality will gradually decrease.

In the second sensitivity experiment, we explore the effect of the $PM_{2.5}$ concentration on premature mortality assuming a constant future population distribution and size. Disease burden alleviation resulting from implementing air pollution control measures will become apparent in the near future under the SSP1-2.6 and SSP5-8.5 scenarios. SSP1-2.6 is the only scenario in which the effect of the $PM_{2.5}$ concentration will be greater than the effect of population size by the end of the century. Rapidly declining emissions would successfully offset the burden of premature mortality resulting from population growth by the end of the century. Under the SSP3-7.0 scenario, the planetary boundary layer height (PBLH) exerts strong influence on $PM_{2.5}$ dispersion, and thus its decreases in East Asia, South Asia, and eastern Africa (Figure S10) will increase the $PM_{2.5}$ concentrations. Besides PBLH, other meteorological conditions, such as higher temperature,[74] are also favorable for $PM_{2.5}$ accumulation in these regions and therefore exacerbate the $PM_{2.5}$-associated mortality burden until the 2050s.

3.6. Implications and limitations

Global climate change is a significant challenge for society, and its impact on future air pollution is a critical perspective that requires quantitative assessment. Herein, a global $PM_{2.5}$ concentration dataset with a spatial resolution of 0.1° × 0.1° was estimated based on SSP scenarios.

From the methodology and dataset perspectives, this work provides a new set of global-scale future $PM_{2.5}$ dataset in 10km spatial resolution. This dataset can be used by others for air quality-related studies at the national and even regional scales. The dataset can be downloaded from the link listed in Text S8. The method developed in this work can also be implemented for other air pollution-related research. Researchers can further develop other more advanced deep learning frameworks for relevant studies based on the design of the method proposed in this work.

From the results perspective, this work has quantified how the future $PM_{2.5}$ and its associated adverse health impacts will change based on different SSP scenarios. Based on our results, governments and relevant stakeholders from different countries can generally understand to what extent can $PM_{2.5}$ influence their specific local health burdens. This can provide useful scientific references for future air pollution control policy design. In addition, when other studies come out in the future, the results from this work can also be used for the comparison. For example, compared to the adverse effects caused by other pollutants, such as O_3, which pollutant should the government put onto the priority position under different SSP scenarios.

From the health-economic impact perspective, the results of economic burdens shed light on the relationship between mortality cost that is associated with $PM_{2.5}$ pollution and economic development in various countries under different future scenarios. The economic burdens related to future $PM_{2.5}$ pollution are discussed in Text S9. Figure S31 and Figure S32 show the economic loss that is associated with $PM_{2.5}$-related health burdens. For most OECD countries, China, and Central Asia, air pollution mitigation and economic development can have a beneficial synergistic effect. The ratio of economic loss associated with $PM_{2.5}$ pollution over the total GDP (PPP based) is minimal in the sustainable development scenario (SSP1-2.6). For Central Africa and South America, from $PM_{2.5}$ associated economic loss perspective, these countries may consider choosing SSP2-4.5 pathway as their development modes.

This work has some limitations. First, satellite-retrieved $PM_{2.5}$ datasets were used as training targets, but according to the results in Table S6, there were discrepancies with the observational data obtained from ground measurements. Second, future climate, emission, and population projections harbor relatively large uncertainty, even if they have been calibrated against observed patterns of changes using historical data.[23, 71] Third, there are no generalizable and accurate findings that indicate how baseline mortality rates will change in the future. Therefore, in accordance with previous studies[75, 76] in the projection literature, we assumed that the nonlinear relationship between $PM_{2.5}$ concentrations and the baseline mortality rate would also be consistent. Fourth, the $PM_{2.5}$ projections derived in this study were based on several underlying assumptions. Primarily, in line with previous works,[75, 76] the relationships between $PM_{2.5}$ concentrations and meteorological conditions and precursor emissions explored in this study were assumed to be true for future climate and emissions scenarios. Fifth, our predictions were based on the premise that the world is steadily developing, and our method cannot predict the effects of uncontrollable factors (such as war and strong earthquakes) on $PM_{2.5}$ and population distributions. Finally, the biases in emissions data (e.g., bias in future wildfires and missing windblown dust), can be directly propagated to the air pollution concentration estimation. Thus, $PM_{2.5}$ projections in this work contain unavoidable uncertainty. The spatial pattern of windblown dust was not included in this study, which may have an influence on our results, especially for the Sahara and Middle East. Given the proximity of these regions to large sources of dust emissions, there is a possibility that an underestimation of $PM_{2.5}$ concentrations would occur in these regions. However, the impact on the mortality estimations is limited since these regions are more sparsely populated. Despite these limitations, this work helps quantify the extent to which climate change will influence $PM_{2.5}$ concentrations worldwide. The results can contribute to the ongoing assessment of $PM_{2.5}$-associated exposure and vulnerability under different climate change scenarios, and governments can use this information to design useful strategies to reduce pollution.

Acknowledgment

The work described in this paper was supported by National Natural Science Foundation of China (Project No. 42007203), Guangzhou Scientific and Technological Planning Project (Project No. 202102021297), the Research Grants Council of Hong Kong Government (Project No.16305921), the Environment and Conservation Fund (ECF 2020123), and a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project Nos. AoE/E-603/18 and T31-603/21-N).

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