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Evaluation of Premature Mortality Caused by Exposure to $PM_{2.5}$ and Ozone in East Asia: 2000, 2005, 2020

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Abstract The aim of this study is to assess the premature mortality risks caused by exposure to particulate matter with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) and ozone elevated concentrations for the years 2000, 2005, and 2020 in East Asia. The spatial distributions and temporal variations of $PM_{2.5}$ and ozone concentrations are simulated using the Models-3 Community Multiscale Air Quality Modeling System coupled with the Regional Emission Inventory in Asia. The premature mortality risks caused by exposure to $PM_{2.5}$ and ozone are calculated based on a relative risk (RR) value of 1.04 (95 % confidence interval (CI): 1.01–1.08) for $PM_{2.5}$ concentrations above the annual mean limit of 10 μg m^{-3} taken from the World Health Organization–Air Quality Guideline and based on a RR value of 1.003 (95 % CI: 1.001–1.004) for ozone concentration above 35 ppb of the SOMO35 index (the sum of ozone daily maximum 8-h mean concentrations above 35 ppb). We demonstrate one of the implications of the policy making in the area of environmental atmospheric management in East Asia by highlighting the annual premature mortalities associated with exposure to $PM_{2.5}$ concentrations that just meet an annual mean concentration of 10 μg m^{-3}, as well as ozone concentrations that have a daily zero SOMO35 index in vulnerable places. Our results point to a growing health risk that may endanger human life in East Asia. We find that the effect of $PM_{2.5}$ on human health is greater than the effect of ozone for the age group of 30 years and above. We estimate the corresponding premature mortality due to the effects of both ozone and $PM_{2.5}$ in East Asia for the years 2000 and 2005 to be around 316,000 and 520,000 cases, respectively. For future scenarios of the year 2020, policy succeed case, reference, and policy failed case, the estimated annual premature mortality rates are 451,000, 649,000, and 1,035,000 respectively.

Keywords East Asia · Premature mortality · Ozone · $PM_{2.5}$ · Relative risk · SOMO35

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1 Introduction

In recent years, the environmental risks caused by exposure to particulate matter with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) and ozone in East Asia have been increasing annually. The management of these risks requires a multidisciplinary regional atmospheric management that is based on science–policy interactions. The primary and secondary $PM_{2.5}$ and ozone originating from primary sources in East Asia, which remain suspended for hours to days and can travel long distances, endanger local and regional receptors. According to China Statistical Year Book (1999–2007), respiratory diseases, which are affected by air pollution, caused 19.5 and 14.6 % of the total deaths in rural and urban areas, respectively. Further, according to the annual reports of the Ministry of Health, Labor and Welfare in Japan (2008), respiratory diseases in prefectures located along the Sea of Japan, such as Niigata and Shimane, caused 10–15 % of all deaths. Therefore, attempts to quantify health and ecosystem impacts caused by exposure to $PM_{2.5}$ and ozone making use of the available emission inventories and emission reduction scenarios, are viewed as an efficient tool to draw the attention of policy makers and to protect the environment for the coming generations (Cohen et al. 2005; Mauzerall et al. 2005; Wang and Mauzerall 2006; Tong et al. 2006; Osada et al. 2009; Liu et al. 2009; Saikawa et al. 2009; Zhou et al. 2010, Aikawa et al. 2010).

Positive correlations and statistically significant relationships have been identified between $PM_{2.5}$ concentrations and premature mortality, lung cancer, and reduced lung function in human populations (Pope et al. 2002; Pope and Dockery 2006; Lippmann 2009). Similarly, statistically significant relationships have been identified between elevated concentrations of ozone and premature mortality (WHO 2008; Lippmann 2009). However, the spatial variability, and the fact that there are no thresholds for mortality and morbidity caused by exposure to $PM_{2.5}$ and ozone, complicate the process of establishing clear well-defined standards and exposure guidelines that can be realized from the World Health Organization (WHO); the US Environmental Protection Agency (USEPA) guidelines and standards of $PM_{2.5}$; 25/10 (WHO 2005) and 35/15 (USEPA 2010) [daily mean (μg m^{-3})/annual mean limit (μg m^{-3})]; and the Japanese environmental quality standards (35/15), respectively. The USEPA 35/15 guidelines were discussed during the 2010 public meeting of the USEPA–Clean Air Scientific Advisory Committee. Also, there were requests to assess the environmental risks caused by levels of $PM_{2.5}$ below an annual mean of 15 μg m^{-3}, and also to consider the effect of high relative humidity (>90 %) on the reliability of the measured concentrations (USEPA 2010). In addition, a recent study done by White (2009) showed that an enhanced spatial resolution of $PM_{2.5}$ and ozone may have a limited value for health risk assessments unless there is enhanced chemical resolution provided by measurements of additional species (e.g., sulfur dioxide, SO_2).

The available knowledge about concentration–response (CR) relationships of $PM_{2.5}$, as reviewed by Pope and Dockery (2006) and Cohen et al. (2005), was limited to concentrations around 7.5–30 μg m^{-3} for all causes of mortality and morbidity risks. Therefore, we limit our analysis to concentrations 10 μg m^{-3} and above. On the other hand, due to the lack of comprehensive epidemiological studies on $PM_{2.5}$ effects on human health for all age groups in East Asia, we use the adjusted mortality relative risk (RR, 1.04; 95 % confidence interval (CI): 1.01–1.08) associated with a 10 μg m^{-3} change in $PM_{2.5}$ mean annual concentration from Pope et al. (2002) to estimate the number of premature deaths only for the age group of 30 years and above. Human health risks from ozone exposure are calculated based on a RR value of 1.003 (0.3 % increase in daily premature mortality caused by a 10 μg m^{-3} change in concentration above 70 μg m^{-3}; 95 % CI: 1.001–1.004; WHO 2005, 2008). However, the available dose–response functions for $PM_{2.5}$ and ozone do not consider combined effects from exposure to different pollutants simultaneously because the health effects such as respiratory diseases may be caused by simultaneous exposure to particulate matters, SO_2, smoking, and other air pollutants. However, in China, the main SO_2 emissions have been decreasing annually due to flue-gas desulfurization installations in power plants (Lu et al. 2010), accordingly, the future health impacts caused by SO_2 could be limited.

During the past 10 years, there were many studies on $PM_{2.5}$ and ozone effects on human health (see Table 1): (1) Cohen et al. (2005) estimated the concentrations of $PM_{2.5}$ using the available information on geographic variation in the $PM_{2.5}/PM_{10}$; (2) Wang and Mauzerall (2006) evaluated the effect of the 2020 $PM_{2.5}$ emissions in China on public health there; (3) Saikawa et al. (2009) and Liu et al. (2009) evaluated the effects of Asia's emissions of sulfur dioxide, sulfate, and organic and

Table 1 Characteristics of the modeling systems used to estimate the effects of ozone and $PM_{2.5}$ on human health in East Asia

Reference	Models	Grid size [resolution×height (m)]	Emission inventory (resolution in degrees)	Relative risk (RR) source	Simulated years
Wang and Mauzerall (2006)	CMAQ	China: 12×12 km×18	SMOKE (1×1): CO, NH_3,NO_x, NMVOC, SO_2, $PM_{2.5}$, PM_{10}	$PM_{2.5}$ (Pope et al. 2002)	2000, 2020
Saikawa et al. (2009)	MOZART-2	Global: 1.9 latitude×1.9 longitude×120	Based on REAS (0.5×0.5): SO_2, OC, BC	$PM_{2.5}$ (Pope et al. 2002)	2000, 2030
Anenberg et al. (2010)	MOZART-2	Global: 2.8 latitude×2.8 longitude×120	O_3, OC, NH_4, NO_3, SO_4	$PM_{2.5}$ (Krewski et al. 2009) O_3 (Jerrett et al. 2009)	Preindustrial, 2000
Liu et al. (2009)	MOZART-2	Global: 2.8 latitude×2.8 longitude×120	Based on RAINS-ASIA methodology: (1×1): sulfate, BC, OC, fine mineral dusts	$PM_{2.5}$ (Pope et al. 2002)	2000
This study	CMAQ/REAS	East Asia: 0.7×0.7×150	REAS: (0.5×0.5): O_3, OC, EC, NH_4, NO_3, SO_4	$PM_{2.5}$ (Pope et al 2002) O_3 (WHO)	2000, 2005, 2020

black carbons on global premature mortality rates; (4) Anenberg et al. (2010) evaluated the global mortality caused by long-term exposure to ozone and $PM_{2.5}$ for the year 2000. However, in this study, we consider achieving a daily zero SOMO35 index (sum of the daily maximum 8-h mean concentrations above 35 ppb) for ozone and the WHO-Air Quality Guideline (AQG) for $PM_{2.5}$ (10 μg m^{-3} annual mean), which is the lowest level at which total, cardiopulmonary, and lung cancer mortality have been shown to increase with more than 95 % confidence in response to long-term exposure to $PM_{2.5}$ (WHO 2005), in assessing the transboundary health risks in East Asia caused by ozone and the following $PM_{2.5}$ components: elemental carbon (EC), organic carbon (OC), nitrate (NO_3^-), sulfate (SO_4^{2-}), and ammonium (NH_4^+). We use the SOMO35 index in our evaluations of the human health risks in East Asia because it was found by Ellingsen et al. (2008) that this index was the most robust indicator for ozone in global model calculations.

The spatiotemporal concentrations of the components of $PM_{2.5}$ were simulated by Uno et al. (2005), Kurokawa et al. (2009), and Yamaji et al. (2008) using the Models-3 Community Multiscale Air Quality Modeling System coupled with the Regional Emission Inventory in Asia (CMAQ/REAS) for the years 1980–2020. REAS is the only emission inventory in East Asia for the years 1980–2020 based on a consistent methodology. It includes the following emissions: SO_2, NO_x, CO, NMVOC, black carbon (BC), and OC from fuel combustion and industrial sources. The simulated $PM_{2.5}$ spatial distributions and temporal variations indicate that $PM_{2.5}$ in China is dominated by sulfate. Also, the $PM_{2.5}$ 24-h mean guideline, 25 μg m^{-3} (WHO 2005), is increasingly exceeded within the simulation domain. The ozone spatial distributions and temporal variations by CMAQ/REAS indicate that elevated ozone concentrations, 55 ppb and above, in China, DPR Korea and Republic of Korea are obviously increasing, and the annual averages exceed 50 ppb (daily maximum 8-h mean concentrations, WHO-AQG; WHO 2005). Also, the hourly elevated concentrations exceed the Japanese air quality hourly standard (60 ppb). The CMAQ/REAS simulations show that the daily maximum 8-h mean concentration of 35 ppb is exceeded in many places in East Asia. Also, the monitored concentrations of ozone have been increasing annually. At the Banryu ozone monitoring station in Japan, the numbers of hours exceeding 35 ppb for the years 2001–2005 were 4,226, 3,864, 3,717, 4,426, and 4,523 h, respectively. Accordingly, the findings of this study are proposed to be a step toward a better understanding of the health impact of $PM_{2.5}$ and ozone in East Asia. We also show the predicted health effects based on different emission reduction scenarios in 2020.

2 Methodology

2.1 CMAQ/REAS Modeling System

The CMAQ/REAS modeling system is used to simulate the spatial distributions and temporal variations of $PM_{2.5}$ components and ozone for the simulation domain shown in Figs. 1 and 2. The ozone and $PM_{2.5}$ concentrations were simulated by Uno et al. (2005) and Kurokawa et al. (2009) for the years 2000 and 2005 and by Yamaji et al. (2006 and 2008) for the year 2020 scenarios using the three-dimensional regional-scale chemical transport model, based on the CMAQ ver. 4.4 released by the USEPA. This model is driven by the meteorological field simulated by the Regional Atmospheric Modeling System (RAMS) ver. 4.3 (for the year 2020) and ver. 4.4 (for the years 2000–2005). The grid resolution is 80×80 km, 14 layers for 23 km in the sigma-*z* coordinate system, and the height of the first layer is 150 m. In this modeling system, the Statewide Air Pollution Research Center-99 scheme was used for gas chemistry (including more than 214 chemical reactions). For aerosol concentrations, the third-generation CMAQ aerosol module (AERO3) was used. The initial and boundary conditions of the RAMS were obtained from the National Center of Environmental Prediction/National Center for Atmospheric Research. The initial and boundary conditions have a resolution of 2.5×2.5° and temporal resolution of 6 h. This dataset includes meteorological parameters that were previously validated. The initial conditions of the chemical transport modeling were obtained from the CHemical AGCM for Study of atmospheric Environment and Radiative forcing for the simulation period from 2000 to 2005. However, for future scenarios, the default values were used.

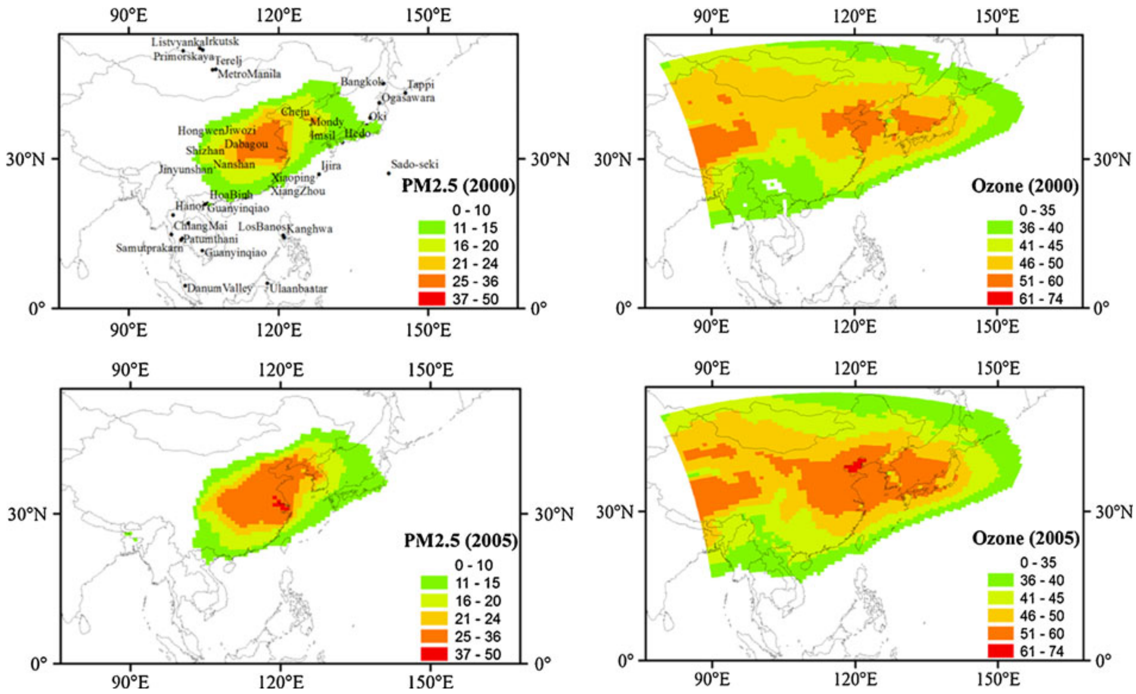

Fig. 1 $PM_{2.5}$ and ozone annual mean concentrations (μg m^{-3}, ppb) in East Asia for the years 2000 and 2005 within the CMAQ simulation domain; 6,240×5,440 km^2 on a rotated polar stereographic map projection centered at 25 N, 115 E, with a grid size of 80×80 km in the ground surface layer, which is 150 m high. *Solid circles* in the $PM_{2.5}$ maps are the locations of the Acid Deposition Monitoring Network in East Asia (EANET)

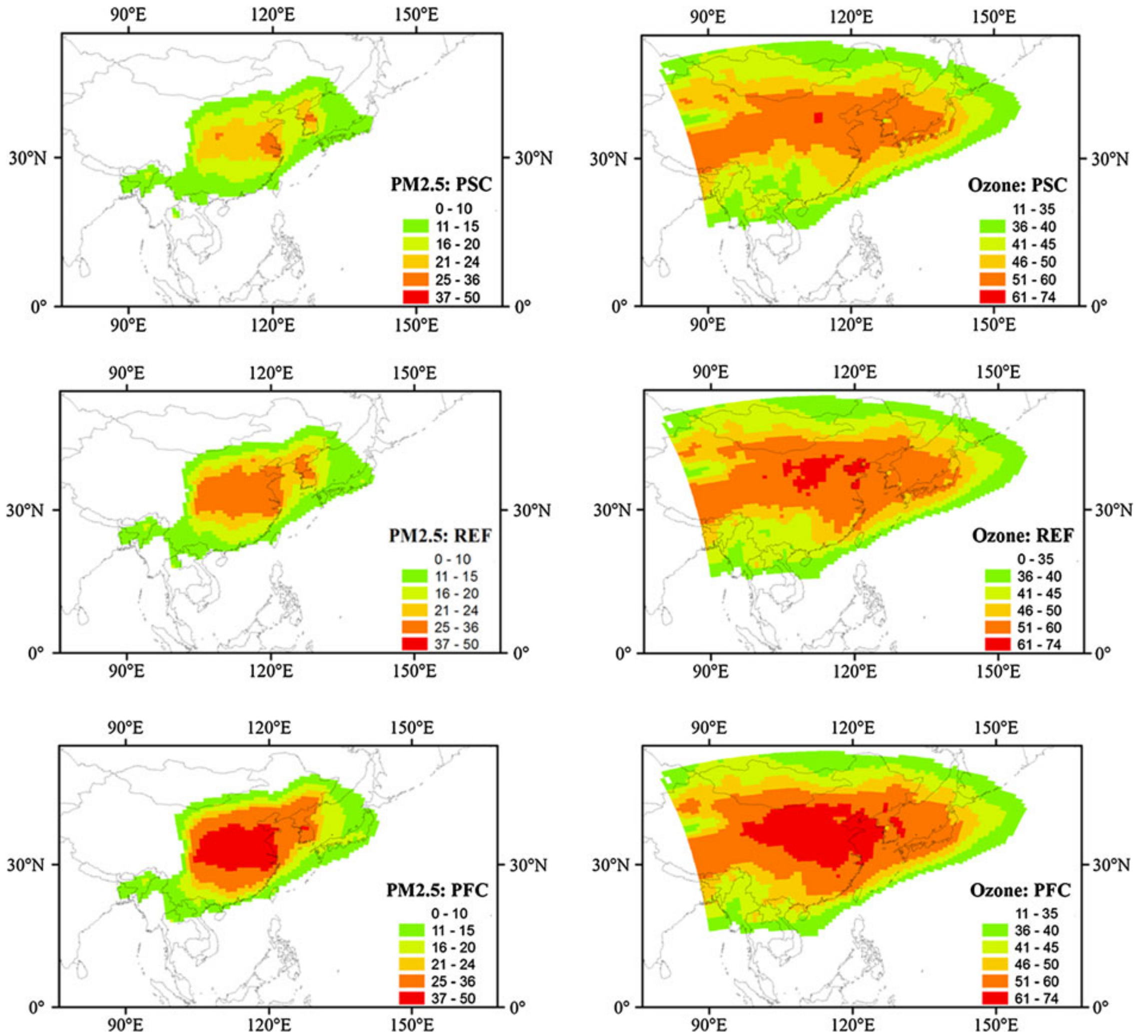

Fig. 2 $PM_{2.5}$ and ozone annual mean concentrations (μg m^{-3}, ppb) in East Asia for the year 2020 (PSC, REF, PFC) within the CMAQ/REAS simulation domain

The CMAQ modeling system is coupled with REAS, which includes the following emissions: SO_2, NO_x, CO, NMVOC, BC, and OC from fuel combustion and industrial sources. REAS involves the following countries and regions: China, Japan, Other East Asia, Southeast Asia, India, Other South Asia, and All Asia. In the 2020 reference (REF) scenario, NO_x emissions in China (15.6 Tg) will increase by 40 % from 2000 (11.2 Tg). In the 2020 policy succeed case (PSC) scenario, the NO_x emissions in China will have a slight decrease of 1 % from 2000 to 2020. In the 2020 policy failed case (PFC) scenario, NO_x emissions emitted in China will increase by 128 % from 2000. In the 2020 REF scenario, NMVOC emissions in China (35.1 Tg) will increase rapidly by 128 % from 2000 (14.7 Tg). In the 2020 PSC scenario, the NMVOC emissions emitted in China will have a large increase of 97 % from 2000. In the 2020 PFC scenario, NMVOC emissions in China will increase by 163 % from 2000 (Ohara et al. 2007). Detailed descriptions of the modeling system and simulations, including parameterization, meteorological inputs, emission inventory, and evaluation of the simulations, were given by Uno et al. (2005), Ohara et al. (2007), Yamaji et al. (2008), Kurokawa et al.

(2009), and Aikawa et al. (2010). The spatial distributions and annual variations of the annual mean $PM_{2.5}$ concentrations are calculated based on the annual mean concentrations of the following components; EC, OC, NO_3^-, SO_4^{2-}, and NH_4^+.

2.2 $PM_{2.5}$: Exposure and Premature Mortality Analysis

The distributed annual premature mortality rate in each grid cell is calculated as follows using Eq. (1) for $PM_{2.5}$ mean annual concentrations above 10 μg m^{-3} for the age group of 30 years and above:

$$\mathrm{mortality}_{\mathrm{PM2.5}}(i,j,t)=\mathrm{pop}(i,j,t)M_b(i,j,t)\beta_{\mathrm{PM2.5}}\Delta\mathrm{PM}_{2.5}(i,j,t) \quad (1)$$

$$\beta=\ln(\mathrm{RR})/\Delta C_{\mathrm{PM2.5}} \quad (2)$$

where, *mortality* indicates premature mortality, *i, j* specify the location of a grid cell within the simulation domain, *t* is the year of simulation, *pop* is the expsosed population, M_b is the annual baseline mortality, β is the $PM_{2.5}$ CR coefficient, which can be calculated using Eq. (2), $\triangle C$ is the change in concentration. According to Pope et al. (2002), an increase of 10 μg m^{-3} annual average of $PM_{2.5}$, within a range from around 7.5 to 30 μg m^{-3}, caused a 4 % (95 % confidence interval: 1.01–1.08) increase in mortality rate for the age group of 30 years and above. This gives β a value around 0.004 and $\triangle PM_{2.5}(i,j,t)$ is the change in the annual mean concentrations above 10 μg m^{-3}. We use the same β value also for mean annual concentrations above 30 μg m^{-3} similar to Cohen et al. (2005); they linearly extrapolated the $PM_{2.5}$ CR function to cover a wider range from 0 to 90 μg m^{-3}.

2.3 Ozone: Exposure and Premature Mortality Analysis

The distributed annual premature mortality rate based on a RR value of 1.003 (95 % CI: 1.001–1.004) [0.3 % increase in daily premature mortality caused by a 10 μg m^{-3} (~5 ppb) change in 8 h maximum mean concentration above 70 μg m^{-3} (~35 ppb)] at each grid cell are calculated by summing the daily premature mortality, which can be calculated using the following function (USEPA 2006):

$$\mathrm{mortality}_{\mathrm{O3}}(i,j,n)=Y_o(i,j,n)\{1-\exp[-\beta_{\mathrm{O3}}\Delta\mathrm{O}_3(i,j,n)]\} \quad (3)$$

where, n is the calculation day and Y_o is the daily incidence of premature mortality at a certain ozone level where there is no clear health effect likely to occur. We estimate it in our study by multiplying the population of the age group of 30 years and above by the daily baseline mortality for this age group. β is estimated using Eq. (2) based on a RR value of 1.003, which gives β a value around 0.0003. ΔO_3 is the change in ozone concentration calculated based on the daily maximum 8-h mean concentrations above 35 ppb (or the value of the SOMO35 index of the day n) as follows:

$$\mathrm{SOMO35}(i,j,n)=[\max 8\,\mathrm{h\ mean}-35]_n \quad (4)$$

The daily maximum 8-h mean concentration is the highest moving 8 h average to occur from hour 0:00–hour 23:00 in a day.

2.4 Population Distribution

We obtain the population distribution in East Asia from the Gridded Population of the World (GPWv3; CIESIN 2005); the size of the population grid cell is around 0.04167°. The total population within the simulation domain shown in Fig. 1 was about 1,970 million in 2000 and 2,057 million in 2005. In this study, we estimate the premature mortality rate for the age group of 30 years and above, which includes most of the working age groups in East Asia (WHO 2010). According to the United Nations Department of Economic and Social Affairs/Population Division (2008), the fractions of population in East Asia that were 30 years and above for the years 2000 and 2005 were 51 and 55 %, respectively. The distributed population for the year 2020 is estimated based on the population projections for the year 2015 by GPWv3 and the estimated growth rate of 0.42 % in East Asia for the period from 2015 to 2020 by the United Nations Department of Economic and Social Affairs/Population Division (2008). However, there is no information about age-specific mortality rates for most of the countries in East Asia. Therefore, we estimate the baseline mortality for the age group of 30 years and above based on the WHO mortality database (WHO 2006) as shown in Table 2. The uncertainty in the obtained values is high because the WHO mortality datasets in East Asia are only for selected areas in China,

Table 2 Population structure in East Asia from 2000 to 2020 and the corresponding baseline mortality

Year	2000	2005	2015	2020
Total population (thousand)	1,472,443	1,520,717	2,227,350	2,236,705
Population (+30; thousand)	748,632	838,554	1,403,231	1,409,124
+30 years (%)	50.8	55.1	63	63
Total deaths (thousand)	10,063	10,063	–[a]	–[a]
Baseline mortality	0.0068	0.0066	–[a]	–[a]
+30 years baseline mortality	0.0103	0.0102	0.0102	0.0102

[a] No data

which has the largest population within the simulation domain, and represents only 10 % of all deaths occurring there (WHO 2010). Also, the age-specific mortality rates in these data sets cover the ages from 25 years and above. The estimated average value of the baseline mortality of the age group 30 years and above 0.01025 is close to the following published values: 0.0117 by Lu et al. (2010), 0.0139 by Saikawa et al. (2009), and 0.01013 by Wang and Mauzerall (2006).

The flowchart in Fig. 3 summarizes the methodology used to assess the premature mortality caused by exposure to ozone and $PM_{2.5}$. It shows the input data, data processing steps, and the outputs. We use Intel-FORTRAN to calculate the annual $\triangle PM_{2.5}(i,j,t)$ in Eq. (1), and to calculate and sum the parameters within the braces in the right hand of Eqs. (3) and (4). Also, we use Arc-GIS to implement Eqs. (1) and (3) due to different map projections and different grid cells of CMAQ/REAS and the population distribution.

3 Results

3.1 Premature Mortality

The premature mortality caused by exposure to both ozone and PM2.5 in East Asia for the years 2000, 2005, and 2020 (PSC, REF, PFC) are estimated to be about 316,000, 520,000, 451,000, 649,000 and 1,035,000 deaths, respectively. The estimated distributed premature mortality, caused by exposure to $PM_{2.5}$ annual mean concentrations above10 μg m^{-3} and the daily maximum 8-h mean concentrations of ozone are above 35 ppb for the age group of 30 years and above in East Asia for the years 2000, 2005, and 2020 are shown in Tables 3 and 4, and Figs. 4 and 5. Figure 6 shows the total premature mortality per population grid cell (0.04167× 0.04167°) caused by exposure to both $PM_{2.5}$ and ozone in East Asia for the years 2000, 2005, and 2020 (based on REF scenario). Most of the vulnerable places are shown to be mainly located in China, DPR Korea, Republic of Korea, and Japan, and the number of premature mortality there is increasing annually.

4 Discussion

Our estimated total premature mortality in East Asia accounts for a high percentage of the estimated values of the comparative quantification of the PM pollutant-related health risks study by WHO. It was estimated that 375,000 deaths were caused by major air pollutants in the year 2000 within the Western Pacific subregion, with a region of low child and adult mortality rates (WPR-B and A) that includes Cambodia, China, the Cook Islands, Fiji, Kiribati, Lao People's Democratic Republic, Malaysia, Marshall Islands, Micronesia (Federated States of), Mongolia, Nauru, Niue, Palau, Papua New Guinea, the Philippines, Republic of Korea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, Vietnam, Japan, Australia, New Zealand, and Singapore (WHO 2004). Additionally, we compared our estimations of the deaths caused by exposure to $PM_{2.5}$ with the findings of Saikawa et al. (2009). Eventhough we use the same RR value (1.04 %) and the same data source for population distribution, our estimation of the premature deaths for the year 2000 is about half of the estimation of Saikawa et al. (2009); they estimated the effect of SO_4, OC, and BC aerosols (see Table 1) from China to be around 500,000 premature mortality cases for a population of around 1,471 million in East Asia for the year 2000. This difference can be explained partly because we assess the premature deaths caused by exposure to concentrations of different $PM_{2.5}$

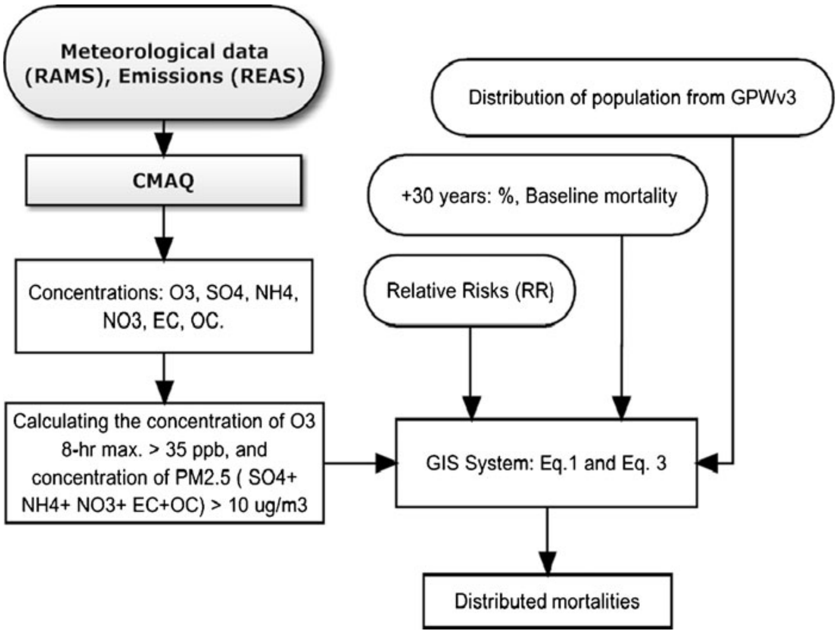

Fig. 3 Flowchart showing the steps and processes used to estimate the distributed premature mortality in East Asia for the years 2000, 2005, and the future scenarios of the year 2020

components above 10 μg m^{-3}, and we use a different modeling system and inventories.

We believe that our estimations of the annual distributed premature deaths caused by exposure to $PM_{2.5}$ and ozone in East Asia may be conservative. This is mainly caused by the common high uncertainties in global health risk assessments, which were discussed in details as follows, Lu et al. (2010) discussed the uncertainty in the estimation of $PM_{2.5}$ concentrations, and they conducted a detailed quantification of the uncertainty caused by the 95 % confidence interval of the RR value of $PM_{2.5}$ for mortality. Saikawa et al. (2009) discussed the uncertainty in the concentration–response relationships caused by different background pollution levels in the USA and other countries, and the uncertainty caused by the coarse size of the grid cells in the simulation model. Finally, Wang and Mauzerall (2006) discussed the uncertainty in the emission inventory in China caused by the Chinese government's statistics on energy consumption. Additionally, we raise the following uncertainties:

Validation of CMAQ/REAS simulations of ground level ozone and $PM_{2.5}$ To check the validity of the simulated concentrations of ground level ozone, we use the observed data from the Acid Deposition Monitoring Network in East Asia (EANET). There are three types of EANET air quality monitoring stations: urban, rural, and remote stations in East Asia. We find good agreement between the simulated annual mean ozone concentrations using CMAQ/REAS and the observed concentrations in remote stations. However, in urban and rural stations, the simulated ground level ozone concentrations are higher than the measured concentrations. Kurokawa et al. (2009) proposed a correction of the simulated ozone by subtracting 0.9 NO_2 and 0.1 NO. Another thing that may affect our results slightly is related to the vertical profile of ground level ozone in the atmosphere, as explained by Lorenzini and Nail (1995). The simulated ozone concentrations are the concentrations of the first layer of CMAQ/REAS, which has a height of 150 m above the ground surface, where ozone concentrations are higher than the monitored values at the ground surface. It is difficult to validate the simulated $PM_{2.5}$ because of the very limited number of monitoring stations in East Asia. For example, within the simulation domain there are only two monitoring stations of $PM_{2.5}$, namely the Rishiri and Oki stations in Japan. On the other hand, different places may have the same concentration of $PM_{2.5}$ with different "mixing-ratios" of the primary species. This may result in an over/underestimate of the effect because some species have recognized effects compared to the others, such as EC,

Table 3 Estimated premature mortality in the countries located within the CMAQ/REAS simulation domain for the years 2000, 2005, and 2020 (PSC, REF, PFC)

Country	2000		2005		2020 (PSC)		2020 (REF)		2020 (PFC)	
	O_3 deaths	$PM_{2.5}$ deaths	O_3 deaths	$PM_{2.5}$ deaths	O_3 deaths	$PM_{2.5}$ deaths	O_3 deaths	$PM_{2.5}$ deaths	O_3 deaths	$PM_{2.5}$ deaths
Mongolia	101	0	112	0	151	0	162	0	178	2
Bangladesh	5,328	0	6,803	33	9,998	2,619	9,951	2,634	10,052	2,673
Bhutan	79	0	101	0	186	1	186	1	187	1
China	60,388	220,183	90,497	376,429	105,536	278,611	128,932	441,947	165,603	769,181
Japan	7,050	2,841	8,612	6,662	9,822	6,480	10,509	9,529	11,522	15,411
DPR Korea	1,220	3,852	1,711	6,634	2,139	6,740	2,433	8,931	2,800	12,720
Philippines	103	0	271	0	389	0	403	0	437	0
Republic of Korea	2,503	10,751	3,440	14,364	4,580	17,948	5,063	21,779	5,706	28,681
Cambodia	29	0	65	0	94	0	110	0	137	0
Lao PDR	59	0	102	0	182	1	203	10	250	90
Myanmar	638	0	773	0	1,278	46	1,322	62	1,435	110
Thailand	480	0	704	0	1,256	121	1,352	154	1,546	245
Vietnam	684	38	1,379	913	1,754	871	2,012	1,583	2,586	3,586
Total	78,662	237,665	114,570	405,035	137,365	313,438	162,638	486,630	202,439	832,700
95 % CI (lower)	55,063	59,416	80,199	101,259	96,156	78,360	113,847	121,658	141,707	208,175
95 % CI (upper)	235,986	475,330	343,710	810,070	412,095	626,876	487,914	973,260	607,317	1,665,400

Table 4 Estimated premature mortality per million in the countries located within the CMAQ/REAS simulation domain for the years 2000, 2005, and 2020 (PSC, REF, PFC scenarios)

Country	2000		2005		2020 (PSC)		2020 (REF)	2020 (PFC)
	Pop. (×1,000)	Deaths/million	Pop. (×1,000)	Deaths/million	Pop. (×1,000)	Deaths/million	Deaths/million	Deaths/million
Mongolia	2,538	40	2,686	42	3,102	49	52	58
Bangladesh	134,959	39	149,792	46	180,598	70	70	70
Bhutan	2,163	37	2,457	41	3,161	59	59	59
China	1,267,220	221	1,312,430	356	1,405,458	273	406	665
Japan	121,601	81	122,504	125	122,681	133	163	220
DPR Korea	21,640	234	22,385	373	23,800	373	477	652
Philippines	70,943	1	77,848	3	90,328	4	4	5
Republic of Korea	44,222	300	45,840	388	48,626	463	552	707
Cambodia	13,105	2	14,793	4	18,638	5	6	7
Lao PDR	5,286	11	5,918	17	7,326	25	29	46
Myanmar	47,107	14	49,928	15	54,762	24	25	28
Thailand	62,048	8	65,664	11	71,814	19	21	25
Vietnam	75,400	10	80,479	28	91,495	29	39	67

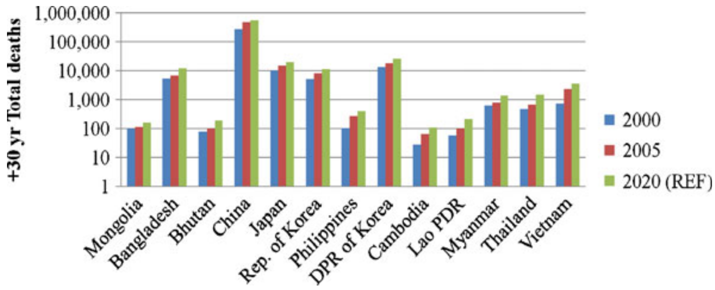

Fig. 4 Estimated premature mortality in the countries located within the CMAQ/REAS simulation domain for the years 2000, 2005, and 2020 (REF scenario)

which has a significant effect on cardiovascular-related mortality (Mar et al. 2000).

Population distribution The GPWv3 datasets, which have been used widely in most of the published research on global risk assessment of air pollutants, are an approximation of the real population and involve uncertainty. According to CIESIN (2005), the errors in population estimations are caused by the interpolation method, the timeliness of the census, the number of estimations and their accuracy, and the boundaries.

Baseline mortality We assume a constant baseline mortality in East Asia for the age group 30 years and above during the period from 2000 to 2020. This may involve high uncertainty because of the clear difference between rural and urban areas, such as the example of China in the introduction section. However, the limited information on spatiotemporal mortality in East Asia may justify our assumption of constant baseline mortality.

The RR values of $PM_{2.5}$ and ozone $PM_{2.5}$ concentrations above 30 μg m^{-3} and elevated ozone concentrations are noticed in EANET monitoring stations; accordingly, the assumption of constant CR coefficients, which are obtained from the CR functions in Eqs. (1) and (3), may involve uncertainty in assessing the risks especially in urban areas where we find high population and high concentrations in the CMAQ/REAS 80×80 km grid cells. In these equations, we consider the 1.003 value of RR for ozone (95 % CI: 1.001–1.004; WHO 2005) and the 1.04 value of RR for $PM_{2.5}$ (95 % CI: 1.01–1.08; Pope et al. 2002). Considering the CI of ozone and $PM_{2.5}$ gives possible effects that ranges from 0.7 to 3.0 times the estimated premature mortality caused by ozone, and 0.25 to 2.0 times the estimated total premature mortality caused by exposure to $PM_{2.5}$. Accordingly, the expected uncertainty in the estimated excess deaths caused by exposure to ozone could be higher than those caused by exposure to $PM_{2.5}$. On the other hand, most of the published CR functions of ozone and $PM_{2.5}$ do not consider the influence of the existing "similarly-acting" air pollutants, such as the combined effect of ozone and $PM_{2.5}$. Also, the recognized relationship between race and health may affect our estimations of the health risks that are based on CR functions from studies on American and European communities. The difference between races is caused by many factors. The main factors are: environment, economy and life quality, culture, religion, nutrition, and genes. However, limited epidemiological studies on the health effects caused by exposure to ozone and $PM_{2.5}$ in East Asia, except for limited studies in Bangkok, Hong Kong, Shanghai, and Wuhan by the

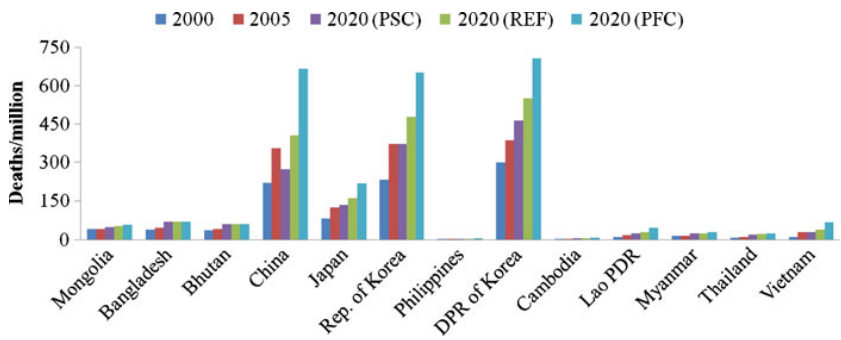

Fig. 5 Estimated premature mortality per million in the countries located within the CMAQ/REAS simulation domain for the years 2000, 2005, and 2020 (REF, PFC, and PSC scenarios)

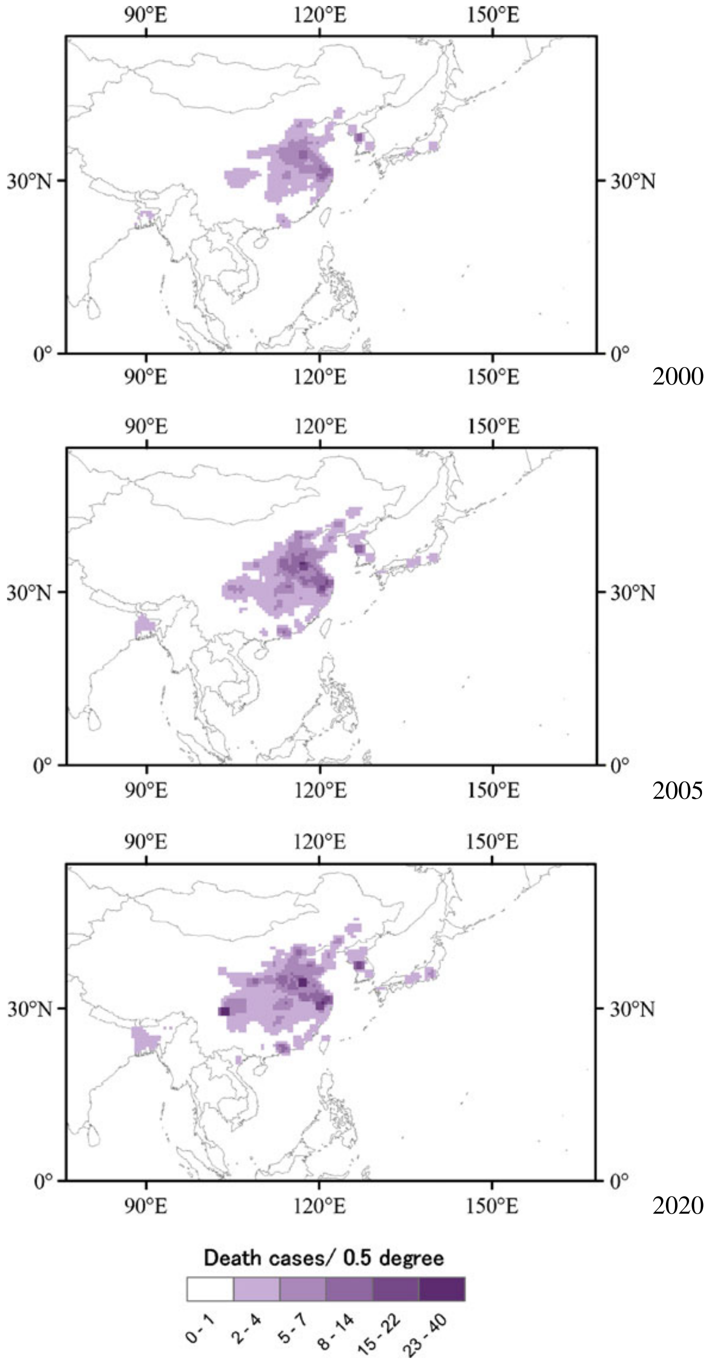

Fig. 6 Distributed premature mortality among the age group 30 years and above caused by $PM_{2.5}$ and ozone emissions in East Asia for the years 2000, 2005, and 2020 (REF scenario) per grid cell. Grid cell resolution is 0.5° for visible clarification, although the calculation of mortality is done in the resolution of 0.0417°

Health Effects Institute (HEI 2008) and in Japan by Ueda et al. (2011), limit further discussions, and it can be considered an area of promising research in the near future.

We think that due to the spatial variability of the exposed population and the concentrations of $PM_{2.5}$ and ozone, there might be both underestimation and overestimation of the effect in our results due to the uncertainties discussed above. For example, respiratory diseases in China caused at least an average of 17.55 % of the total deaths during the period from 1999 to 2006, as shown in the introduction section, this is because China is 70 % rural areas (Liu et al. 1998). According to the United Nations Department of Economic and Social Affairs/Population Division (2008), the average annual deaths for the years 2000–2005 are estimated to be around 8,500,000 in China, accordingly, respiratory diseases, which are not only related to $PM_{2.5}$ and ozone, caused about 1,490,000 deaths. For the age group of 30 years and above in the years 2000 and 2005, deaths related to respiratory disease accounted for 50.8 and 55.1 % of the 1,490,000 deaths, respectively, which amounts to about 757,000 and 821,000 deaths, respectively. Table 4 shows the estimated number of premature deaths for the years 2000 and 2005 in China, which equal about 221 cases per million and 356 cases per million, respectively. These values represent 37 % of the 757,000 deaths in 2000 and 57 % of the 821,000 deaths in 2005. On the other hand, it was estimated that for the year 2000, the smoking-related deaths for the age group 35–69 in China were around 500,000, amounts to about 66 % of the 757,000 deaths. The smoking RR values for mortality, which depend on age, gender, and location (urban/rural), vary from 1.14 (standard error, 0.04) to 1.7 (standard error, 0.05) in China (Liu et al. 1998). It is hard to evaluate the validity of our estimations of premature mortality caused by $PM_{2.5}$ and ozone by comparing the RR values of $PM_{2.5}$ and ozone with those of smoking because they differ and can cause similar effects. However, our estimation of premature mortality for the year 2000, which is 316,000 cases, is less than the 500,000 deaths caused by smoking, and may be somewhat reasonable. The big difference between the two estimations is due to the following three reasons: different RR values, ignoring the exposure of the age group of 30 years and below, and not assessing the effect of $PM_{2.5}$ concentrations below 10 $\mu g\ m^{-3}$ and ozone concentrations below 70 $\mu g\ m^{-3}$. However, there is a lack of Asian epidemiological studies on the health effects of ozone and $PM_{2.5}$, as well as on smoking and the effects of secondary smoke. Consequently, there are needs for extensive research to be done on the effect of exposure to elevated concentrations of both $PM_{2.5}$ and ozone, even though a recent study (Anenberg et al. 2010) showed that the effects of ozone and $PM_{2.5}$ on health are independent of each other and combined effects are not significant enough to be tangible.

All these uncertainties and the absence of epidemiological information limit the applicability of more detailed assessments, such as an economical evaluation of the losses as well as future predictions, of human health risks in East Asia. However, this study gives an indication of an annually growing threat caused by exposure to $PM_{2.5}$ and ozone, mainly in major sources and receptors, i.e., China, DPR Korea, Republic of Korea, and Japan (as shown in Table 3). It also provides a tool that can be used to examine many what-if pollution reduction scenarios. The findings of this study show that the effects of ozone and $PM_{2.5}$ on human health are likely to increase, as can be seen from the predictions of their future concentrations for the year 2020 based on the REF, PSC, and PFC scenarios.

5 Conclusions

Assessing premature mortality risks caused by exposure to elevated concentrations of $PM_{2.5}$ and ozone in East Asia, where rapid development and exploding urbanizing have been increasing annually, involves unique challenges in a region that lacks adequate ozone and $PM_{2.5}$ epidemiological studies. In addition, there are many uncertainties with regard to emission inventories, modeling systems, population distribution, and age-specific mortality rates. Our results, which are based on the CMAQ modeling system coupled with the emission inventory, REAS, for the years 2000, 2005, and 2020, show that ozone and $PM_{2.5}$ elevated concentrations in East Asia probably cause environmental risks. Our results show that the effect of $PM_{2.5}$ on human health is greater than the effect of ozone for the age group 30 years and above. The cases of premature deaths caused by exposure to $PM_{2.5}$ and ozone in East Asia are estimated to be 316,000 and 520,000 for the age group 30 years and above for the years 2000 and 2005, respectively. For future scenarios in 2020, PSC, REF, and PFC, the estimated premature mortality rates are 451,000, 649,000, and 1,035,000, respectively. We think these estimations include certain levels of uncertainty. Quantifying the uncertainty in CMAQ/REAS simulations and the RR values of $PM_{2.5}$ and ozone cannot be achieved easily unless there is comprehensive validation of the simulated ozone and $PM_{2.5}$ concentrations in all Asian countries within the simulation domain of CMAQ/REAS, especially in urban areas, as well as recognized statistically significant Asian epidemiological studies for ozone and

$PM_{2.5}$ effects on human health. Additionally, there is a need to update the available emission inventories taking into account the recent rapid development in East Asia.

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