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Co-benefits of China's climate policy for air quality and human health in China and transboundary regions in 2030

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—*Ronald G. Prinn and John M. Reilly,*
Joint Program Co-Directors

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Climate policies targeting CO₂ emissions from fossil fuels can simultaneously reduce emissions of air pollutants and their precursors, thus mitigating air pollution and associated health impacts. Previous work has examined co-benefits of climate policy from reducing PM_{2.5} in rapidly-developing countries such as China, but have not examined co-benefits from ozone and its transboundary impact for both PM_{2.5} and ozone. Here, we compare the air quality and health co-benefits of China's climate policy on both PM_{2.5} and ozone in China to their co-benefits in three downwind and populous countries (South Korea, Japan and the United States) using a coupled modeling framework. In a policy scenario consistent with China's pledge to peak CO₂ emissions in approximately 2030, avoided premature deaths from ozone reductions are 54 300 (95% confidence interval: 37 100–71 000) in China in 2030, nearly 60% of those from PM_{2.5}. Total avoided premature deaths in South Korea, Japan, and the US are 1200 (900–1600), 3500 (2800–4300), and 1900 (1400–2500), respectively. Total avoided deaths in South Korea and Japan are dominated by reductions in PM_{2.5}-related mortality, but ozone plays a more important role in the US. Similar to co-benefits for PM_{2.5} in China, co-benefits of China's policy for ozone and for both pollutants in those downwind countries also rise with increasing policy stringency.

1. Introduction

Exposure to outdoor air pollution, including PM_{2.5} (particulate matter with a diameter less than or equal to 2.5 μm) and ozone can cause cardiovascular and respiratory diseases, and is estimated to be responsible for 3.3 million premature deaths in 2010 worldwide (Lelieveld *et al* 2015). Combustion of fossil fuels, particularly coal, is a major source of both primary PM_{2.5} and precursors that lead to formation of PM_{2.5} and ozone, such as sulfur dioxide (SO₂) and nitrogen oxides (NO_x). China's dense population and high coal share in energy consumption make it one of the world's most polluted countries (van Donkelaar *et al* 2016, Ma *et al* 2017). Air pollutants and their

precursors from China can also travel long distances. Studies have estimated that Asian anthropogenic emissions contributed to ~1 ppb of surface ozone averaged in the US for 2001–2005 with higher influence over the western US and in spring (Zhang *et al* 2008, Brown-Steiner and Hess 2011), and ~0.2 μg m⁻³ of surface PM_{2.5} in the US in 2000 (Lebensperger *et al* 2011). Anenberg *et al* (2009) found that about 27% of the reduced premature deaths that resulted from a 20% decrease in anthropogenic precursors of ozone in East Asia occur outside of this region, compared to only 2% for PM_{2.5} due to its shorter lifetime in the atmosphere (Anenberg *et al* 2014). However, the absolute reduction in deaths due to changes in PM_{2.5} is greater than that of ozone

because of the larger effect of $PM_{2.5}$ on mortality (Anenberg *et al* 2014). Zhang *et al* (2017) estimated that $PM_{2.5}$ pollution produced in China in 2007 was responsible for 64 800 premature deaths in regions other than China.

Climate policies that limit fossil fuel combustion can also reduce co-emitted air pollutants, thus having co-benefits for air quality and human health. This effect has been quantified extensively in the literature on both global and regional scales (e.g. West *et al* 2013, Thompson *et al* 2014). Under the 2015 Paris Agreement, China has committed to achieve a peak in national CO_2 emissions and to increase its non-fossil share of primary energy to 20% by 2030. A global study (West *et al* 2013) quantified the co-benefits of climate policy under the representative concentration pathways for $PM_{2.5}$ and ozone concentrations, and their associated premature deaths in 2030, 2050 and 2100, but did not take into account China's recent climate policy, nor did it separate the influence from Chinese anthropogenic emissions on transboundary regions. Some more recent studies have considered China's up-to-date climate policy and evaluated its air quality and health co-benefits. Peng *et al* (2018) found that electrification of transport and residential sectors with a half-decarbonized power supply (50% coal) can prevent 55 000–69 000 deaths nationally in 2030. Li *et al* (2018) found that a climate policy scenario in which CO_2 emissions peaked in approximately 2030 would avoid 94 000 premature mortalities in 2030. Both studies only quantified co-benefits from $PM_{2.5}$ reduction, since $PM_{2.5}$ is found to have a much larger contribution to premature deaths than ozone (Lelieveld *et al* 2015). However, a recent study estimated a higher positive association between ozone concentration and respiratory mortality (Turner *et al* 2016), which would lead to larger co-benefits from ozone reductions. In addition, ozone has a longer lifetime in the atmosphere than $PM_{2.5}$, making it relatively more important in transboundary regions.

In this study, we quantify the co-benefits of China's climate policy under three different stringencies on both $PM_{2.5}$ and ozone concentrations and their associated health impact in China and three downwind and populous countries: South Korea, Japan, and the US. We use the simulations performed by Li *et al* (2018) which links an energy-economic model with sub-national detail for China (the China Regional Energy Model, or C-REM) and a global atmospheric chemistry model (GEOS-Chem). Three climate policy scenarios are designed by implementing different carbon prices in C-REM that result in reductions of CO_2 intensity (defined as CO_2 emissions per unit of real GDP) by 3%, 4%, and 5% per year between 2015 and 2030 (denoted as the 3% Policy, 4% Policy, and 5% Policy scenarios). The 4% Policy scenario is consistent with China's pledge to peak CO_2 emissions in approximately 2030, and is the main scenario examined in this study.

2. Methods

Using C-REM, we simulate a No Policy scenario and three policy scenarios that target CO_2 intensity reductions of 3%, 4%, and 5% per year between 2015 and 2030. Gridded emissions of air pollutants in 2030 for each scenario are derived by scaling gridded emissions in 2015 based on projected provincial-level emissions from C-REM, and then used as input to GEOS-Chem to simulate $PM_{2.5}$ and ozone concentrations. Air quality co-benefits of climate policy are defined as the reduction in surface concentrations of $PM_{2.5}$ and ozone between the No Policy scenario and each of the three policy scenarios in 2030. Associated avoided $PM_{2.5}$ - and ozone-related premature deaths due to climate policy are calculated using the concentration-response functions (CRFs) in Burnett *et al* (2014) and Turner *et al* (2016), respectively.

2.1. C-REM

C-REM is a global general equilibrium model that resolves China's economy and energy system at the provincial-level, including production, consumption, interprovincial and international trade, energy use, and emissions of CO_2 and air pollutants. The model has a base year of 2007 and is solved at five-year intervals through 2030. It is calibrated to historical data in 2010 and 2015. CO_2 intensity reduction targets under the three policy scenarios are achieved by establishing different CO_2 prices in C-REM that lead to deployment of least-cost CO_2 reduction strategies. Besides the 4% Policy, the less stringent 3% Policy simulates a continuation of China's CO_2 intensity reduction commitment prior to the 2015 Paris Agreement, and the more stringent 5% Policy reduces China's CO_2 intensity to the model-projected world average in 2030. In C-REM, emissions of air pollutants by province and by sector are calculated from projected energy use (for combustion sources) or economic activity (for non-combustion sources), multiplied by corresponding emissions factors. In this study, we consider all the major precursors of $PM_{2.5}$ and ozone— SO_2 , NO_x , ammonia (NH_3), black carbon (BC), organic carbon (OC), carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs). Emissions factors by province, by sector and by energy type for each pollutant in 2007 are derived from the Regional Emission inventory in Asia (REAS, Kurokawa *et al* 2013). Emissions factors in 2010 and 2015 are calibrated based on national total emissions reported in the Multi-resolution Emission Inventory for China (MEIC, <http://meicmodel.org>). In order to account for future improvement in emission control measures, we assume emission factors continue to decrease exponentially after 2015 by adopting the methodology from Webster *et al* (2008), where the exponential decay factors for each species are determined based on historical emission

trends in 15 developed countries (US, Japan, Australia, and 12 European countries) from 1971 to 1999 (Stern 2005). Further details on C-REM, matching of sectors and energy type between C-REM and REAS, calibration in 2010 and 2015 to the MEIC inventory, and exponential decay in emissions factors after 2015 are documented in Li *et al* (2018). In addition, emission trajectories for CO₂ and air pollutants under the four scenarios are shown in figure 2 of Li *et al* (2018).

2.2. GEOS-Chem

Provincial-level emission outputs from C-REM in 2007, 2010, 2015 and the four scenarios in 2030 are used to scale gridded REAS emissions in 2007 to estimate gridded emissions in later years, which are then used in the chemical transport model GEOS-Chem to simulate PM_{2.5} and ozone concentrations. We use GEOS-Chem version 9-01-03 with a horizontal resolution of 2° × 2.5° globally and 0.5° × 0.667° in East Asia. Each simulation is one-year long with a 6-month spin-up period that uses meteorological fields from July 2009 to December 2010. Other emissions are kept constant at current levels in all simulations. Further information on the simulation configuration can be found in Li *et al* (2018). PM_{2.5} concentrations reported here are calculated by summing over sulfate, nitrate, ammonium, BC, OC, and dust concentrations as follows:

$$\begin{aligned} \text{PM}_{2.5} = & 1.33 \times (\text{SO}_4 + \text{NIT} + \text{NH}_4) + \text{BC} + 1.8 \\ & \times (1.16 \times \text{OCPI} + \text{OCPO}) + 1.86 \\ & \times \text{SALA} + \text{DST}_1 + 0.38 \times \text{DST}_2, \end{aligned}$$

where SO₄, NIT, and NH₄ represent sulfate, nitrate, and ammonium aerosols, respectively, OCPI and OCPO represent hydrophilic and hydrophobic organic carbon, and SALA represent accumulation mode sea salt. DST₁ and DST₂ represent dust with size bins of 0.2–2.0 and 2.0–3.6 μm in diameter, respectively. Scaling factors of 1.33, 1.16, and 1.86 are used for SO₄-NIT-NH₄, OCPI, and SALC respectively to convert dry aerosol concentrations from GEOS-Chem outputs to measured PM_{2.5} which is often under a relative humidity of 35% (Chow and Watson 1998). We convert organic carbon to organic matter using a ratio of 1.8 based on measurements in Chinese cities (Xing *et al* 2013). DST₂ is multiplied by 0.38 to reflect the mass fraction of PM_{2.5} in this size bin, assuming a log-normal size distribution.

Using measurements of sulfate, nitrate, ammonium, BC, OC, and total PM_{2.5} taken between 2005 and 2010, we find that GEOS-Chem can generally reproduce the observed spatial distribution of PM_{2.5} and its species with correlation coefficients (*R*) greater than 0.6 (detailed comparisons are shown in Li *et al* 2018). We also compare our simulated monthly ozone concentrations in 2007 with the available measured monthly values near 2007 at seven observation sites in East China (Li *et al* 2007, Lin *et al* 2008, Yang *et al* 2008,

Wang *et al* 2009, 2011). Despite the differences in year, they are comparable given that the interannual variations of surface ozone in China due to emissions and meteorology are generally within 4 ppb (Lou *et al* 2015), much smaller than the observed seasonal cycles which are usually as large as 20 ppb. Details of the observation sites are listed in supplementary table S1 (available online at stacks.iop.org/ERL/14/084006/mmedia) and a comparison for each site is shown in supplementary figure S1. GEOS-Chem captures the seasonal variation in ozone concentrations indicated by correlation coefficients (*R*) ranging from 0.62 to 0.91, and annual-average model biases are within 5 ppb (with the exception of the Miyun site).

2.3. Health analysis

Premature deaths attributed to PM_{2.5} from acute lower respiratory illness (ALRI), ischemic heart disease (IHD), cerebrovascular disease (CEV), chronic obstructive pulmonary disease (COPD), and lung cancer (LC) in 2030 in each grid cell are estimated from:

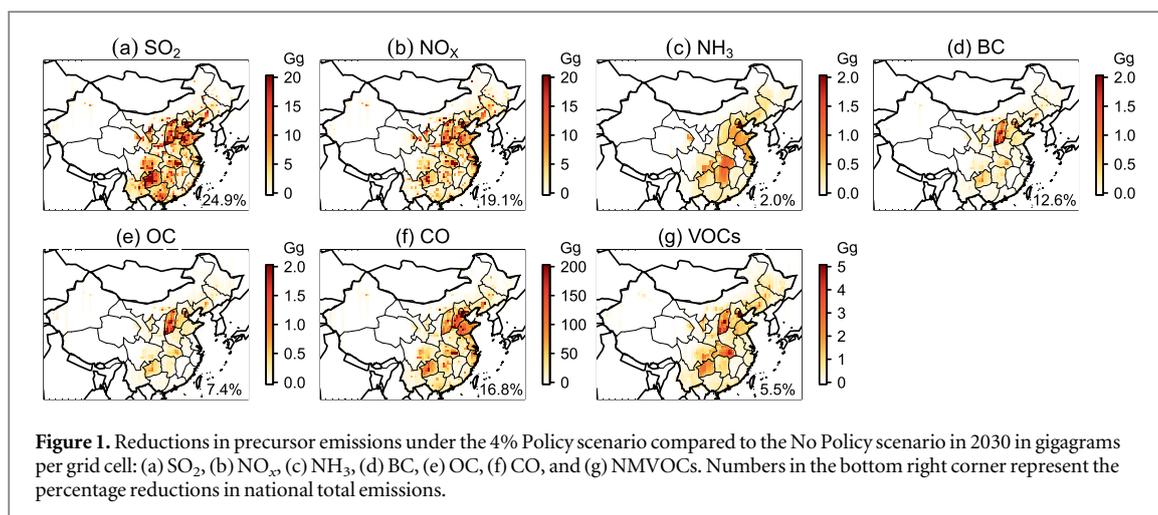
$$\text{Mort}_i = \text{pop}_i \times y_{0i} \times (1 - 1/\text{RR}_i),$$

where *i* represents each of the five diseases, pop is the population of either children younger than 5 years (for ALRI) or adults older than 30 years (for IHD, CEV, COPD, and LC), *y*₀ is the baseline incidence rate of a certain disease, (1 - 1/RR) is the attributable fraction of deaths due to PM_{2.5}, and RR is the relative risk defined as the ratio of incidence rates between exposed and unexposed populations. Here RR is calculated from the CRF in the 2010 GBD study (Burnett *et al* 2014), which incorporates epidemiological studies of passive and active smoking and indoor air pollution to account for high PM_{2.5} concentrations:

$$\text{RR} = 1 + \alpha \{1 - \exp[-\gamma(c - c_{cf})^\delta]\},$$

where *c* is the simulated PM_{2.5} concentration in μg m⁻³, *c*_{cf} is the counterfactual concentration below which there is no additional risk, α, γ, and δ are coefficients that determine the shape of the CRF. We use the distribution of CRFs provided by Burnett *et al* (2014) for each disease, specifically, 1000 sets of *c*_{cf}, α, γ, and δ from Monte Carlo simulations for ALRI, COPD and LC, and age-specific CRFs (1000 sets of parameters) in every five-year age interval for IHD and CEV. Avoided deaths due to climate policy from PM_{2.5} are the difference in premature deaths between the No Policy scenario and each of the policy scenarios. We first calculate 1000 country- and disease-specific avoided deaths using the 1000 sets of parameters. Then the total avoided deaths for all five diseases are summed by taking one sample from the 1000 avoided deaths for each disease. This process is repeated 100 000 times to get the median values and 95% confidence intervals (CIs) reported here.

Avoided premature deaths due to climate policy attributable to ozone are estimated from:



$$\Delta \text{Mort} = \text{pop} \times y_0 \times (1 - 1/\text{RR}).$$

We use a log-linear CRF between change in ozone concentration and RR:

$$\text{RR} = \exp(-\beta \Delta c),$$

where pop is the population of adults older than 30 years, Δc is the change in ozone concentration between No Policy scenario and each of the policy scenarios in ppb, and β is the CRF slope calculated from a recent estimate of RR per 10 ppb increase in annual-mean of maximum daily 8 h average (MDA8) ozone of 1.12 (95% CI: 1.08–1.16) for respiratory diseases and 1.03 (95% CI: 1.01–1.05) for circulatory diseases (Turner *et al* 2016). Avoided deaths of each disease are sampled 100 000 times from the normal distribution of RR, and the median values and 95% CIs of total avoided deaths are derived from 100 000 random samples, similar to PM_{2.5}. We use daily 10am–6pm average ozone concentration as a proxy for MDA8 ozone concentration. For comparison, we also calculated avoided deaths using an older CRF with an RR per 10 ppb increase in the maximum 6 month average of 1 h daily ozone maximum of 1.040 (95% CI: 1.013–1.067) for respiratory diseases (Jerrett *et al* 2009). We increase the Δc of MDA8 ozone averaged from April to September by 10% to represent the maximum 6-month average of 1 h daily ozone maximum following Shen *et al* (2017).

Baseline mortality rates for each country and each disease are obtained from the World Health Organization Mortality Database (World Health Organization 2015). We use mortality rates from the most recent available year in the dataset, which is the year 2000 for China, 2013 for South Korea and Japan, and 2007 for the US. Country-specific baseline mortality rates for PM_{2.5}- and ozone-related diseases are listed in supplementary table S2. We assume mortality rates are unchanged in 2030. Gridded population in 2030 is derived by scaling gridded population data in 2010 from the NASA Socioeconomic Data and Applications Center (NASA SEDAC 2005), based on population projections by country and by age group in 2030 from the United Nations World Population Prospects 2015

revision under a median fertility scenario (United Nations 2015) assuming that the spatial distribution of population in each country in 2030 is the same as that in 2010.

3. Results

3.1. Co-benefits under the 4% Policy scenario

Figure 1 shows reductions in precursor emissions under the 4% Policy scenario compared to the No Policy scenario in 2030. Climate policy limits fossil fuels by use in proportion to carbon content, therefore air pollutants that mostly come from fossil fuel such as SO₂, NO_x, and CO emissions are reduced by 17%–25%. Their reductions are much greater than NH₃ and NMVOCs (2%–6%), which are mainly from agriculture and industrial processes, respectively. Emissions from non-combustion sources are affected by climate policies indirectly due to a reduction in the activity levels of those sectors, thus percentage reductions are smaller. Emissions reduction also differs by province. Larger reductions of SO₂ and NO_x emissions are found in Guizhou, Shanxi, and Shandong provinces since they have a larger share of energy-intensive industries and abundant low-cost opportunities to improve coal use efficiency. NH₃ emissions decline more in Hunan and Hubei provinces since their baseline emissions are higher.

Figures 2(a) and (b) show the reductions in simulated annual-mean surface concentrations of PM_{2.5} under the 4% Policy scenario compared to the No Policy scenario in East Asia and the US in 2030. Larger PM_{2.5} co-benefits are found in North China, Central China, Sichuan, and Guizhou provinces, due to a larger reduction in both sulfate and nitrate aerosols in these regions (supplementary figures S2(a) and (c)). Table 1 lists the population-weighted air quality co-benefits for China and three downwind countries in 2030 under the 4% scenario, and co-benefits as percent changes are shown in table S3. The population-weighted concentration of PM_{2.5} in China is reduced by 8.3 $\mu\text{g m}^{-3}$ from 69.9 $\mu\text{g m}^{-3}$ in the No Policy scenario to 61.6 $\mu\text{g m}^{-3}$ in

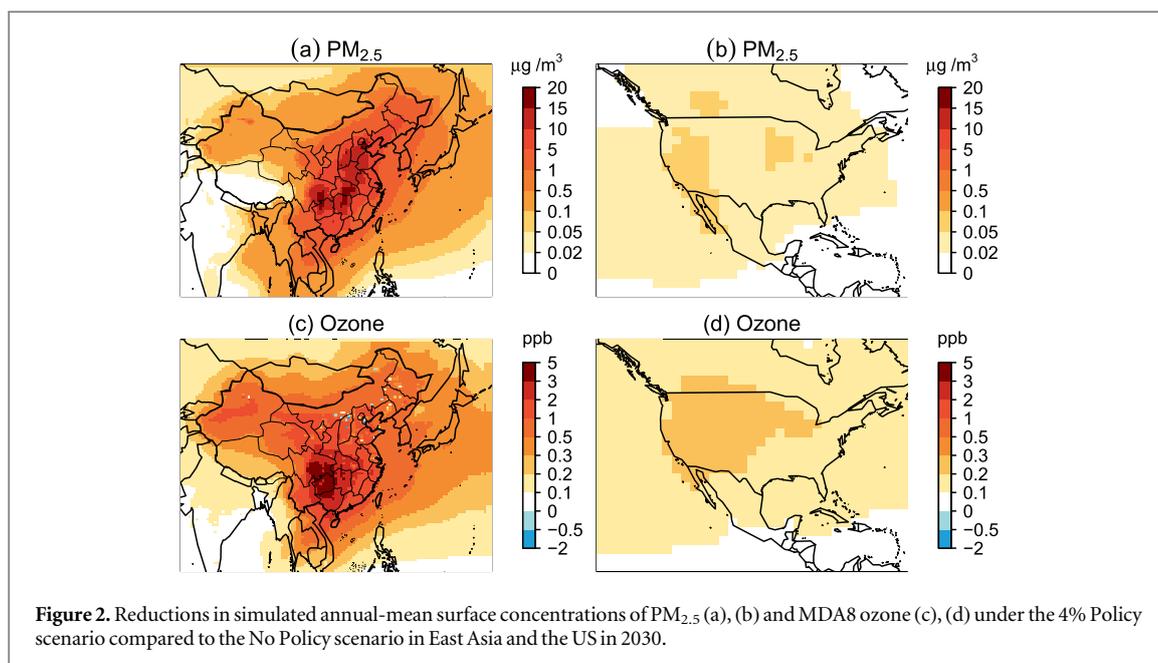


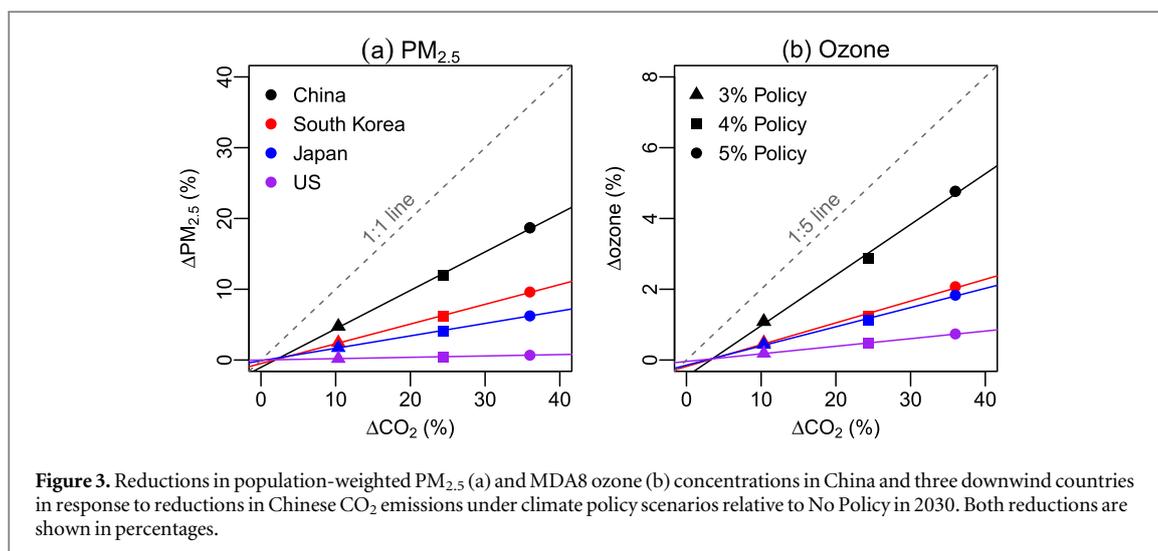
Table 1. Projected air quality co-benefits for the 4% Policy scenario in China and three downwind countries in 2030. Values are population-weighted averages.

	PM _{2.5} ($\mu\text{g m}^{-3}$)	Sulfate ($\mu\text{g m}^{-3}$)	Nitrate ($\mu\text{g m}^{-3}$)	Ammonium ($\mu\text{g m}^{-3}$)	BC ($\mu\text{g m}^{-3}$)	OC ($\mu\text{g m}^{-3}$)	MDA8 ozone (ppb)
China	8.33	3.21	2.20	1.82	0.37	0.74	1.57
South Korea	1.66	0.87	0.22	0.38	0.06	0.13	0.55
Japan	0.51	0.32	0.02	0.12	0.02	0.04	0.46
US	0.04	0.03	0.001	0.01	0.001	0.001	0.20

the 4% Policy scenario, as discussed further in Li *et al* (2018). Inorganic aerosols (sulfate, nitrate, and ammonium) account for 87% of the total co-benefits, with sulfate contributing 39% and nitrate contributing 26%. Reduction in PM_{2.5} is diluted downwind of China. As a result, population-weighted PM_{2.5} in South Korea, Japan, and the US are reduced by 1.7, 0.5, and 0.04 $\mu\text{g m}^{-3}$, respectively, relative to No Policy. These reductions are one to two orders of magnitude smaller than that in China. Reductions in downwind countries are also primarily due to sulfate. The percentage reduction due to sulfate is 53% in South Korea and 70% in the US. The dilution effect of sulfate reduction is weaker than that of nitrate, because transported SO₂ continues to oxidize to sulfate along the transport pathway (supplementary figure S3). Sulfate reduction is fairly uniform over the US, whereas nitrate reduction occurs in the Midwest where local NO_x emissions are higher (supplementary figure S2).

Figures 2(c) and (d) shows the reductions in simulated annual-mean surface concentrations in MDA8 ozone under the 4% Policy scenario compared to the No Policy scenario in East Asia and the US in 2030. Following reduction in precursor emissions, the population-weighted MDA8 ozone concentration in China is reduced by 1.6 ppb from 54.4 ppb under the No Policy scenario to 52.8 ppb under the 4% Policy

scenario. Co-benefits of MDA8 ozone are higher in Sichuan and Guizhou provinces, and are negative in some areas in North China. Despite NO_x emissions reductions in both North and South China (figure 1(b)), ozone co-benefits in South China are positive (that is, climate policies result in ozone reductions) throughout the year, but are negative (result in ozone increases) in some places in North China in spring and fall, and negative in most of North China in winter (supplementary figures S4(a)–(d)). To examine whether the ozone co-benefits are due to reductions in NO_x emissions or other ozone precursors (e.g. NMVOCs and CO), we conducted sensitivity simulations of the 4% Policy scenario in one month of each season—January, April, July, and October, in which only NO_x emissions are changed, while emissions of all the other species follow the No Policy scenario. We found that ozone co-benefits under the 4% Policy case are predominantly due to the reduction in NO_x emissions in every season (supplementary figure S5). Compared to the co-benefits in seasonal averages of MDA8 ozone, co-benefits in seasonal averages of 24 h ozone are similar in pattern, but smaller in magnitude (supplementary figures S4(e)–(h)). The direction of the latter can be explained by whether the ozone formation is in a NO_x-limited or NO_x-saturated regime. We use the surface ratio of



formaldehyde (HCHO) to nitrogen dioxide (NO₂) as a regime indicator, and regime thresholds identified by Jin *et al* (2017) over East Asia (a ratio <0.5 being NO_x-saturated and >0.8 being NO_x-limited). Supplementary figures S4(i)–(l) show that South China is in a NO_x-limited regime in all seasons where ozone decreases (or co-benefits are positive) as NO_x decreases. North China is primarily in a NO_x-saturated regime in winter, spring, and fall, where ozone increases (or co-benefits are negative) when NO_x decreases. Population-weighted co-benefits in South Korea, Japan, and the US under this policy scenario are 0.6, 0.5, and 0.2 ppb, respectively, which are 13%–35% of that in China. Ozone co-benefits in the US are higher in the west.

3.2. Co-benefits under different policy stringencies

Figure 3 compares the percentage reductions in PM_{2.5} and ozone in China and its downwind countries (ΔPM_{2.5} and ΔOzone) to reductions in Chinese CO₂ emissions (ΔCO₂) under different policy stringencies. Li *et al* (2018) found that the relationship between ΔPM_{2.5} and ΔCO₂ in China is linear, but the regression slope is less than 1 (0.54) largely because NH₃ emissions, a precursor of PM_{2.5} formation, are barely affected by climate policy. This linearity also holds for downwind countries, but with smaller slopes of 0.28, 0.18, and 0.02 in South Korea, Japan, and the US, respectively, as different scenarios only change the PM_{2.5} originating from Chinese emissions which is a small fraction of the total PM_{2.5} in each country. Between the two dominant species of PM_{2.5}—sulfate and nitrate, the percentage reductions of nitrate are less than those of sulfate in China (supplementary figure S6). The smaller slope of nitrate occurs because the percentage reduction of NO_x emissions is less than that of SO₂ emissions as discussed in Li *et al* (2018), and the percentage reduction of nitrate is lower than that of NO_x emissions, especially in winter, in contrast to the nearly 1:1 ratio in the reductions of sulfate to SO₂ emissions (supplementary figure S7).

Relative reductions in ozone are also reduced linearly with CO₂ emissions under different scenarios in these four countries. The regression slope between reductions in ozone and CO₂ emissions in China is 0.14, one fourth of that for PM_{2.5}. This is because Chinese anthropogenic emissions only contribute to a small fraction of the total ozone over China, with contributions from natural sources and anthropogenic emissions from elsewhere. By conducting a sensitivity simulation in which Chinese anthropogenic emissions of NO_x, CO, and NMVOCs are zeroed out in 2010, we found that the fraction of ozone from Chinese anthropogenic emissions is about 25% averaged over China, consistent with Wang *et al* (2011). The slopes in downwind countries decay from 0.06 in South Korea to 0.02 in the US, which is slower than for PM_{2.5} due to the longer lifetime of ozone compared to aerosols.

3.3. Avoided premature deaths

Table 2 lists avoided PM_{2.5}- and ozone-related premature deaths in the 4% Policy scenario. Supplementary table S4 further lists avoided deaths due to the five PM_{2.5}-related diseases. Compared to the No Policy scenario, the 4% Policy scenario prevents 95 200 (78 500–112 000; 95% CI) PM_{2.5}-related premature deaths in China in 2030. Avoided deaths from PM_{2.5} in South Korea, Japan, and the US are 1000 (600–1200), 2000 (1400–2600), and 600 (400–900), respectively, two orders of magnitude smaller than those in China. Avoided PM_{2.5}-related deaths in Japan are double those in South Korea (primarily from IHD, CEV, and LC) even though the reduction in population-weighted PM_{2.5} in Japan is only 30% of that in South Korea. This is because Japan has an exposed population that is 2.3 times as large as South Korea's, and baseline mortality rates of IHD, CEV, and LC for Japan are 54%–100% higher than those for South Korea (supplementary table S2).

The 4% Policy scenario also reduces ozone-related premature deaths in China by 54 300 (37 100–71 000;

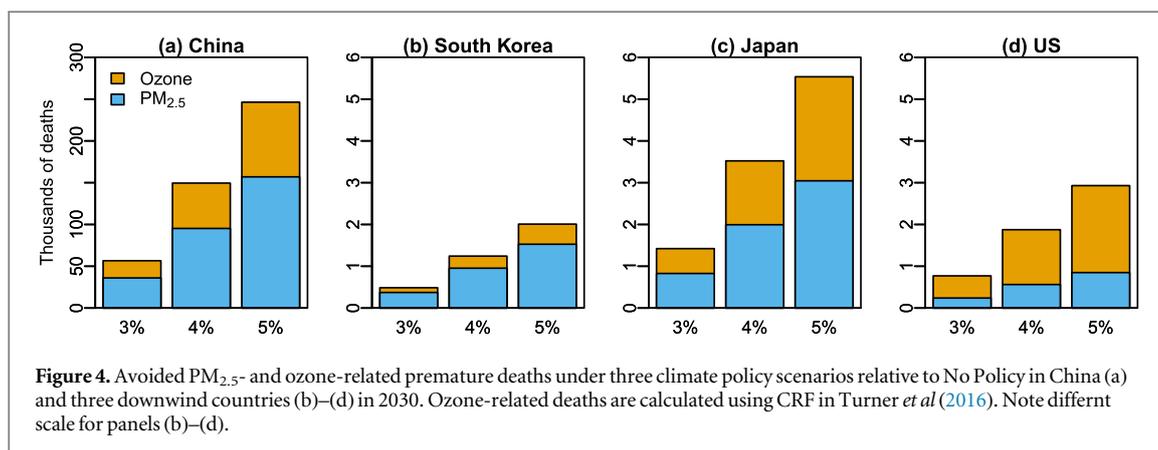


Figure 4. Avoided PM_{2.5}- and ozone-related premature deaths under three climate policy scenarios relative to No Policy in China (a) and three downwind countries (b)–(d) in 2030. Ozone-related deaths are calculated using CRF in Turner *et al* (2016). Note different scale for panels (b)–(d).

Table 2. Avoided PM_{2.5}- and ozone-related premature deaths under the 4% Policy scenario compared to the No Policy scenario in China and three downwind countries in 2030. Ozone-related deaths are calculated using two different CRFs. Values in parenthesis represent 95% confidence intervals.

	Population of adults older than 30 years in 2030	Avoided deaths per year			
		PM _{2.5}	Ozone (CRF from Turner <i>et al</i> 2016)	Ozone (CRF from Jerrett <i>et al</i> 2009)	PM _{2.5} and ozone (ozone CRF from Turner <i>et al</i> 2016)
China	971 139 000	95 200 (78 500–112 000)	54 300 (37 100–71 000)	21 100 (7000–34 600)	149 400 (125 400–173 300)
South Korea	38371000	1000 (600–1200)	300 (200–400)	90 (30–150)	1200 (900–1600)
Japan	88 977 000	2000 (1400–2600)	1500 (1100–2000)	500 (200–800)	3500 (2800–4300)
US	224 712 000	600 (400–900)	1300 (800–1800)	200 (100–400)	1900 (1400–2500)

95% CI) using CRF from Turner *et al* (2016), which is nearly 60% of those from PM_{2.5}. In contrast, this figure is only 22% using an older CRF from Jerrett *et al* (2009) for an April–September average of 1 h daily maximum ozone. Building on Jerrett *et al*, Turner *et al* used improved exposure models and a larger dataset for that observed more participants over a longer time period and found significant positive associations between ozone and both respiratory and circulatory mortality, which led to the difference between the two estimates. Avoided deaths due to ozone in South Korea are 30% of those from PM_{2.5}, much lower than the fraction in China (57%) and Japan (76%), since the baseline incidence rate of ozone-related respiratory disease in South Korea is much smaller (supplementary table S2). In contrast, avoided deaths from ozone in the US are double those from PM_{2.5} because of a relatively larger reduction in ozone concentration compared to PM_{2.5}—ozone reduction between China and US differs by a factor of eight, while PM_{2.5} reduction differs by two orders of magnitude (table 1). Avoided premature deaths in the four countries from both PM_{2.5} and ozone also rise proportionally as policy stringency increases (figure 4). We note that simulated concentrations for the US use a coarser resolution (2° × 2.5°) than the other countries examined (0.5° × 0.667°). To quantify the effect of this

difference in resolution, we calculated impacts at 2° × 2.5° for other countries for comparison. At coarser resolution, changes in total avoided deaths in China, South Korea and Japan are within 4%, with a 4%–8% decrease for PM_{2.5}, and a 9%–18% increase for ozone. Thus, we conclude that the difference in resolution plays only a minor role in the projection of avoided deaths for the US.

4. Conclusions

Using model simulations performed in Li *et al* (2018) which examines co-benefits of China's climate policy from reducing PM_{2.5} in China, this study further quantifies the co-benefits from ozone in China and from both pollutants in three downwind countries. We find that under a policy scenario consistent with China's pledge to peak CO₂ emissions in approximately 2030 (4% Policy scenario), population-weighted concentrations of MDA8 ozone in China would reduce by 1.6 ppb in 2030 compared to the No Policy scenario, preventing 54 300 (95% CI: 37 100–71 000) premature deaths using a recently updated CRF, which is 57% of the avoided deaths from PM_{2.5}. Co-benefits from PM_{2.5} in the downwind countries are one to two orders of magnitude smaller

than those in China, and are mainly due to a reduction in sulfate, followed by nitrate. Avoided deaths from PM_{2.5} are more than those from ozone in South Korea and Japan, while ozone is more important in the US, since it has a longer lifetime. Under the 4% Policy scenario, avoided premature deaths from both pollutants are 1200 (900–1600), 3500 (2800–4300), and 1900 (1400–2500) in South Korea, Japan, and the US, respectively. Total avoided deaths in these three downwind countries are about 4% of those in China. Similar to co-benefits from PM_{2.5} in China, co-benefits from ozone and in downwind countries for both PM_{2.5} and ozone also rise with increasing policy stringency. The co-benefits quantified in this study are for the year 2030, and are expected to increase over time from the baseline year to 2030.

Assumptions underlying our emissions projection and health analysis may affect the magnitude of these calculated co-benefits. First, a recent bottom-up inventory study suggested reductions in Chinese SO₂ and NO_x emissions from 2010 to 2017 of 62% and 17%, respectively (Zheng *et al* 2018), while increases of 25% and 15% between 2010 and 2015 are used in this study. These reductions would reduce calculated co-benefits of sulfate and nitrate proportionally. Second, we assume emission factors would decay exponentially over time based on estimates for several developed countries in the past. Large uncertainties exist when applying these parameters to China, and again would affect the absolute (but not relative) levels of co-benefits. Third, a recent study (Burnett *et al* 2018) using the Global Exposure Mortality Model suggested that outdoor PM_{2.5} pollution causes several-fold more deaths than previous estimates; health co-benefits from PM_{2.5} estimated here would be larger if using this CRF. We chose to use the older CRF to enable comparison with previous work for China (Li *et al* 2018). Finally, the 95% CIs of avoided premature deaths reported here only represent uncertainties in the CRF, and recent studies suggested that it may be exceeded by uncertainties from either simulated air pollution among different models (Liang *et al* 2018) or climate variability (Saari *et al* 2019).

Despite these uncertainties, our study shows that co-benefits of climate policy from reducing ozone-related premature deaths in China are comparable to those from PM_{2.5}. Ozone-related co-benefits have often been omitted in previous studies. Further, we found co-benefits from Chinese climate policy outside of China's borders. While avoided premature deaths in transboundary regions are only 4% of those in China, avoided premature deaths of 1900 in the US from China's climate policy in 2030 in this study is 4%–17% of the health co-benefits from climate policy in the US in either 2030 or 2050 (Thompson *et al* 2014, Shindell *et al* 2016, Zhang *et al* 2017). Similar comparisons for South Korea and Japan would also be of interest, but co-benefits studies conducted specifically for these countries are not yet available.

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