Present and potential future contributions of sulfate, black and organic carbon aerosols from China to global air quality, premature mortality and radiative forcing

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ABSTRACT

Aerosols are harmful to human health and have both direct and indirect effects on climate. China is a major contributor to global emissions of sulfur dioxide (SO_2), a sulfate (SO_4^{2-}) precursor, organic carbon (OC), and black carbon (BC) aerosols. Although increasingly examined, the effect of present and potential future levels of these emissions on global premature mortality and climate change has not been well quantified. Through both direct radiative effects and indirect effects on clouds, SO_4^{2-} and OC exert negative radiative forcing (cooling) while BC exerts positive forcing (warming). We analyze the effect of China's emissions of SO_2, SO_4^{2-}, OC and BC in 2000 and for three emission scenarios in 2030 on global surface aerosol concentrations, premature mortality, and radiative forcing (RF). Using global models of chemical transport (MOZART-2) and radiative transfer (GFDL RTM), and combining simulation results with gridded population data, mortality rates, and concentration–response relationships from the epidemiological literature, we estimate the contribution of Chinese aerosols to global annual premature mortality and to RF in 2000 and 2030. In 2000, we estimate these aerosols cause approximately 470 000 premature deaths in China and an additional 30 000 deaths globally. In 2030, aggressive emission controls lead to a 50% reduction in premature deaths from the 2000 level to 240 000 in China and 10 000 elsewhere, while under a high emissions scenario premature deaths increase 50% from the 2000 level to 720 000 in China and to 40 000 elsewhere. Because the negative RF from SO_4^{2-} and OC is larger than the positive forcing from BC, Chinese aerosols lead to global net direct RF of -74 mW m^{-2} in 2000 and between -15 and -97 mW m^{-2} in 2030 depending on the emissions scenario. Our analysis indicates that increased effort to reduce greenhouse gases is essential to address climate change as China's anticipated reduction of aerosols will result in the loss of net negative radiative forcing.

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1. Introduction

Particulate air pollutants including sulfate (SO_4^{2-}), organic carbon (OC) and black carbon (BC) damage human health and the environment, increase morbidity and premature mortality, degrade visibility, and contribute to acid deposition (Andreae et al., 2005; Pope et al., 2002). These aerosols also perturb the radiative balance of the earth directly by scattering and absorbing incoming solar radiation and indirectly by modifying cloud properties (Andreae et al., 2005). Many air pollution control policies aimed at reducing tropospheric aerosol concentrations are designed to protect human health and reduce direct adverse impacts on the environment. However, to date, they have not considered the effect of aerosols on radiative forcing (RF) and climate change.

Although the magnitude is uncertain, predominantly scattering aerosols like SO_4^{2-} and OC have negative RF, thereby cooling climate, while strongly absorbing aerosols like BC have positive RF and contribute to atmospheric warming (Forster et al., 2007). The effect of past and present anthropogenic emissions of short-lived species including aerosols on RF and climate change has been estimated (see references in Forster et al., 2007), and recent research projects their potential future impacts on climate (Levy et al., 2008; Shindell et al., 2008). However, no study has conducted a thorough analysis of the impacts that China's aerosols have on air quality and climate change.

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China is a major emitter of carbonaceous aerosols (Cao et al., 2006) and sulfur dioxide (SO_2) (Streets et al., 2003), a precursor to SO_4^{2-}. Although industrializing rapidly, China has passed and continues to develop many environmental regulations (Liu and Diamond, 2005). Future emissions, however, remain highly uncertain and are of interest for regional and global air quality and climate change.

Most emissions of SO_2, OC and BC in China result from fossil fuel and biofuel combustion (Table 1) (Ohara et al., 2007). A full review of estimates of such emissions is beyond the scope of this paper. Briefly, SO_2 emissions primarily originate from the industrial, power plant and domestic sectors (Cofala et al., 2005; Ohara et al., 2007). Sulfate (SO_4^{2-}) is produced in the troposphere by the oxidation of SO_2 in the gas-phase (by the hydroxyl radical, OH) and in the aqueous-phase (mainly by hydrogen peroxide, H_2O_2 and, to a lesser extent, ozone, O_3). The majority of China's OC comes from the combustion of coal and biofuels in households. Black carbon (BC) is emitted directly by the incomplete combustion of fossil and biomass fuels; new estimates indicate BC emissions from China doubled between 2000 and 2006 (Ramanathan and Carmichael, 2008). These aerosol species are removed from the troposphere on a time-scale of approximately a week primarily by wet scavenging and secondarily by dry deposition, resulting in spatially inhomogeneous distributions.

Aerosols have adverse health impacts including premature mortality (Pope et al., 2002, 2004) and their weeklong lifetime allows them to be transported internationally (Haywood and Boucher, 2000). Wang and Mauzerall (2006) calculated the adverse health impacts due to aerosols of anthropogenic origin emitted from Zaozhuang Municipality in Shangdong Province in eastern China. They found that exposure to PM_{10} (particulate matter with a diameter of 10 μm or less) originating from Zaozhuang resulted in approximately 6000 premature mortalities in the year 2000 and forecast 11 000 premature mortalities in 2020 using a BAU (Business-As-Usual) scenario. A World Bank study jointly conducted with the Chinese government estimated that as many as 750 000 premature mortalities per year resulted from respiratory disease related to air pollution in China (Economy, 2007). Liu et al. (submitted for publication-a,b) calculated that in 2000, trans-Pacific transport of East Asian aerosols may cause nearly 1200 premature deaths in North America.

Koch et al. (2007) estimates that during the mid 1990s industrial emissions from Southeast Asia contributed approximately 10%, 4%, and 16% to the global burden of SO_4^{2-}, OC, and BC, respectively. They state that these emissions result in annual global mean aerosol RF of -30 mW m^{-2}.

In this study, we analyze the effect of China's anthropogenic emissions of SO_2, SO_4^{2-}, OC and BC in 2000 and in three possible 2030 emission scenarios on global surface concentrations, premature mortality, and RF. This study adds to the previous literature by calculating for both present-day and future scenarios the effect of aerosols originating from China on premature mortality globally as well as estimating the resulting RF.

Section 2 describes our methodology. Our results for China's contribution to global surface aerosol concentrations are in Section 3. In Section 4 we calculate the contribution of China's aerosols to premature mortality in each region. In Section 5 we examine the contribution of China's aerosols to RF. Section 6 discusses uncertainties associated with our analyses. In Section 7, we discuss the policy implications of the findings and conclusions.

2. Methods

Our methodology is presented in four steps. First, we describe the emission inventories we use for the year 2000 and for the three 2030 scenarios. Second, we describe the global chemical transport model used to simulate global aerosol distributions. Third, we illustrate how we estimate annual premature mortalities in each region due to aerosols originating from China. Finally, we explain how we calculate net global RF resulting from the simulated aerosol distributions.

2.1. Emissions

For year 2000 (2000 BASE), we use emissions projected by the "Current Legislation" CLE scenario (Cofala et al., 2005; Dentener et al., 2005), which starts from a base year of 1990. The CLE scenario includes expected national economic growth and assumes full compliance with current air quality legislation globally by 2030 (Amann et al., 1999). Fig. 1 shows the spatial distribution of annual-mean surface emissions of SO_2, SO_4^{2-}, OC and BC in the year 2000. SO_2 and SO_4^{2-} emissions are distributed around the Northern Hemisphere, with maxima in eastern China, the United States and Europe. OC and BC originate from biomass burning as well as fossil fuel combustion and as a result have more widely distributed emissions. However, eastern China is still among the regions of highest emissions.

For 2030, we use three global emission scenarios to emphasize the range of possible future emissions from China depending on future policy implementation and enforcement. They are a Business-As-Usual (BAU) scenario based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) A2 (Nakicenovic et al., 2000); a "Current Legislation" (CLE); and a "Maximum Feasible Reduction" (MFR) scenario, the latter two developed at the International Institute for Applied Systems Analysis (IIASA) using the global version of the Regional Air Pollution Information and Simulation (RAINS) model (Amann et al., 1999; Dentener et al., 2005). All emission scenarios used in this study were previously used in MOZART-2 simulations as part of the multi-model IPCC-AR4 ACCENT/PHOTOCOMP study (Dentener et al., 2006a,b).

Table 2 summarizes emissions of SO_2, SO_4^{2-}, OC and BC from China and the world for the 2000 BASE and 2030 BAU, CLE and MFR scenarios. In 2000, China emitted 27% of global SO_2 and SO_4^{2-}, and 16% of global OC and BC. Although the SO_2 emissions data we use (Table 2) and that of Ohara et al. (2007) (Table 1) are approximately the same, they are both significantly higher than the official Chinese inventory. SO_2 emissions from China total 27 Tg year^{-1} in our 2000 BASE emission inventory whereas the official Chinese statistics report 20 Tg year^{-1} in 2000 and 26 Tg year^{-1} in 2006 (National Bureau of Statistics of China, 2006, 2007). This suggests we may be overestimating China's SO_2 emissions in 2000. However, considering the debate surrounding China's official energy statistics (Sinton, 2001), the estimates we use appear reasonable.

Table 1
China's emissions of SO_2, OC, and BC by sector in 2000 taken from Ohara et al. (2007) (unit: Tg year^{-1} (%)).

	Power plants	Industrial combustion	Industrial processes	Residential fossil fuel	Residential biofuel	Transport	Total
SO_2	11 (40%)	11 (41%)	1.8 (7%)	2.5 (9%)	0.27 (1%)	0.4 (1%)	28
OC	0.007 (0.3%)	0.027 (1.1%)	–	0.39 (15%)	2.1 (82%)	0.032 (1.2%)	2.6
BC	0.018 (1.6%)	0.099 (9.1%)	–	0.47 (43%)	0.47 (43%)	0.038 (3.5%)	1.1
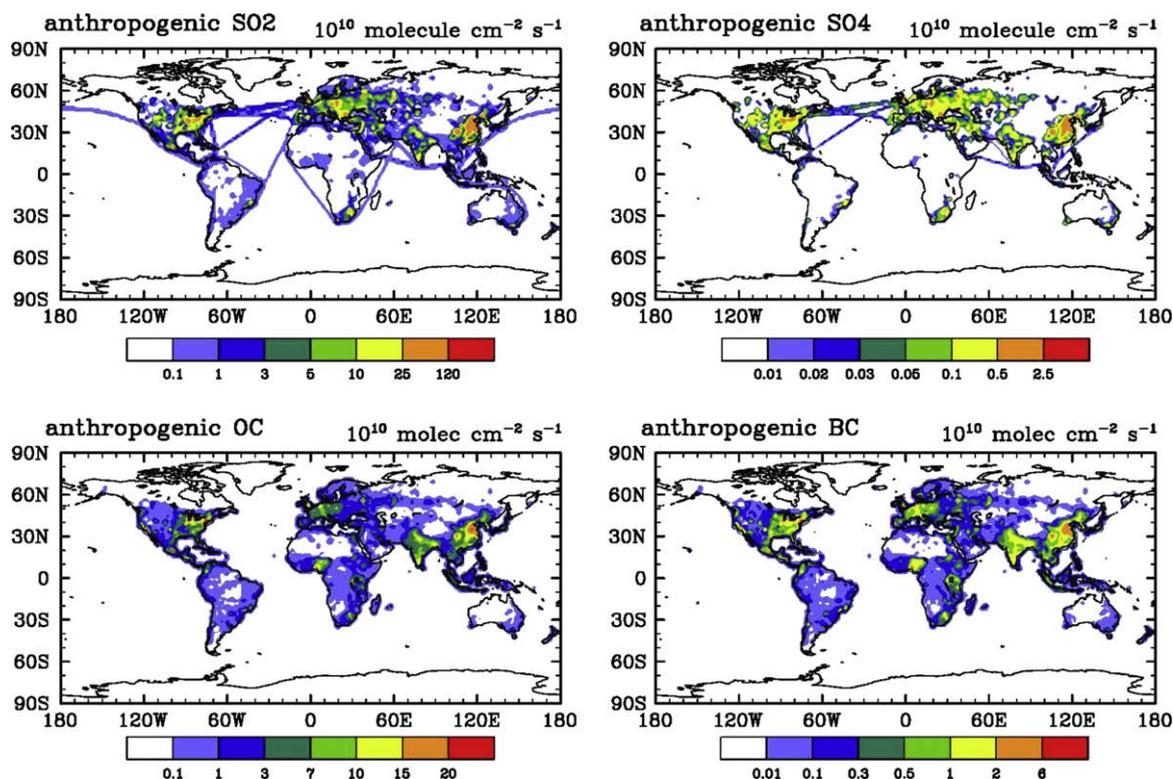
Fig. 1. Surface emissions of anthropogenic SO_2, SO_4^{2-}, OC, and BC in year 2000.

Furthermore, as indicated in Tables 1 and 2, the emissions data we use for OC is approximately 1.8 times smaller than those of Ohara et al. (2007), while our BC emissions are approximately 1.6 times larger. These differences likely result from uncertainties in China's energy use and emissions per unit activity and cannot be resolved at this time.

For BAU, we use the SRES A2 scenario projections of emissions in 2030 assuming economic growth continues and no new pollution control technology is utilized. Because the CLE scenario assumes full compliance with current air quality legislation globally by 2030, China's SO_2 emissions under CLE are estimated to peak in 2010 at 30 Tg year^{-1}, and to decrease to 27.8 Tg year^{-1} in 2030 (only slightly higher than the 2000 emissions of 27 Tg year^{-1}) (Cofala et al., 2005). The MFR scenario assumes global implementation by 2030 of the most advanced currently utilized emission control technologies without regard to cost. In the MFR scenario, Chinese emissions of SO_2 in 2030 are 78% below those in 2000. Emissions of OC in China in 2030 are largest under BAU increasing 66% from the 2000 BASE scenario. The 2030 CLE and MFR scenarios result in 26%

and 49% decreases in OC emissions, respectively, from 2000. Emissions of BC in China in 2030 are also largest under BAU, although 2030 emissions under CLE and MFR are also larger than emissions in the 2000 BASE scenario primarily because the increases in BC emissions from coal combustion exceed the decrease in biofuel use in the residential sector (Ohara et al., 2007; Streets et al., 2004; Zhang et al., 2007).

2.2. Chemical transport model

We use the global three-dimensional chemical transport model, Model for Ozone and Related Tracers version 2.4 (MOZART-2) (Horowitz, 2006; Horowitz et al., 2003) to evaluate the contribution of China's emissions to the global distribution of aerosols in 2000 and 2030. MOZART-2 simulates the chemistry and transport of 73 chemical species, including carbonaceous and sulfate aerosols, from the surface to 2.7 mb at a horizontal resolution of 1.9° latitude × 1.9° longitude. Chemical transformation of hydrophobic carbonaceous aerosols into hydrophilic particles occurs with a time constant of 1.63 days (Tie et al., 2005). Aerosol species in the model are assumed to be mixed externally and do not interact with each other. Chemical and transport processes are simulated with a 15 min time step. Our MOZART-2 simulations, described below, are driven by the meteorological fields from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al., 1996).

To quantify the contribution of Chinese emissions in 2000 to the global surface concentration and distribution of SO_4^{2-}, OC and BC, we subtract the results of a simulation without anthropogenic SO_2, SO_4^{2-}, OC and BC emissions from China (2000 BASE No China) from the 2000 BASE simulation results. To assess the potential contribution of China's emissions in the future, we perform a similar subtraction of the results of 2030 simulations using the BAU, CLE and MFR scenarios. The difference between each pair of simulations

Table 2
Global BASE (year 2000) and BAU, CLE, and MFR (year 2030) anthropogenic emissions (Tg year^{-1}). China's share of the global total is shown in parenthesis.

	2000 BASE	2030 BAU	2030 CLE	2030 MFR
China				
SO_2	27 (27%)	40 (21%)	28 (26%)	6.1 (24%)
SO_4^{2-}	0.56 (27%)	0.83 (21%)	0.57 (26%)	0.13 (24%)
OC	4.7 (16%)	7.8 (17%)	3.5 (14%)	2.4 (17%)
BC	0.70 (16%)	2.7 (17%)	1.2 (14%)	0.83 (17%)
Global total				
SO_2	102	191	105	25
SO_4^{2-}	2.2	4.0	2.3	0.66
OC	29	47	24	14
BC	4.3	16	8.5	4.8
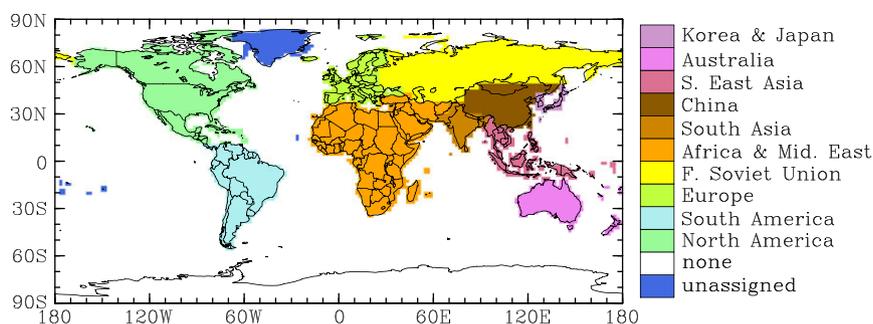
Fig. 2. Map of the world showing the regions examined in this study.

(20X0 Scenario–20X0 Scenario No China) indicates the influence of Chinese emissions on global aerosol distributions. All 8 simulations use 30 months of NCEP meteorology (July 1998–December 2000) with the last 12 used for analyses. Thus, we only consider here the direct effects of anthropogenic emission changes and neglect any effects of climate change. Identical initial conditions are used for each model simulation followed by 18 months of model spin-up to permit transient changes in concentrations resulting from the significant differences in emissions for each simulation to be eliminated.

2.3. Premature mortality

The surface concentration of $PM_{2.5}$ (fine particulate matter with a diameter of 2.5 μm or less) is found to be linearly associated with increased risk of various adverse health impacts including lung cancer, cardiopulmonary disease and premature mortality without a threshold (Pope et al., 2002, 2004; Schwartz et al., 2008). In this study, we focus on premature mortality following the methodology used in Wang and Mauzerall (2006), Liu and Mauzerall (2007), and Liu et al. (submitted for publication-a,b). For each scenario, we quantify the annual premature mortality resulting from exposure to $PM_{2.5}$ originating from China. We calculate premature mortality in each of ten regions (Fig. 2) using the global surface concentration difference (in the lowest model level, which is 70 m thick) of $PM_{2.5}$ for each scenario taken from simulations using MOZART-2 (with and without Chinese emissions), combined with gridded population data, mortality rates, and a concentration–response relationship.

We use the estimate by Pope et al. (2002) that each 10 μg m^{-3} elevation in $PM_{2.5}$ concentration is associated with approximately a 4% increased risk of all-cause mortality in individuals 30 years and older. We assume that all SO_4^{2-}, OC and BC originating from China contributes to $PM_{2.5}$ and we do not account for any additional aerosol components in this study. Because the epidemiological data does not permit us to differentiate the effects of specific particulate species, we report our results in aggregate.

We quantify annual premature mortalities for every grid cell using population-weighted (P-W) concentrations and the following concentration–response function:

$$\Delta \text{Deaths}(R) = POP(R)M_b(R)r\Delta C_{P\text{-}W}(R)$$

where ΔDeaths(R) is the number of premature mortalities in region R resulting from exposure to aerosols originating from China; POP(R) is the exposed population 30 years and older in region R, $M_b(R)$ is the annual baseline mortality rate in the receptor region R for those 30 years and older, r is the concentration–response relationship relating a unit increase in $PM_{2.5}$ with the increased risk of premature mortality from Pope et al. (2002), and $\Delta C_{P\text{-}W}(R)$ is the

change in P-W aerosol concentrations due to China's emissions in the receptor region.

For the 2000 BASE simulation, we use the year 2000 distribution of global population (CIESIN, 2000), regridded to our 1.9° latitude × 1.9° longitude resolution as in Liu and Mauzerall (2007). For 2030 simulations, we extrapolate from the year 2000 global population distribution (CIESIN, 2000), using the regional population growth rate for each region derived from population estimates for 2000 and 2030 (UN, 2006). For calculating annual premature mortality, we use the mortality rate for adults 30 years and older obtained for year 2000 from the WHO for both current and future scenarios (WHO, 2000). We assume that the baseline mortality and age structure are uniformly distributed within each region and remain unchanged between 2000 and 2030. Table 3 summarizes the values used for estimating annual premature mortality in each region.

2.4. Radiative forcing

The total net irradiance (solar + terrestrial) at the top of the atmosphere (TOA) is calculated using the Geophysical Fluid Dynamics Laboratory (GFDL) global three-dimensional radiative transfer model (RTM) as employed by Naik et al. (2007). The RTM is a component of the global atmosphere model (AM2) developed at the GFDL (GFDL GAMDT, 2004). In this study, the RTM simulations use archived meteorological fields from the GFDL global climate model (GCM) including insolation, temperature, specific humidity, cloud amount, and surface reflectance simulated for the early 1990s. The RTM has a horizontal resolution of 2° latitude × 2.5° longitude with 24 vertical levels from the surface to 3 mb. It is run for each grid column with random cloud overlap assumed.

We calculate the net global direct RF due to each aerosol species originating from China by subtracting the net TOA irradiance simulated without China's emissions from that with China's

Table 3
Total population (millions) in 2000 and 2030, fraction of population 30 years and older (F30+), baseline mortality rate (M30+) for each region in 2000, and population growth rate from 2000 to 2030 (PGR00-30).

	2000 POP	2030 POP	F30+	M30+	PGR00-30
North America	478.3	614.3	0.527	0.0132	1.28
South America	353.2	483.2	0.418	0.0123	1.37
Europe	537.0	537.3	0.583	0.0175	1.00
F. Soviet Union	252.1	246.9	0.503	0.0220	0.98
Africa & ME	1073	1893	0.307	0.0192	1.76
South Asia	1316	1952	0.377	0.0156	1.48
China	1265	1454	0.500	0.0117	1.15
S. East Asia	537.5	734.5	0.389	0.0139	1.37
Australia	23.8	31.2	0.575	0.0112	1.31
Korea & Japan	206.7	202.2	0.599	0.0115	0.98

emissions for each aerosol species and for each scenario (20X0 Scenario–20X0 Scenario No China) allowing for stratospheric temperature adjustment. To calculate the total annual RF, we sum the net direct RF of all three aerosol types, assumed to be externally mixed.

In this study, we do not consider the indirect effects of aerosols on cloud properties. Because the cloud albedo and cloud lifetime effects likely lead to net negative RF for all three aerosol species (Haywood and Boucher, 2000), we are likely underestimating the net negative RF due to total aerosols originating from China.

3. Contribution of China's aerosols to surface concentrations

We focus here on China's contribution to surface concentrations of SO_4^{2-}, OC and BC. Fig. 3 shows the annual-mean global distribution of total surface aerosol concentrations (left) and China's contribution to those concentrations in 2000 (right). For each aerosol species, China's emissions affect its own domestic surface aerosol concentrations more than any other region. However, aerosol concentrations over neighboring regions (including the Korean peninsula, Japan and Southeast Asia) are also significantly impacted by China's emissions (Fig. 3). In the Korean peninsula and Japan, an annual average concentration of 1.4 $\mu g\,m^{-3}$ of PM$_{2.5}$ (including SO_4^{-2}, OC, and BC only) results from China's emissions. North America has an annual average concentration of 0.018 $\mu g\,m^{-3}$ of PM$_{2.5}$ originating from China. Liu (2006) calculated the contribution of PM$_{2.5}$ from the East Asian region to North America to be 0.087 $\mu g\,m^{-3}$ for SO_4^{2-}, OC and BC and fine dust aerosols combined. Liu's study includes the transport of fine dust aerosols that contribute to PM$_{2.5}$ as well as anthropogenic emissions from Korea and Japan. Considering these differences, our results appear consistent with theirs.

China's contributions to global annual average surface PM$_{2.5}$ concentrations for 2030 are calculated in the same way as for 2000. Fig. 4 and Supplementary Figs. S1 and S2 show China's contributions to the surface concentrations in 2030 for the BAU, CLE, and
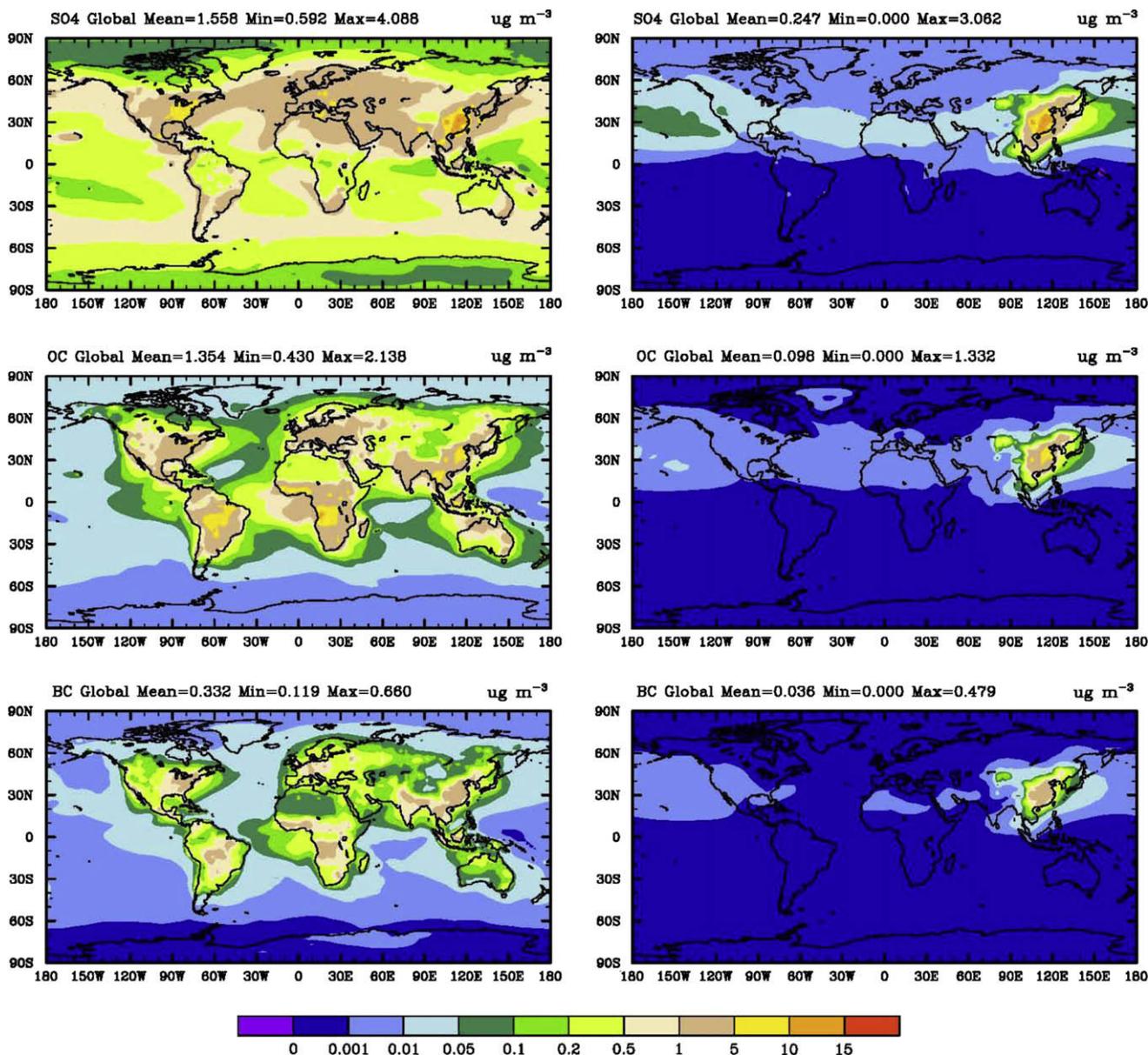
Fig. 3. Annual average global surface aerosol concentrations (left) and China's contribution to annual average global surface aerosol concentrations (right) in year 2000 (2000 BASE).
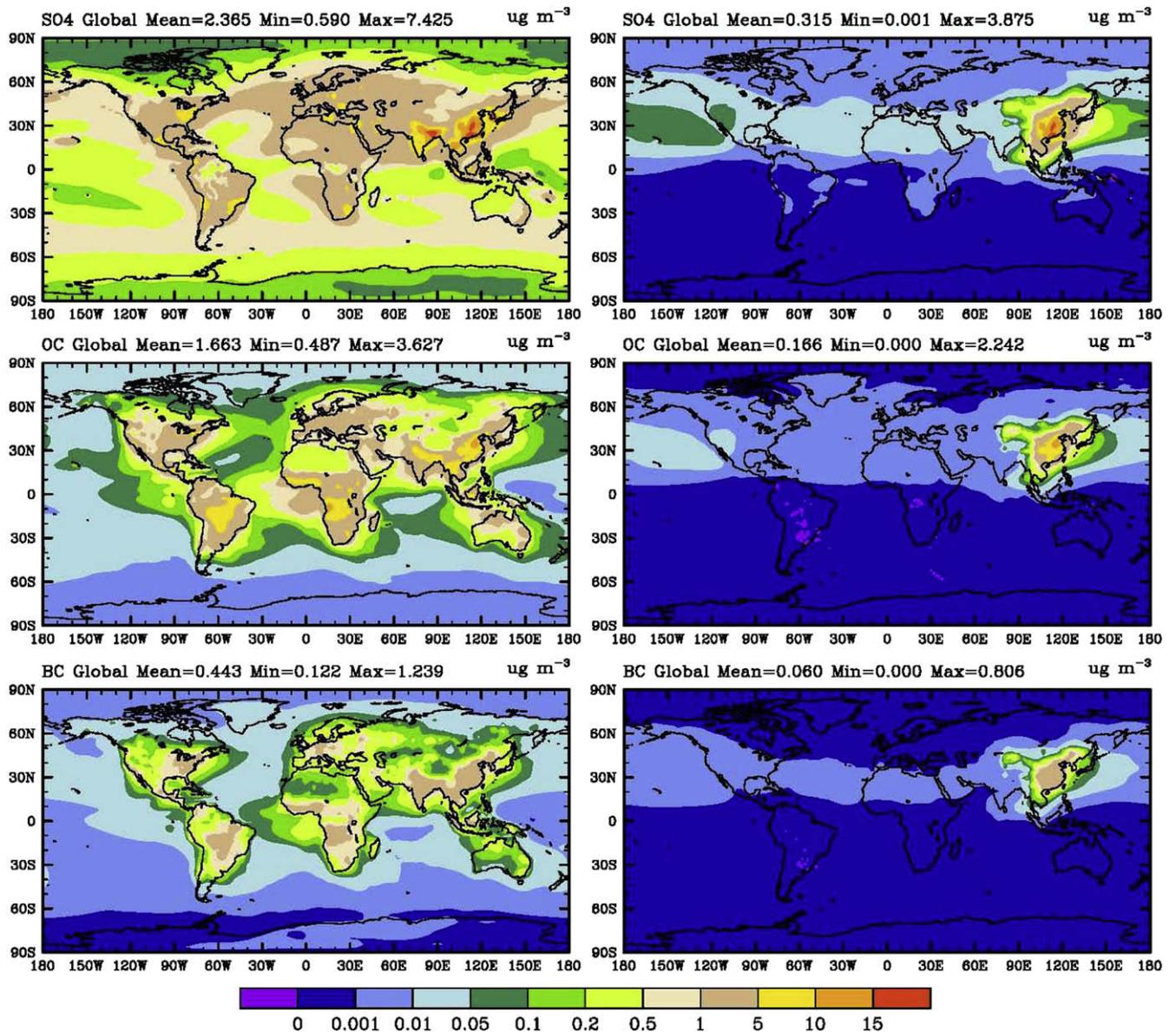
Fig. 4. Annual average global surface aerosol concentrations (left) and China's contribution to annual average global surface aerosol concentrations (right) for 2030 BAU.

MFR scenarios, respectively. Fig. 4 shows the substantial impact that emissions from China have on Northeast Asia under 2030 BAU. Under this scenario, area-weighted annual average surface concentrations in China of 3.9 $\mu g\ m^{-3}$ of SO_4^{2-}, 2.2 $\mu g\ m^{-3}$ of OC and 0.81 $\mu g\ m^{-3}$ of BC result from its own emissions. Because these are annual averages across all of China, the values are lower than they would be if eastern China were considered alone (see Fig. 4).

4. Contribution of Chinese aerosols to global premature mortality

Using the simulated surface aerosol concentrations from MOZART-2 for each scenario, we estimate premature mortalities (in persons 30 years and older) in ten continental regions (Fig. 2) resulting from exposure to total SO_4^{2-}, OC and BC anthropogenic aerosols originating from China. Table 4 summarizes the global and regional population-weighted (P-W) concentrations of total anthropogenic aerosol originating from China in 2000 and for each

2030 scenario for each region. Total regional premature mortality is summarized in Table 5.

We calculate that nearly 500 000 premature deaths occur in China in 2000 as a result of SO_4^{2-}, OC and BC aerosols of domestic

Table 4
Population-weighted concentration of SO_4^{2-}, OC and BC aerosols originating from China ($ng\ m^{-3}$).

	2000 BASE	2030 BAU	2030 CLE	2030 MFR
North America	25	35	24	7
South America	1	2	1	0
Europe	10	15	10	3
F. Soviet Union	19	29	18	7
Africa	10	15	10	3
South Asia	27	43	25	9
China	16 000	22 000	15 000	7000
S. East Asia	900	1300	800	300
Australia	0	1	0	0
Korea & Japan	2000	2400	1900	700

Table 5
Effect of SO_4^{2-}, OC and BC aerosols originating from China on annual premature mortality in each region (number of persons).

	2000 BASE	2030 BAU	2030 CLE	2030 MFR
North America	320	580	400	120
South America	10	20	10	0
Europe	230	320	220	60
F. Soviet Union	200	310	190	70
Africa	250	660	440	140
South Asia	830	2000	1200	430
China	470 000	720 000	500 000	240 000
S. East Asia	10 000	20 000	13 000	5000
Australia	0	0	0	0
Korea & Japan	11 000	13 000	10 000	4000
Total	500 000	760 000	520 000	250 000

Chinese origin. Our value is approximately 70% of the premature mortalities in China attributed to respiratory disease from air pollution by Economy (2007) who did not provide details on how their value was obtained. In 2000 we estimate that exposure to SO_4^{2-}, OC and BC aerosols of Chinese origin resulted in approximately 11 000 premature deaths in Korea and Japan and 10 000 in Southeast Asia annually. P-W concentrations of SO_4^{2-} in Korea and Japan are approximately twice as large as that in Southeast Asia. However, because the population 30 years and older is approximately 1.7 times larger in Southeast Asia, the number of annual premature deaths is similar for the two regions. Following these two regions and South Asia, where approximately 800 premature mortalities occur annually as a result of aerosols of Chinese origin, the next most impacted region is North America. However, in North America the number of annual premature mortalities is significantly smaller (approximately 300) – only 3% of the deaths in Korea and Japan combined.

In 2030, we calculate annual global premature mortalities associated with exposure to anthropogenic aerosols originating from China under the BAU, CLE and MFR scenarios. We estimate annual premature mortalities in China to be approximately 720 000, 500 000, and 240 000, respectively, in the three scenarios. On the Korean peninsula and Japan combined, we estimate for BAU, CLE and MFR approximately 13 000, 10 000, and 4000 premature deaths, respectively, result from exposure to SO_4^{2-}, OC and BC of Chinese origin annually. The annual premature deaths projected for Southeast Asia are approximately 20 000, 13 000 and 5000 for the BAU, CLE and MFR scenarios, respectively, surpassing the deaths in the Korean peninsula and Japan combined. The primary explanation for this regional shift is the projected 48% increase in population from 2000 to 2030 in Southeast Asia versus an estimated decrease of 2% over the same period in Korea and Japan. The P-W concentration for all the species remains higher in Korea and Japan than in Southeast Asia for all scenarios.

5. China's contribution to net aerosol radiative forcing (RF)

Although in the previous section we assumed that all three aerosol species have the same effect per unit mass on premature mortality, their effects on direct RF differ significantly. In this study, for each scenario we quantify China's total contribution to net aerosol direct RF, calculated as the sum of the RFs from SO_4^{2-}, OC and BC.

For 2000, China's contribution to global total-sky direct RF at the TOA is calculated for each aerosol species (Fig. 5). The negative RF due to SO_4^{2-} originating from China is highest in the Northeast Asian region. On the other hand, China's BC emissions lead to strong positive RF in Northeast Asia. As summarized in Table 6, China's 2000 emissions result in a global positive forcing from BC

$(+42 \text{ mW m}^{-2})$ and negative forcing from SO_4^{2-} (-108 mW m^{-2}) and OC (-7 mW m^{-2}). Overall, we find that in 2000 China's aerosols result in net negative RF of -74 mW m^{-2}, dominated by the strong negative RF of SO_4^{2-}.

China's emissions cause the largest net negative RF under the 2030 BAU scenario (-97 mW m^{-2}) because SO_2 and OC emissions are the largest in this worst-case scenario (Table 2), with smaller negative global RF for 2030 CLE (-83 mW m^{-2}) and 2030 MFR (-15 mW m^{-2}) scenarios (Table 6). Under MFR, China's emissions of SO_2 and OC are much lower than other scenarios, so net negative forcing is smaller. The net positive RF of BC is approximately 35%, 40%, 26% and 55% of the negative forcing due to SO_4^{2-} and OC combined in the 2000 BASE, 2030 BAU, CLE and MFR scenarios, respectively. In all the future scenarios, the largest change in RF from aerosols of Chinese origin occurs over Northeast Asia (Supplementary Figs. S3–S5).

6. Uncertainties

There are substantial uncertainties associated with this study that require attention. Nevertheless, we believe that as a first estimate of the impacts of three major anthropogenic aerosol species originating from China on both premature mortality and RF in 2000 and 2030, our analysis provides valuable, policy-relevant insight on the benefits of air pollution control for health and climate change. Some of key areas of uncertainty are highlighted below.

(1) *Emission inventories and model simulations*. Due to the differences between the 2000 BASE OC and BC emissions data we use and those of Ohara et al. (2007) and official Chinese emission estimates, our results are potentially conservative regarding RF. There may possibly be a larger net negative RF resulting from SO_4^{2-}, BC and OC originating from China than we calculate.

(2) *Concentration–response (CR) relationship*. We use the concentration–response relationship derived from a U.S. cohort study to estimate annual premature mortality globally. We realize that the baseline health status and background pollution levels in the U.S. may differ from those in other parts of the world.

(3) *Population data*. Uncertainties exist regarding population age structure, baseline mortality and population growth rates. We assume that the baseline mortality and age structure are uniformly distributed over each region and remain unchanged between 2000 and 2030. More precise analyses will be possible once more data becomes available.

(4) *Premature mortality*. Our MOZART-2 model resolution is too coarse to accurately simulate high aerosol concentrations in urban centers where population densities are also high. As a result we underestimate premature mortalities in China that result from aerosols of domestic origin. This issue is much less of concern for regions downwind of China as long-range transport sufficiently mixes and dilutes aerosols so that aerosol concentrations downwind of China are adequately represented at our resolution as indicated by Liu et al. (2008). We further assume, due to a lack of separation in the epidemiological literature, that the three aerosol species have the same impact on premature mortality.

(5) *Radiative forcing*. Two major uncertainties in our calculation of RF are that we are unable to include the indirect effects of aerosols on cloud properties or the internal mixing of aerosols. Indirect effects of aerosols lead to negative RF, but internal mixing has inconsistent effects based on how they are mixed. There is a lack of understanding to provide definitive impacts of aerosols from China.
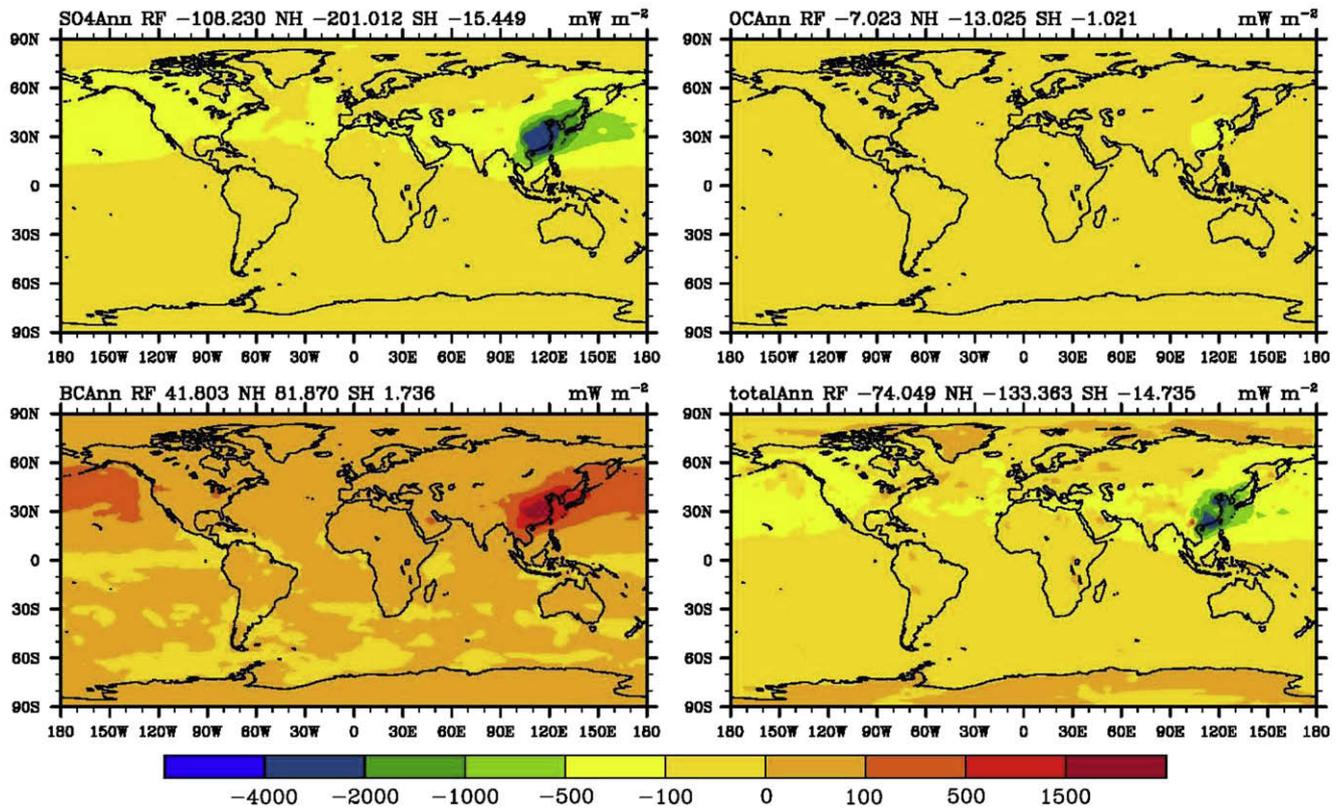
Fig. 5. China's contribution to total-sky annual adjusted radiative forcing (in mW m^{-2}) at the top of the atmosphere for 2000 BASE.

7. Policy implications and conclusions

Our findings have implications for the development of policy to mitigate air pollution and climate change. Our findings for 2000 indicate that China suffers over 90% of premature mortalities resulting from anthropogenic SO$_4^{2-}$, OC and BC aerosols originating from China while Asian countries downwind of China are also significantly affected. At the same time, these aerosols of Chinese origin result in a net negative RF (cooling climate), primarily due to the effect of SO$_4^{2-}$. Although reductions in SO$_4^{2-}$ concentrations would decrease the incidence of PM$_{2.5}$ related premature mortality, it would also lead to less negative RF (i.e., less offsetting of the positive RF from greenhouse gases) and hence likely result in additional climate warming. This sensitivity of RF to aerosols is borne out in our three simulations for 2030 which range from a Business-As-Usual (2030 BAU) case to a Maximum Feasible Reduction (2030 MFR) case. In 2030 BAU, emissions of SO$_2$, SO$_4^{2-}$, OC and BC all rise, with an associated increase in premature mortalities and in negative RF. In 2030 MFR, emissions of the four constituents decrease relative to 2000, causing decreases in premature mortalities and in the magnitude of the net negative RF.

Our research shows the importance of reducing emissions of aerosols and their precursors in order to protect human health.

Based on our estimation, if China implemented currently legislated decreases in emissions (CLE scenario) rather than following a BAU emission trajectory, approximately 240 000 lives would be saved in 2030 globally. Similarly, if China were to decrease emissions from BAU by the Maximum Feasible Reductions (MFR scenario), over 500 000 lives would be saved globally.

Our work also indicates that although reduction of BC emissions, an aerosol with positive RF, would be beneficial for climate, reduction of SO$_4^{2-}$ and OC would decrease negative RF. It is therefore clear that in order to compensate for such loss of negative RF from possible future reduction of SO$_4^{2-}$ and OC aerosols, further effort to reduce emissions of greenhouse gases is essential to slow climate change.

A variety of policy options that reduce both aerosol and greenhouse gas emissions include increasing energy efficiency and renewable energy use as well as implementing advanced coal gasification technology with separation and sequestration of air pollutants and carbon dioxide (CO$_2$). These measures would reduce SO$_4^{2-}$, OC and BC concentrations, hence protecting health, as well as reduce CO$_2$ emissions in addition to BC, hence benefiting climate.

Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.atmosenv.2009.02.017.

Table 6
Annual-mean global adjusted radiative forcing (mW m^{-2}) from SO$_4^{2-}$, OC and BC aerosols originating from China in each scenario.

	2000 BASE	2030 BAU	2030 CLE	2030 MFR
SO$_4^{2-}$	−108	−154	−109	−33
OC	−7	−11	−5	−4
BC	42	70	32	21
Net	−74	−97	−83	−15

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