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Projecting Fine Particulate Matter-related Mortality in East China

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Abstract:

China is suffering from severe air pollution from fine particulate matter [≤2.5μm in aerodynamic diameter ($PM_{2.5}$)], especially East China. But its future trends and potential health impacts remain unclear. The study objectives were to project future trends of $PM_{2.5}$ and its short-term effect on mortality in East China by 2030. First, daily changes in $PM_{2.5}$ concentrations between 2005 and 2030 were projected under "current legislation" scenario (CLE) and "maximum technically feasible reduction" scenario (MFR). Then, they were linked to six population projections, two mortality rate projections, and $PM_{2.5}$-mortality associations to estimate the changes in $PM_{2.5}$-related mortality in East China between 2005 and 2030. Under the CLE scenario, the annual mean $PM_{2.5}$ concentration was projected to decrease by 0.62μg/m^3 in East China, which could cause up to 124, 000 additional deaths, when considering the population growth. Under the MFR scenario, the annual mean $PM_{2.5}$ concentration was projected to decrease by 20.41μg/m^3 in East China. At least 230, 000 deaths could be avoided by such a large reduction in $PM_{2.5}$ concentration under MFR scenario, even after accounting for the population growth. Therefore, our results suggest that reducing $PM_{2.5}$ concentration substantially in East China would benefit the public health. Otherwise, it may still remain as a big health risk in the future, especially when the population keeps growing.

Key words: Fine Particulate Matter, Mortality, Emissions, Projection, China

Introduction:

Fine particulate matter [≤2.5μm in aerodynamic diameter ($PM_{2.5}$)] is among the most important air pollutants.[1-5] Evidence from epidemiological and toxicological studies has consistently linked $PM_{2.5}$ exposure to adverse health outcomes, especially, mortality. A recent study reported that 3, 223, 540 deaths were attributed to $PM_{2.5}$ worldwide in 2010. [6]

$PM_{2.5}$ can originate from natural sources, like forest fires and wind erosion, and from human activities, like coal burning, agricultural practices, mobile source emissions, and construction.[1] The concentration of $PM_{2.5}$ depends on both emissions and meteorological parameters. Increased emissions of primary $PM_{2.5}$ and precursors of secondary $PM_{2.5}$ will result in increased concentration of $PM_{2.5}$.[7] On the other hand, the $PM_{2.5}$ concentration could be scavenged by precipitation.[8]

Given that climate and emission levels may change in the future, there is growing interest in studying the potential effect of future weather patterns and emission levels on $PM_{2.5}$ levels, and its subsequent impact on public health.[9] Several studies projected the concentrations of $PM_{2.5}$ and related mortality in the future under a changing climate and emission levels on different spatial scales, ranging from a region to the globe.[9] According to global projections, the largest increased air pollutants-related mortality is more likely to happen in those areas with large precursor’s emissions and/or tropical and/or rapidly growing area, such as Eastern United States, central Africa, and Asia.[10, 11] These regions are highly populated and hence, increases in air pollutants’ levels will substantially impact human health.[11] However, compared with developed counties, there is less evidence on such issue in the developing regions with large emissions and dense population, for instance, China.[9]

From January to March in 2013, China experienced extremely severe and persistent haze pollution, affecting 1.3 million km^2 and 800 million people.[12] In order to cope with severe air pollution, the central government of China issued a comprehensive air pollution prevention and control plan (Document NO. GUOFA[2013]37) in September, 2013 for three key regions in East China (Beijing-Tianjin-Hebei, Yangtze River Delta (YRD) and Pearl River Delta (PRD)) and 10 cities clusters across China. [13]

East China, the most developed and densely populated area in China, is experiencing serious air pollution and its health impacts.[14-17] Due to an increasing trend of rural-urban migration of labour force and families in China, the population sizes in East China will continue to increase in the future.[18] Hence, even a slight increase in $PM_{2.5}$ levels in the future may lead to a substantial excess mortality. In addition, there is evidence that air pollution in China is influencing not only local or regional, but also the global atmospheric conditions and the subsequent public health.[19, 20] Thus, it is important to investigate what will happen in the future trends of $PM_{2.5}$ concentration and its related health impact in East China. Our study aims to answer these two research questions, which will undoubtedly help decision makers both in East China and other developing regions in planning emission control legislation and reducing future health risks of air pollution.

Method:

Study area:

East China is most developed and densely populated area in China.[21, 22] Based on the general classification of different regions of National Bureau of Statistics of China, East China in our study includes Beijing, Tianjin, Hebei, Liaoning, Shandong, Jiangsu, Zhejiang, Shanghai, Guangdong, Fujian, and Hainan.

Our study was designed to project future $PM_{2.5}$-related mortality in each province and municipality in East China. Figure 1 illustrates the basic structure of our analysis. Projecting $PM_{2.5}$-related mortality involves assumptions on future $PM_{2.5}$ concentration, population, mortality rate and $PM_{2.5}$-mortality associations, which may have many uncertainties. Thus, instead of relying on only one set of assumptions, we estimated the possible ranges of potential future outcomes for $PM_{2.5}$-related total, cardiovascular and respiratory mortality, by allowing different assumptions on emission scenario, population, mortality rate, and $PM_{2.5}$-mortality associations.

Projection of future $PM_{2.5}$ concentrations:

We jointly used global scale chemical transport model (CTM) and regional scales chemical transport modelling system to estimate $PM_{2.5}$ concentration. The daily mean $PM_{2.5}$ concentrations for 2005 and 2030 were calculated to estimate $PM_{2.5}$-related mortality.

The global CTM (MIROC-ESM-CHEM [23]) was used to simulate the global scale distribution of $PM_{2.5}$ with the horizontal grid spacing of 300km × 300km. The 6-hourly output of meteorological variables and daily output of chemical variables from MIROC-ESM-CHEM were then introduced as the boundary conditions for regional chemical transport modelling system which was composed of regional weather and air quality models: the Weather Research and Forecasting model (WRF) [24] and the Community Multiscale Air Quality model (CMAQ) ,[25] respectively. The regional chemical transport modelling system could simulate $PM_{2.5}$ concentrations at a horizontal resolution of 80 km. The $PM_{2.5}$ in CMAQ was composed of sulphate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), black carbon (BC), organic aerosols (OAs), and some other minor components. The CTMs calculate the atmospheric concentrations of each $PM_{2.5}$ species, considering the amount of those species or their precursors emitted into the atmosphere, transport by atmospheric motion, bunch of chemical reactions, and deposition process onto the earth's surface.

The global and regional modelling system were performed under the following scenarios developed by the International Institute of Applied Systems Analysis (IIASA).[26] Each of them projects a scenario for the emissions of primary $PM_{2.5}$ and sources of secondary $PM_{2.5}$ (including nitrogen oxides (NO_x), volatile organic compounds (VOCs), sulphur dioxide (SO_2), etc.), based on the social and economic assumptions described below:

(a) The "current legislation" scenario (CLE): it takes into consideration of the current economic development and the anticipated effects of presently decided emission control legislation on province and mega-cities levels based on the Tenth Plan (2001-2005) of the Five-Year Plans of China (FYP).

(b) The "maximum technically feasible reduction" scenario (MFR): it takes into account the emission reduction through a full implementation of the best available emission control technologies based on the Tenth Plan (2001-2005) of the FYP, regardless of the cost.

The CLE and MFR scenarios were used to project the $PM_{2.5}$ concentration in 2030. By adopting emission levels and economic developments in 2005, a present day scenario (year 2005) was used to simulate $PM_{2.5}$ concentration in 2005.

Population projections:

To explore the sensitivity of $PM_{2.5}$-related mortality to assumptions about the exposed population, six population projections were selected for our analysis: a) the first was the population for each province and municipality collected from statistical yearbook for 2005, and we assumed no change in populations from 2005 to 2030; b) the other five were selected from the IIASA regional population projections under five scenarios - L1, L2, C, H1, and H2 - to provide lower, central and higher bound for regional population projections in 2030 on a provincial or municipality's scale. These scenarios were developed based on assumptions on fertility, mortality, migration and urbanization: a) L1: low fertility, low mortality, low migration, and low urbanization; b) L2: low fertility, low mortality, low migration and high urbanization; c) C: central fertility, central mortality, central migration, and median urbanization; d) H1: high fertility, high mortality, high migration and low urbanization; e) H2: high fertility, high mortality, high migration and high urbanization. The details for the IIASA regional population projections were described elsewhere.[27]

Mortality rate projections:

Two projections of total mortality rate for each province and municipality were selected for analysing the sensitivity of $PM_{2.5}$-related mortality to assumptions about the mortality rate: a) firstly, we simply used the total mortality rate for year 2005, and assumed no change in mortality rate from 2005 to 2030; b) secondly, we used the IIASA regional total mortality rate projections in 2030 on a provincial and municipality's scale, which were described in detail elsewhere.[27] Briefly, changing trends in annual regional total mortality rate from 1965 to 2000 were used to develop logistic approximations. The parameters from the logistic approximations with the best fitness were treated as input parameters for the logistic forecasting model to project total mortality rate in 2030 for each region.

For cardiovascular and respiratory mortality rates, because there is no such projection by the IIASA, we assumed no change in the cardiovascular and respiratory mortality rates from 2005 to 2030.

The data on mortality rates for year 2005 were collected from statistical yearbook for 2005 in each province and municipality. The annual mortality rate was converted evenly to a daily rate.

The $PM_{2.5}$-mortality associations (Concentration-response function (CRF)):

The $PM_{2.5}$-mortality association is expressed as CRF, which is an estimate of the percentage change in daily mortality due to a change in daily $PM_{2.5}$ concentration (Δx), derived from the log-linear function: [28]

$$\mathrm{CRF} = e^{\beta \Delta x} - 1$$

Where β is the regression coefficient slope of $PM_{2.5}$ concentration.

Several studies have been conducted in China to investigate the relationships between $PM_{2.5}$ and mortality. The studies conducted in East China were collected. Then a meta-analysis was used to pool averaged associations of $PM_{2.5}$ with total, cardiovascular and respiratory mortality from these studies. The details of the meta-analysis were described in Supporting Information.

Seven studies were included in our meta-analysis (Table S1). Because one of them was conducted in three cities, including Beijing, Shanghai and Shenyang, there are nine estimates for CRF in total: five for Shanghai, two for Shenyang, and one for each of Beijing and Guangzhou. Thus, except from using pooled CRF for every province and municipality, we pooled local CRF specifically for Shanghai from five studies in Shanghai, and applied it as the second choice on CRF for Shanghai. We used CRFs reported in two studies conducted in Beijing and Guangzhou as the second choice for Beijing and Guangdong Province, respectively. We also applied CRFs from those two studies conducted in Shenyang as second and third choice on CRF for Liaoning Province.

Projection of $PM_{2.5}$-related mortality:

The changes in $PM_{2.5}$-related mortality between 2005 and 2030 in each province and municipality were evaluated as: [28]

$$M = M_0 \times P \times CRF \times C,$$

where M is the estimated number of daily mortality due to changes in daily $PM_{2.5}$ concentration; M_0 is the baseline regional level daily mortality rate; P is the regional level population; CRF is the concentration-response function, which is described above; C is daily $PM_{2.5}$ concentrations, which is interpolated from $PM_{2.5}$ concentration modelling system. The daily $PM_{2.5}$-related deaths were estimated to calculate the annual $PM_{2.5}$-related mortality in 2005 and 2030, respectively. No threshold was assumed for $PM_{2.5}$-mortality associations.

The source of uncertainty

In order to investigate which factor has the largest effect on the estimated changes in $PM_{2.5}$-related total mortality and explore the source of the greatest uncertainty of the final results, analysis of variance was conducted for each region, which decomposed the total variability due to the choices on emission scenarios for projecting $PM_{2.5}$ concentration, total mortality rate, population, CRF and interaction between these modelling choices, respectively. Because there are more than one choice on CRF for Beijing, Shanghai, Liaoning and Guangdong, CRF was only included in the analysis of variance for these regions.

Package “metafor” in R3.1.1 was used to conduct meta-analysis. Packages “fields” and “ggplot2” in R3.1.1 were used to plot figures.

Results:

Changes in $PM_{2.5}$ concentration:

The annual mean $PM_{2.5}$ concentration in East China was projected to decrease by 0.62μg/m^3 under the CLE scenario and 20.41μg/m^3 under the MFR scenario between 2005 and 2030, respectively.

A regional variation was observed in changes of annual mean $PM_{2.5}$ concentrations between 2005 and 2030 among different regions under each scenario (Figures 2 and 3). Under the CLE scenario, the geographical distribution of simulated $PM_{2.5}$ levels indicates that annual mean $PM_{2.5}$ concentrations would increase in most part of Beijing-Tianjin-Hebei, Liaoning and Shanghai, but decrease significantly in Jiangsu, small part of south-western Shandong and southern Hebei by 2030 (Figure 2). Under the MFR scenario, though $PM_{2.5}$ levels simulated to decrease in general across East China, average $PM_{2.5}$ levels would decrease substantially in Jiangsu, most part of western Shandong and southern Hebei by 2030 (Figure 3).

Table 1. The methodological choices for estimating changes in $PM_{2.5}$-related mortality between 2005 and 2030

Region	∆ $PM_{2.5}$ (µg/m^3)		CRF for total mortality (%) (95%CI)		CRF for CVM (%) (95%CI)		CRF for RM (%) (95%CI)		Total mortality rate (1/1000)		CVM rate (1/1000)	RM rate (1/1000)	Population (*10,000)					
	CLE	MFR	CRF1*	CRF2**	CRF1*	CRF2**	CRF1*	CRF2**	Year 2005	Year 2030	Year 2005	Year 2005	Year 2005	C	L1	L2	H1	H2
Beijing	2.53	-11.94	0.44 (0.22,0.66)	0.53 (0.37,0.69)	0.55 (0.25,0.85)	0.58 (0.34,0.82)	0.66 (0.24,1.08)	0.66 (0.21,1.11)	5.2	5.2	2.47	0.53	1538	2206.2	1897.6	2471	1919.1	2496.9
Shanghai	0.29	-28.18	0.44 (0.22,0.66)	0.38 (0.08,0.67)	0.55 (0.25,0.85)	0.46 (0.02,0.90)	0.66 (0.24,1.08)	0.65 (0.01,1.28)	6.08	9.5	2.58	0.94	1890	2493.9	2110.2	2830.8	2131.7	2857.7
Liaoning	2.38	-15.53	0.44 (0.22,0.66)	0.35 (0.17,0.53)	0.55 (0.25,0.85)	0.46 (0.19,0.73)	0.66 (0.24,1.08)	0.29 (-0.29,0.87)	6.04	7.1	2.64	0.5	4221	4196.5	4165.7	4095.1	4239.9	4168.0
Jiangsu	-5.09	-33.4	0.44 (0.22,0.66)	-	0.55 (0.25,0.85)	-	0.66 (0.24,1.08)	-	7.03	7	1.85	0.63	7588	7849.2	7603.2	7851	7741.4	7990.7
Zhejiang	-1.93	-20.32	0.44 (0.22,0.66)	-	0.55 (0.25,0.85)	-	0.66 (0.24,1.08)	-	6.08	6	1.65	1	4991	5564.4	5252.6	5712.5	5344	5808.2
Fujian	-2.76	-12.47	0.44 (0.22,0.66)	-	0.55 (0.25,0.85)	-	0.66 (0.24,1.08)	-	5.62	6	1.87	0.49	3557	4424	4233	4456.6	4329.3	4555.4
Tianjin	1.72	-28.8	0.44 (0.22,0.66)	-	0.55 (0.25,0.85)	-	0.66 (0.24,1.08)	-	6.01	7	3.08	0.67	1043	1217	1128.3	1270.8	1147.3	1291.1
Hebei	0.06	-22.27	0.44 (0.22,0.66)	-	0.55 (0.25,0.85)	-	0.66 (0.24,1.08)	-	6.75	6.1	1.6	0.37	6851	7605.7	7502.8	7431.9	7668.7	7596.0
Shandong	-2.52	-30.5	0.44 (0.22,0.66)	-	0.55 (0.25,0.85)	-	0.66 (0.24,1.08)	-	6.31	6	2.59	0.85	9248	9984.4	9794	9830.8	9996.1	10031.9
Guangdong	-0.74	-11.25	0.44 (0.22,0.66)	0.90 (0.55,1.25)	0.55 (0.25,0.85)	1.22 (0.63,1.81)	0.66 (0.24,1.08)	0.97 (0.16,1.78)	4.68	5.2	2.23	1.42	9194	16597.7	14562.2	18012.9	14935.3	18439.6
Hainan	-0.75	-7.41	0.44 (0.22,0.66)	-	0.55 (0.25,0.85)	-	0.66 (0.24,1.08)	-	5.72	5.4	3	0.49	828	1079.9	1037.6	1073.9	1068.5	1105.2

*The pooled CRF of nine estimates from seven studies conducted in East China.

**The regional CRF for Shanghai, Beijing, Guangdong and Liaoning. CRF2 for Shanghai is the pooled CRF from five studies conducted specifically in Shanghai; CRF2 for Beijing and Guangdong are the reported CRF from two studies conducted in Beijing and Guangzhou, respectively. Specifically, there are two studies conducted in Shenyang in Liaoning province. So the CRFs from these two studies were applied as the second and third choice on CRF for Liaoning Province. The second choice on CRF is shown as CRF2 in this Table. The third choice on CRF for Liaoning province was shown as below: CRF for total mortality: 0.49 (0.19, 0.79); CRF for CVM: 0.53 (0.09, 0.97); CRF for RM: 0.97 (0.01, 1.93).

Abbreviations:

CLE, “Current legislation” scenario; CRF, Concentration-response function; CVM, Cardiovascular mortality; MFR, “Maximum feasible reduction” scenario; RM, Respiratory mortality.

Changes in $PM_{2.5}$-related mortality:

As shown in Figure 1, combining changes in daily mean $PM_{2.5}$ concentration with two total mortality rate projections (only one assumption on cardiovascular and respiratory mortality rate, respectively), six population projections, and one to three choices on CRF (Table 1), we produced 6-36 potential projection answers under both CLE and MFR scenarios, to the following question: how many death cases for $PM_{2.5}$-related total, cardiovascular and respiratory mortality could be caused or avoided under different scenarios in East China by 2030?

Figure 4 summarizes the projection results on $PM_{2.5}$-related mortality in East China, using CRF1 from the meta-analysis. Under the CLE scenario, $PM_{2.5}$-related mortality was projected to decrease by approximately 20, 000 cases in East China when assuming the static mortality rate and population between 2005 and 2030, while increase up to 124, 000 cases when accounting for population growth. Under the MFR scenario, $PM_{2.5}$-related mortality was projected to decrease by at least 230, 000 cases in East China under any assumptions on population, due to the substantial reduction in $PM_{2.5}$ concentration.

Figure 5 and Figure 6 show the ranges of percent changes in $PM_{2.5}$-related mortality in East China, including results in each province and municipality. The ranges of estimated $PM_{2.5}$-related mortality (cases) were summarized in Table S3. Due to regional variation of changes in $PM_{2.5}$ concentrations and other modelling factors, the results on $PM_{2.5}$-related mortality varied spatially among different regions. Under the CLE scenario, positive ranges of percent changes in $PM_{2.5}$-related mortality were observed in Beijing, Tianjin, Hebei, Liaoning and Shanghai, mainly due to the projected increase in $PM_{2.5}$ concentrations. For the other regions, the percent changes of $PM_{2.5}$-related mortality showed a wide range with positive and negative responses, because of the slight reduction of $PM_{2.5}$ concentrations under the CLE scenario and growing population. Under the MFR scenario, negative ranges of percent changes in $PM_{2.5}$-related mortality were observed for each region, mainly due to the substantial reduction of $PM_{2.5}$ concentration.

The source of uncertainty:

Different choices on the modelling factors for the risk assessment model (Table S2), including changes in $PM_{2.5}$ concentration, population, mortality rate and CRF, as well as the different combination of these factors could yield different results. The results of the analysis of variance show that emission scenarios were the major source of uncertainty. Generally, population assumption was the second major source of uncertainty.

Discussion:

In this study, we estimated the changes in $PM_{2.5}$ concentration and its related total, cardiovascular, respiratory mortality between 2005 and 2030 in East China under the CLE and MFR scenarios. By combining all modelling choices on population, mortality and CRF, there are 6-36 projection results on $PM_{2.5}$-related mortality under each scenario.

Changes in $PM_{2.5}$ concentration:

The annual mean $PM_{2.5}$ concentration was projected to decrease slightly under the CLE scenario but substantially under the MFR scenario in East China between 2005 and 2030. The different results under the CLE and MFR scenarios could be explained by different assumptions on future social and economic situations adopted in the CLE and MFR scenario. The CLE scenario takes into account both the emission control legislation in the "Tenth Five Year Plan (2001-2005)" and the current economic development in China, while the MFR scenario assumes that more aggressive legislations or technologies are employed without considering the economic cost. Thus, as would be expected, air pollution from $PM_{2.5}$ could be remarkably improved across East China under the MFR scenario. In addition, it has been reported that $PM_{2.5}$ concentration decreased slightly between 2005 and 2010 in East China, which reflects the projected decreasing trend of $PM_{2.5}$ concentration under the CLE scenario in our study. [29]

Despite the slight reduction in annual mean $PM_{2.5}$ concentration in whole East China under the CLE scenario, results varied spatially among regions. The annual mean $PM_{2.5}$ concentration was projected to increase in Beijing-Tianjin-Hebei, Liaoning, and Shanghai, but decrease in other regions. In order to further explore the possible reason for the regional variation, we analysed the changes in $PM_{2.5}$ compositions between 2005 and 2030. During the "Tenth Five Year Plan" period, efforts were focused on reducing and controlling the emission of SO_2. SO_2 is the precursor of SO_4^{2-} — the most important contributor to secondary $PM_{2.5}$ in China. [30] Hence, the reduction in SO_2 emission may help control $PM_{2.5}$ levels. However, our results illustrate that the concentration of SO_4^{2-} will increase in Beijing-Tianjin-Hebei, Liaoning and Shanghai, while decrease in the other regions between 2005 and 2030 under the CLE scenario (Figure S1). Thus, it indicates that the proposed emission control legislation on SO_2 in the "Tenth Five Year Plan" is not sufficient to improve air pollution from SO_4^{2-} in Beijing-Tianjin-Hebei, Liaoning and Shanghai while it could help control SO_4^{2-} levels in other regions in East China. In addition, the increase of $PM_{2.5}$ concentrations in Beijing-Tianjin-Hebei, Liaoning and Shanghai under the CLE scenario depicted in Figure 2 is not solely attributable to the increase of SO_4^{2-} there, but other $PM_{2.5}$ species such as NO_3^- and NH_4^+ [31] would also increase there (Figure S2). It suggests that the emissions of the precursor of these species-NO_x and ammonia (NH_3)-need to be controlled in Beijing-Tianjin-Hebei, Liaoning and Shanghai to alleviate $PM_{2.5}$ concentrations.

Beijing-Tianjin-Hebei and Liaoning are located in north of Huai River, which always suffer from coal burning-related air pollution. China's Huai River policy, which provided free winter heating via the provision of coal for boilers in cities north of Huai River but denied heat to the south, had a serious impact on air quality in northern China.[32] Air quality of Beijing, Tianjin, Hebei and Liaoning is often deteriorated by the dust or even dust storm mostly from Inner Mongolia, especially in spring.[33] For example, most northern areas in China were affected by a massive dust storm in mid-April, 2015. [34] In addition, Beijing-Tianjin-Hebei area is surrounded by Yanshan and Taihang Mountains, with a dry climate and low precipitation, which can hamper the diffusion of air pollutants. However, unlike Beijing-Tianjin-Hebei and Liaoning, the southern China suffers less from coal and dust-related air pollution. The climatic conditions are more favourable for the diffusion of air pollutants. A slight increase in $PM_{2.5}$ concentration between 2005 and 2010 was reported in most parts of Hebei and Liaoning while a reduction in other regions in East China, which partly reflects the projected results of regional $PM_{2.5}$ concentration in our study. [29]

In this study, Shanghai is the only city in the southern part of East China where $PM_{2.5}$ level was projected to increase under the CLE scenario. It may be because that air pollution in Shanghai is worse than other regions in southern part of East China, due to its higher anthropogenic emission levels and larger vehicle stocks.[35] In addition, the air quality in Shanghai could also be affected by the transported air pollutants from north-western China during winter and spring. [36, 37]

Thus, in order to improve the air quality from $PM_{2.5}$ in Beijing-Tianjin-Hebei, Liaoning and Shanghai, the government should target major air pollution emission sources, and take much stricter emission control policies in these regions.

Changes in $PM_{2.5}$-related mortality:

Under the CLE scenario, $PM_{2.5}$-related mortality in East China was projected to decrease without considering population growth between 2005 and 2030 but increase when accounting for population growth, because the absolute numbers of $PM_{2.5}$-related mortality are a strong function of population. Due to the increasing $PM_{2.5}$ concentration projected in Beijing, Tianjin, Hebei, Liaoning and Shanghai under the CLE scenario, $PM_{2.5}$-related mortality was projected to increase in these regions even when assuming the static population between 2005 and 2030. However, due to the substantial reduction in $PM_{2.5}$ concentration under the MFR scenario, $PM_{2.5}$-related mortality was projected to decrease in East China (including every region) under different assumptions on population growths. Our results indicate that $PM_{2.5}$ concentration should be reduced substantially to control its health impact on public health. Otherwise, it may still remain as a severe health risks in the future.

To data, air pollution-related health impacts have been projected by several studies in China.[20, 38-41] The main characteristics of these studies were summarized in Table S4. Although scenarios vary among studies, the importance of controlling air pollution in East China has been demonstrated by these studies.[20, 38-41] However, these studies were all conducted in a single city, which is difficult to generalize. In addition, most of previous studies projected PM_{10} and SO_2-related health impacts. Only Wang and Mauzerall[20] estimated health benefit of controlling $PM_{2.5}$ by two emission control technologies in 2020 in Zaozhuang. However, they projected $PM_{2.5}$ concentrations for four months in each season (January, April, July and October) and used average concentrations of four months to represent the annual level. In this study, daily $PM_{2.5}$ concentration was used to obtain the annual level and project its health impact. Therefore, this study has advanced the knowledge in this important field.

The source of uncertainty:

In our study, we found that the source of the greatest uncertainty of regional changes in $PM_{2.5}$-related total mortality was the emission scenarios for projecting $PM_{2.5}$ concentration. Similar results have been reported by Post, et al. [42] However, a recent projection study on O_3-related mortality in U.S. found that the greatest source of uncertainty varied among regions: emission scenarios in some states while population in other states.[43] In this study, population assumptions were found to be the second greatest source of uncertainty. Thus, uncertainties of air pollutant-related mortality may be mainly attributed to scenarios and population, which may vary among different regions. Therefore, an ensemble of estimates based on a range of different methodological choices on the regional level, especially scenarios and population, is preferred. [42, 43]

The progress and challenge of controlling $PM_{2.5}$:

The air pollution and emission control strategies in China are changing rapidly, due to the increasing public health concern. More stringent and strengthened air pollution and emission control plan has been introduced in the 12th FYP, [13] which includes ambient air quality concentration targets for the first time and the emission reduction from vehicles by phasing-out heavily-polluted vehicles and supplying cleaner gasoline and diesel from 2013 to 2017. However, the compelling pressure from economic growth may make it difficult to put these environmental policies into practice. [44-46]

In our study, when considering the economic development in the future, $PM_{2.5}$ was projected to decrease slightly under the CLE scenario, which is, however, not enough to reduce its health risk, due to the growing population. As projected under the MFR scenario, if the priority has been given to air pollution control without considering economic development, air pollutant levels would decrease remarkably. However, the economic development will still be the main focus of the government for the next 15-20 years [21] Therefore, reducing $PM_{2.5}$ concentration as it was projected under MFR scenario is quite arduous. On the other hand, developed economics could provide sufficient financial support for implementation of emission control and air pollution prevention plans, e.g., the application of flue gas desulfurization in the power industry. In other words, the performance of air pollutants reduction can be improved by the economic development. Therefore, in order to reduce health risks of air pollution while developing the economics at the same time, a well-balanced air pollution and emission control strategies are essential.

Strengths and limitations:

To the best of our knowledge, this is the first study to project $PM_{2.5}$-related mortality for each province and municipality in East China, by using local health data (including population, mortality and CRF).

Several projection studies on the global and Asian scales found increased national $PM_{2.5}$-related mortality across China in the future.[10, 11, 47] However, these studies did not consider regional population and mortality projections, and applied CRF derived from other countries to China, which might underestimate or overestimate the final outcomes. The CLE and MFR emission scenarios in our study included emission control legislations in each province and megacity in China, which could better simulate and reflect these legislations' impact on $PM_{2.5}$ levels on a regional scale. In addition, six projections on the population size and two projections on total mortality for each province and municipality were included in our projection to cover the possible range of potential final results. Instead of adopting CRF derived from other countries, we collected studies regarding $PM_{2.5}$-mortality associations in

East China and obtained an averaged CRF for East China, which could better reduce the uncertainty of final results.

Several limitations of our study should be acknowledged. The main limitation of our projection is the coarse horizontal resolution of the simulation of $PM_{2.5}$ concentrations, which may not be able to simulate $PM_{2.5}$ levels precisely. Using a present day simulation later than year 2005 would be beneficial for reducing the uncertainties of $PM_{2.5}$ projections. In addition, current air quality models, including CMAQ used in our study, can underestimate $PM_{2.5}$ concentrations. [48, 49] Thus, the health impact of $PM_{2.5}$ may be underestimated in our study. We did not consider the age distribution in our study, which is important when evaluating the health impact of air pollution. Compared with younger people, the elderly may have higher mortality rate [50] and be more vulnerable to air pollution. [51, 52] For example, a 33% increase in the burden of disease attributable to ambient air pollution in China from 1990 to 2010 was partly attributed to the increased rates of cardiovascular disease in China's rapidly aging population.[50] Furthermore, nearly 35% of the population is expected to be 60 or older in 2050 in China.[53] Thus, our results may underestimate the future health impact of air pollution. In addition, due to the lack of data, we assumed static cardiovascular and respiratory mortality rate in 2030, and did not consider the possible change of CRF. We did not consider the long-term effect of $PM_{2.5}$ on mortality. Thus, our estimates may understate the possible range of potential future outcomes. Future studies need to be conducted on these issues.

Although $PM_{2.5}$ levels are projected to decrease in many regions in 2030 under CLE and MFR scenarios, one issue still remains to be investigated- whether or not $PM_{2.5}$ levels will meet the air quality standard of China in the future. The research priority in the future should also be given to the comprehensive analysis on the cost and economic impacts of air-quality-related health damages/benefits of different emission and air pollution control strategies, with information on how different assumptions could result in uncertainties of the estimates. Such research could provide decision-makers important evidence on the cost and benefit of different policies.

Conclusion:

In summary, the annual mean $PM_{2.5}$ concentration in East China between 2005 and 2030 was projected to decrease by 0.62μg/m^3 under the CLE scenario and 20.41μg/m^3 under MFR scenario. The slight reduction in $PM_{2.5}$ concentration under the CLE scenario would lead to an increase in $PM_{2.5}$-related total mortality up to 124, 000 cases under the CLE scenario, when accounting for the population growth. However, the substantial reduction in $PM_{2.5}$ concentration under the MFR scenario would avoid at least 230, 000 total mortality cases, even when considering the population growth. Thus, in order to reduce health risk of $PM_{2.5}$ in East China, more stringent emission control legislations are required for a substantial reduction in $PM_{2.5}$ concentrations. Otherwise, the health impact of control legislations will be offset by the population growth.

Supporting Information Available

Detailed information for the meta-analysis and risk assessment models, and additional tables and figures for the discussion. This material is available free of charge via the Internet at http://pubs.acs.org.

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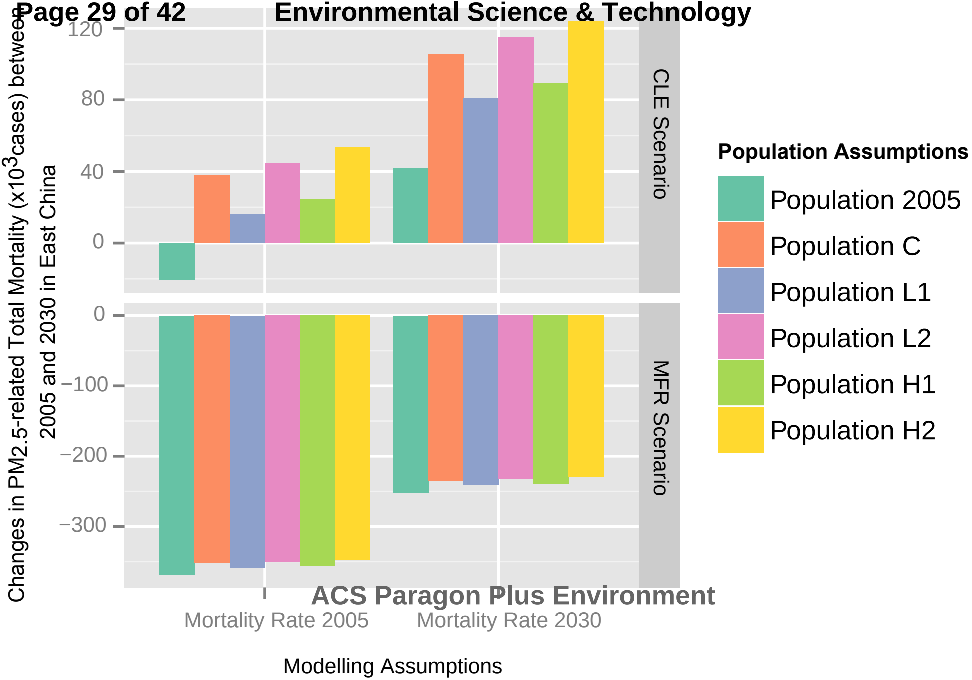
Abstract Art


Changes in PM2.5-related Total Mortality (x10^3 cases) between 2005 and 2030 in East China
120
80
40
0
−100
−200
−300
CLE Scenario
MFR Scenario
Mortality Rate 2005
Mortality Rate 2030
Modelling Assumptions
Population Assumptions
Population 2005
Population C
Population L1
Population L2
Population H1
Population H2

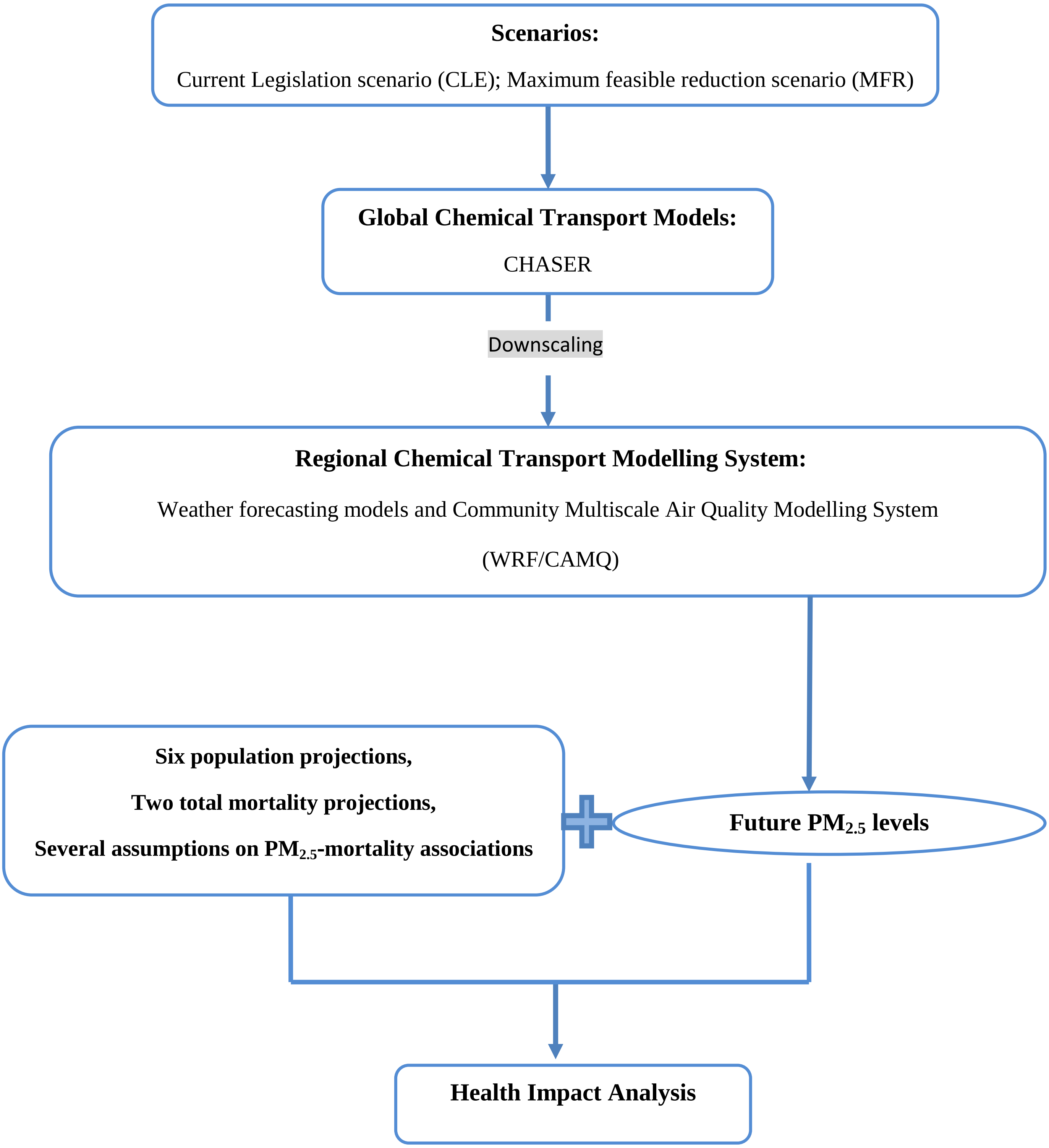
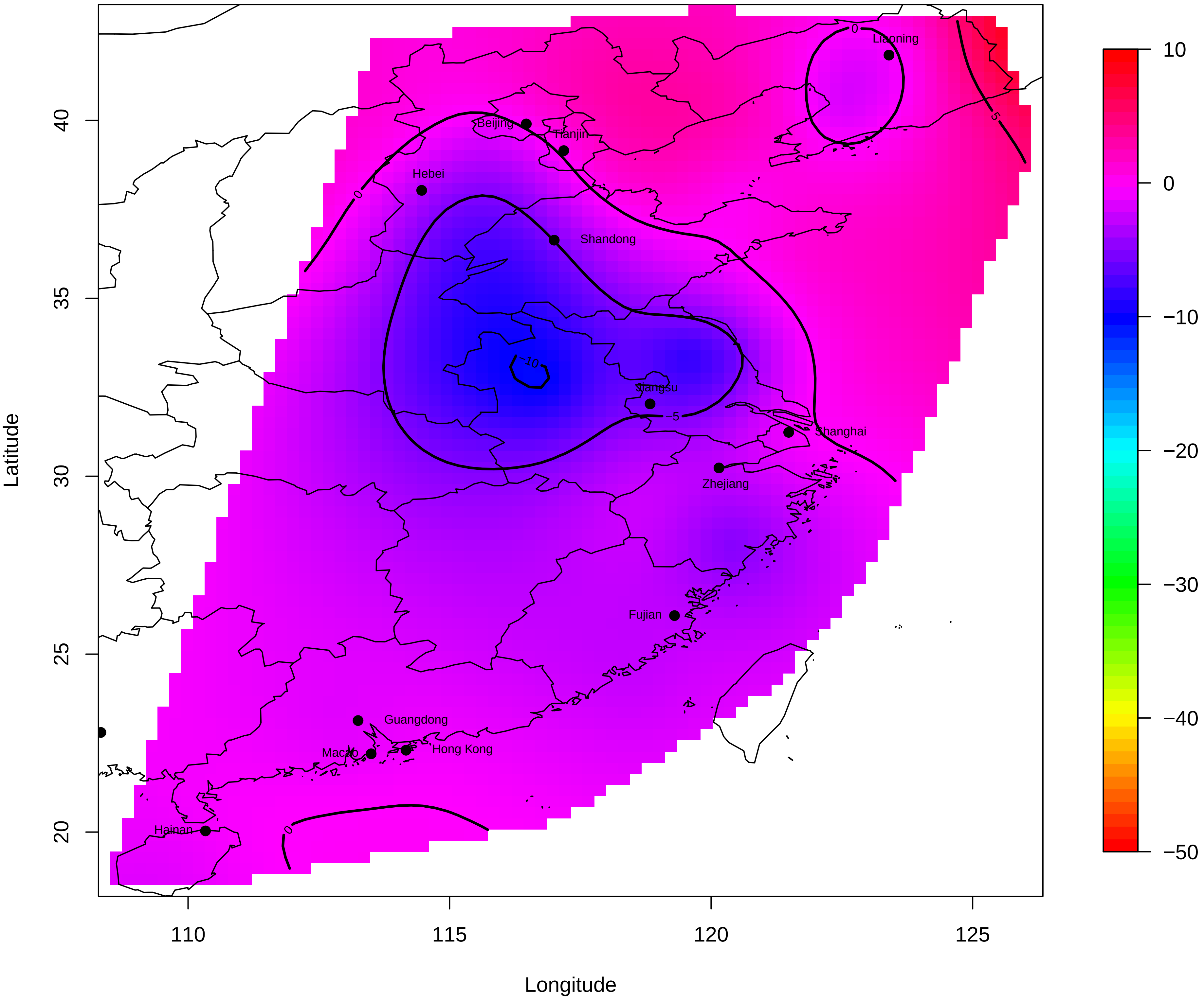

Scenarios:
Current Legislation scenario (CLE); Maximum feasible reduction scenario (MFR)
Global Chemical Transport Models:
CHASER
Downscaling
Regional Chemical Transport Modelling System:
Weather forecasting models and Community Multiscale Air Quality Modelling System (WRF/CAMQ)
Six population projections,
Two total mortality projections,
Several assumptions on $PM_{2.5}$-mortality associations
Future $PM_{2.5}$ levels
Health Impact Analysis

Figure 1. The structure of data analysis of $PM_{2.5}$ -related mortality in the future


Latitude
Longitude
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115
120
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10
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Beijing
Tianjin
Hebei
Shandong
Liaoning
Jiangsu
Shanghai
Zhejiang
Fujian
Guangdong
Macao
Hong Kong
Hainan
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−5
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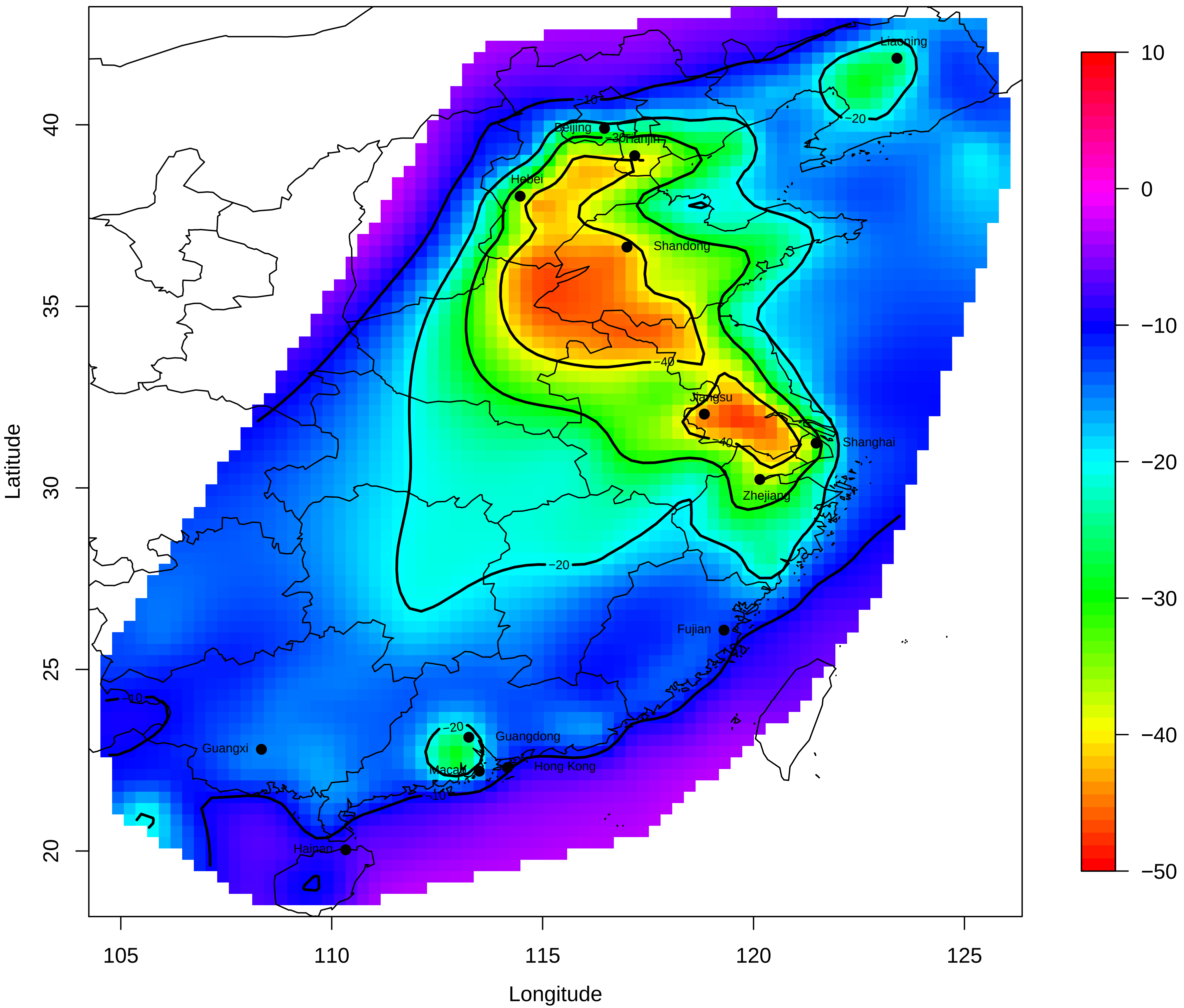
5

Figure 2. The changes in annual mean of daily $PM_{2.5}$ concentrations between 2005 and 2030 under the CLE scenario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Jiangsu
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Zhejiang
Fujian
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Guangxi
Hainan
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Latitude
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110
115
120
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Longitude
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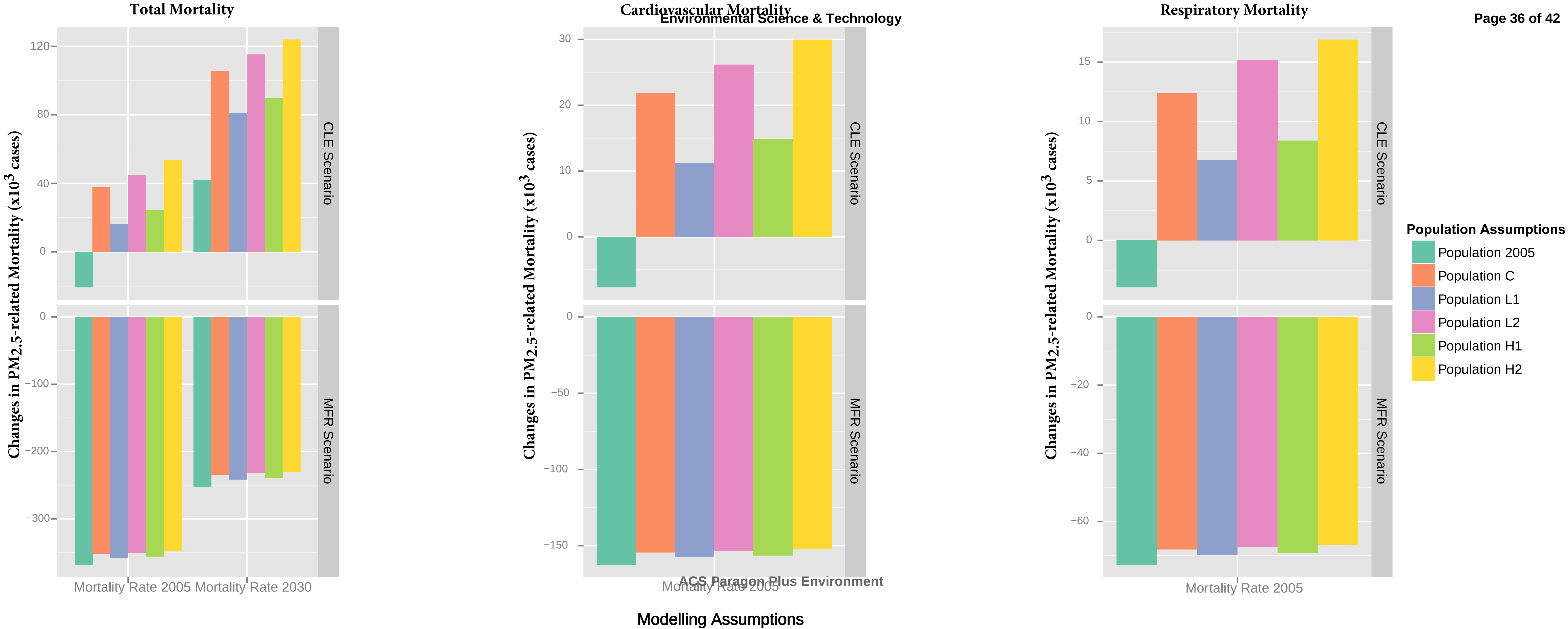
Figure 3. The changes in annual mean of daily $PM_{2.5}$ concentrations between 2005 and 2030 under the MFR scenario


Total Mortality
Cardiovascular Mortality
Respiratory Mortality
Changes in PM$_{2.5}$-related Mortality (x10^3 cases)
120
80
40
0
−100
−200
−300
30
20
10
0
−50
−100
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10
5
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−40
−60
CLE Scenario
MFR Scenario
Mortality Rate 2005
Mortality Rate 2030
Modelling Assumptions
Population Assumptions
🟩 Population 2005
🟧 Population C
🟦 Population L1
🟪 Population L2
🟩 Population H1
🟨 Population H2

Figure 4. The changes in $PM_{2.5}$-related mortality between 2005 and 2030 in East China under the CLE and MFR scenarios (CRF1 from the meta-analysis)

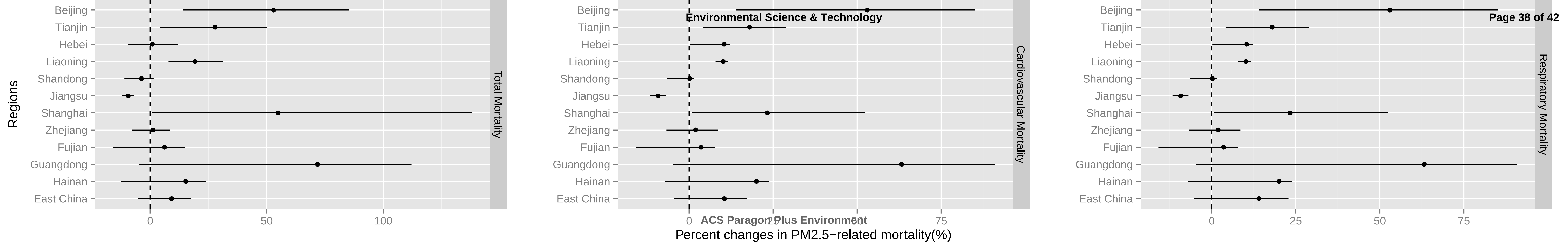

Regions
Beijing
Tianjin
Hebei
Liaoning
Shandong
Jiangsu
Shanghai
Zhejiang
Fujian
Guangdong
Hainan
East China
0
50
100
Total Mortality
0
25
50
75
Cardiovascular Mortality
0
25
50
75
Respiratory Mortality
Percent changes in PM2.5−related mortality(%)

Figure 5. The ranges of percent change in $PM_{2.5}$-related mortality between 2005 and 2030 in East China under the CLE scenario, including results in each province and municipality

(The dot is the medium value of the percent changes in $PM_{2.5}$-related mortality. The horizontal line is the range of percent changes in $PM_{2.5}$-related mortality.)

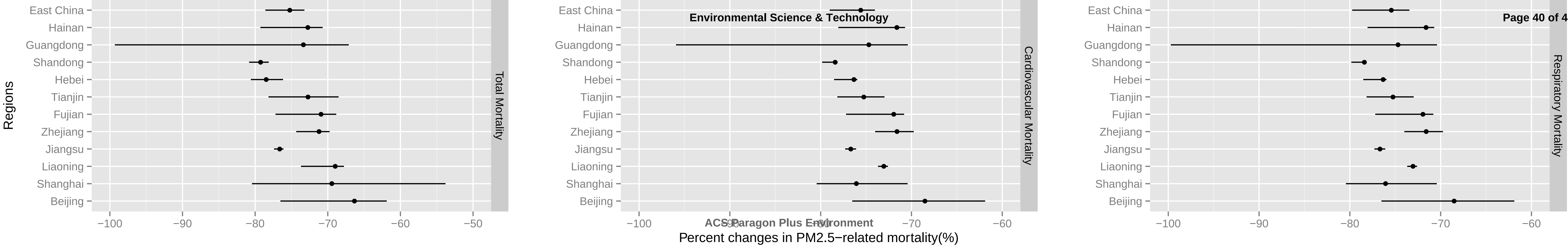
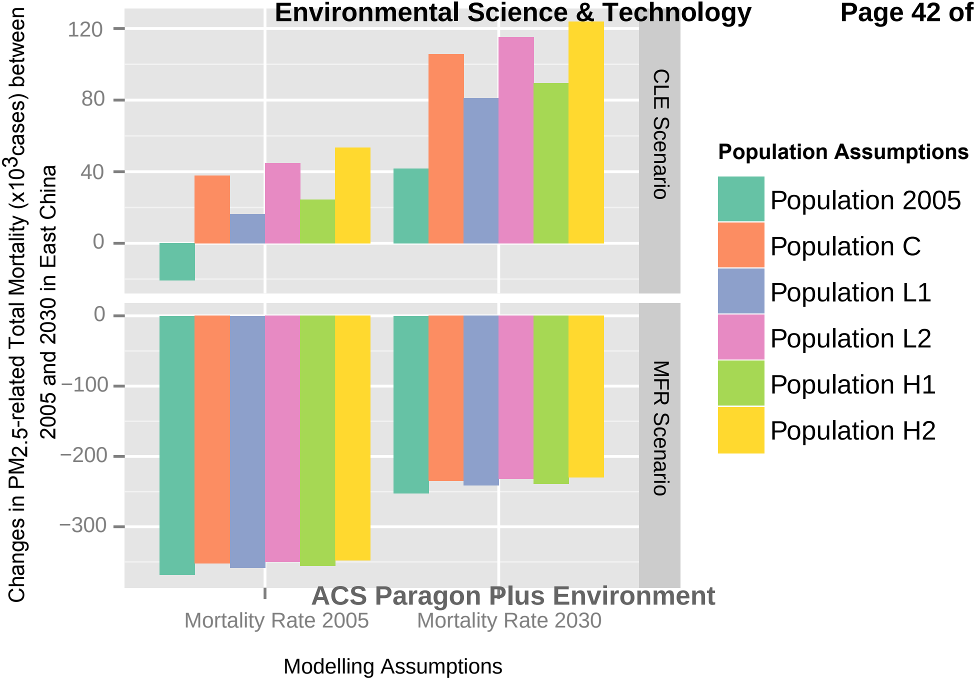

Regions
East China
Hainan
Guangdong
Shandong
Hebei
Tianjin
Fujian
Zhejiang
Jiangsu
Liaoning
Shanghai
Beijing
Total Mortality
Cardiovascular Mortality
Respiratory Mortality
−100
−90
−80
−70
−60
−50
Percent changes in PM2.5−related mortality(%)

Figure 6. The ranges of percent change in $PM_{2.5}$-related mortality between 2005 and 2030 in East China under the MFR scenario, including results in each province and municipality (The dot is the medium value of the percent changes in $PM_{2.5}$-related mortality. The horizontal line is the range of percent changes in $PM_{2.5}$-related mortality.)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Mortality Rate 2005
Mortality Rate 2030
Modelling Assumptions
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Population 2005
Population C
Population L1
Population L2
Population H1
Population H2