Effects of Climate Change on China's Future Air Quality and Health Benefits Associated with Greenhouse Gas Mitigation

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Abstract

Climate change can affect China's air quality through long-term change in meteorology. Using a climate-chemistry-health integrated modeling framework, this study examined the impact of climate change on present and future $PM_{2.5}$ concentrations in China. We found that a changing climate, independent of emission changes, could lead to significant regional differences in $PM_{2.5}$ change. We evaluated the relationship of $PM_{2.5}$ with meteorological variables and identified temperature as a important climate driver for $PM_{2.5}$ response to a changing climate, affecting major inorganic $PM_{2.5}$ during both summer and winter. Physical mechanisms such as relative humidity and boundary layer height could lead to $PM_{2.5}$ decreases across China during winter and in summertime South China. We also evaluated the premature mortality associated with climate-related air pollution and health benefits under multiple greenhouse gas mitigation scenarios. Future climate are expected to create national-level health benefits particularly under stringent climate policies, while we observed both climate penalties and benefits on human health at a regional scale.

1 Introduction

As the greatest environmental health risk identified by World Health Organization (WHO), ambient air pollution has become a major public health concern for many parts of the world. Extensive epidemiological studies have shown strong and consistent positive correlations between human health and air pollution (Pope and Dockery 2006). Acute and chronic exposure to fine particulate matter less than 2.5 um in diameter ($PM_{2.5}$) has been found to be strongly associated with cardiovascular, respiratory and all-cause mortality and various cardio-respiratory and pulmonary diseases (Pope and Dockery, 2006). China is the largest contributor to air pollution induced mortality at a global scale, with 1.36 million death annually resulted from elevated high concentrations of major atmospheric aerosols and gases such as $PM_{2.5}$ and ozone (Lelieveld et al. 2015). Understanding the future changes in air pollution is critical for in designing appropriate energy, environmental and public health policies to promote human health.

Ambient air pollution is a combined result of high pollutant emissions and unfavorable meteorological conditions. Changes in meteorological conditions, such as temperature, precipitation, relative humidity, stagnation frequency, and atmospheric circulation patterns(Jacob and Winner 2009; Isaksen et al. 2009; Fiore et al. 2012). Previous modeling studies have found that an increased number of regional stagnation events could exacerbate ozone (O3) and particulate matter (PM) pollution (Pye et al. 2009; Wu et al. 2008). Under a warmer climate, ozone concentration tends to increase in polluted urban regions (Lin et al. 2008). Particulate matter would also increase due to regional decreases in precipitation. Changes in planetary boundary layer (PBL) depth could affect atmospheric ventilation and stagnation that contribute to PM change. A combination of these long-term meteorological changes alone, independent of anthropogenic greenhouse gas emission changes, could lead to an overall increase in air pollutant levels, thus creating "climate penalty" on air quality. It is also possible that a changing meteorology could lead to benefits, reducing pollutant levels in certain regions. However, the impact of future climate on air quality is still unclear.

This study focuses on the climate impact on $PM_{2.5}$, an important and highly complex atmospheric constituent consisting of sulfate, nitrate, ammonium, organic aerosol, elemental carbon, soil dust, and sea salt. Previous research utilizing fully coupled global chemistry-climate models have found that climate change could lead to a significant change of +/- 1 $\mu g/m^3$ in annual mean PM2.5 in the next century (Jacob and Winner 2009). However, there is little consistency across the studies, even including the sign of the results. Climate impact on $PM_{2.5}$ is difficult to quantify due to varying responses of $PM_{2.5}$ species to climate change. Meteorological conditions that are related to physical mechanisms such as precipitation and wind speed, could affect signs of $PM_{2.5}$ species changes in the same direction through enhanced wet deposition, transport and ventilation. Meanwhile some meteorology parameters such as temperature, cloud cover and humidity influence chemical pathways through reaction rate and oxidant concentrations and results in changes in one species or multiple species in opposite direction. Aside from covariation of multiple meteorological parameters, model differences in treating regional precipitation response to climate change could also contribute to such disagreement in climate-related $PM_{2.5}$ (Dawson, Adams, and Pandis 2007).

Most of existing studies on the "climate penalty" have been focused on United States and Europe. (Garcia-Menendez et al. 2015; Pye et al. 2009; Avise et al. 2009; Jacob and Winner 2009) Few climate-chemistry modeling studies have been targeted at how future climate influences China's $PM_{2.5}$ as future emissions changes account for significant health and economic benefits (west et al),. Jiang et al. 2013 examined the impact of a changing climate in 2050 and found that individual $PM_{2.5}$ species could change by − 1.5 to + 0.8 μgm−3 , and $PM_{2.5}$ levels are projected to vary by about 10–20% in eastern China. However, they only considered climate under A1B, which is under the Intergovernmental Panel on Climate Change' s Special Report on Emissions Scenarios (IPCC SRES). IPCC SRES were developed by different modeling groups under inconsistent baseline assumptions and could not be used to systematically evaluate the impact of specific climate policies with different stringencies (Paltsev et al. 2015). Additionally, a simulation period of 10 years for 2050 in Jiang et al. may not sufficient to eliminate the natural interannual or decadal variability from long-term meteorological changes.

Our study analyzes the effect of climate change on China's anthropogenic $PM_{2.5}$ under three greenhouse gas mitigation scenarios in 2000, 2050 and 2100 using a climate-chemistry-health multi-model assessment framework. We analyze how national and regional $PM_{2.5}$ would change over time in respond to different climate conditions. We also examine long-term changes in meteorological parameters and their relationships with major inorganic $PM_{2.5}$ species to identify key climate drivers. Since no studies have been focused on the health impacts exclusively due to climate-related air pollution in China, our study also provides a first-time estimate of climate-related mortality in China to help Chinese policy makers become better informed on the human health implications of climate change in designing climate mitigation targets.

2 Methods

In order to quantify the impact of climate in China's $PM_{2.5}$, we use the global multi-model framework and its outputs in Garcia-Menendez et al (2015). The framework composed of a policy-based general circulation model (GCM), a Chemical transport model (CTM) and a health assessment modeling software. CTM uses projected climate fields generated from the GCM to produce aerosol and gaseous concentrations in the atmosphere. GCM-CTM linked model address the complex covariance between meteorological variables and climate forcing agents and offer a robust, flexible framework to simulate climate-chemistry interactions in the atmosphere. Global air quality and climate outputs from the GCM-CAM linked model in Garcia-Menendez et al (2015) are extensively used in this study. $PM_{2.5}$ Concentration outputs from the CTM are then used to estimate the associated mortality. To better quantify China's air pollution related deaths, GBD IER Model is implemented in this study, as it is much superior to many other environmental health assessments model in regions with high $PM_{2.5}$ concentrations such as China.

2.1 Climate Projections and Climate Policy Scenarios

This study uses climate projections generated from MIT IGSM-CAM, the Massachusetts Institute of Technology Integrated Global System Model (IGSM) linked to the Community Atmosphere Model (CAM). MIT IGSM is a robust model framework that couples an Earth system model with a human activity model, allowing flexible treatment of climate parameters and emission scenarios from different socio-economic conditions to efficiently estimate uncertainty in climate change (Monier et al. 2013). Climate sensitivity is assumed at 3 °C in all the climate simulations. Five ensembles of different initial conditions have been modeled to capture the natural variability in climate.

As shown in **Figure 1**, three climate policy scenarios will be assessed in this study: (1) a business-as-usual reference scenario (REF) that assumes no GHG mitigation will be taken, which results in a total radiative forcing of 10 W m−2 by 2100; (2) a GHG mitigation scenario that assumes a uniform global carbon tax to achieve a total radiative forcing of 4.5 W m−2 by 2100 (POL4.5); (3) a more stringent stabilization scenario with a total radiative forcing of 3.7 W m−2 by 2100 (POL3.7). These policy scenarios were developed under the framework of EPA's ongoing Climate Change Impacts and Risk Analysis (CIRA) project to provide consistent, comparable estimate of climate change impacts and damages to multiple sectors in the U.S. (Paltsev et al. 2015) These internally consistent policy scenarios are also highly relevant to China because climate policy requires universal commitment of all countries, particularly large GHG emitters such as China. In the CIRA projections, China is largest source of air pollutants such as SO2, CO, VOCs, and NH3 due to its already large and rapidly growing energy use, and limited pollution control. (Paltsev et al. 2015)

2.2 Atmospheric Chemistry Model

China's present and future air quality was simulated by the global Community Atmosphere Model with atmospheric chemistry (CAM-Chem) within the Community Earth System Model framework (CESM version 1.1.2), which contains a comprehensive tropospheric gas phase and aerosol chemical mechanism. CAM-Chem is able to simulate global concentrations of major $PM_{2.5}$ species including total sulfate (SO_4), ammonium nitrate (NH_4NO_3), primary carbonaceous aerosols (black carbon, organic carbon), and secondary organic aerosol (SOA), dust and sea salt. In this study, $PM_{2.5}$ concentrations over China are driven by climate fields from IGSM, while holding the all anthropogenic GHG emissions constant at year 2000 for all simulations to isolate the impact of climate. Due to the interannual variability inherent in global climate models, 30 years of air quality simulation centered at Year 2000 (1981-2010), Year 2050 (2036-2065), Year 2100(2086-2115) for each climate mitigation scenario were conducted by Garcia-Menendez et al. 2015. Effectively, each grid value used in the study is based on 150 years (30 years, 5 ensembles) of simulation are conducted to robustly examine the long-term impacts of a changing climate. All simulations are carried out at 1.9° x 2.5° resolution. Statistical significance in ensemble-mean $PM_{2.5}$ changes was tested using Student's t-test at a 95% confidence interval. Detailed model limitations and set up are described in Garcia-Menendez et al. 2015.

2.3 Health Assessment Model

Using anthropogenic $PM_{2.5}$ outputs from CAM-Chem, an Integrated Exposure-Response function developed for Global Burden of Disease Model of 2010 (GBD2010 IER) was applied to estimate premature mortality due to exposure to ambient $PM_{2.5}$. We used a three-parameter exponential decay saturation model with a power of $PM_{2.5}$ concentration proposed by Burnett et al. 2014. The model increases monotonically with increasing $PM_{2.5}$ exposure concentration with a flexibility to take on a variety of shapes. By integrating available health risk information from studies of second hand tobacco smoke (SHS), household solid cooking fuel (HAP), and active smoking (AS) for a proxy for countries with $PM_{2.5}$ high concentrations but few epidemiological studies on ambient air pollution, GBD EIR provides a more realistic treatment of highly-polluted regions. It is considered superior to other log-linear exposure response functions and have been applied to estimate premature mortality on a global scale as well as in China (Lelieveld et al. 2015; G. Yang et al. 2013). The GBD2010 IER model is written as

$$\boldsymbol{RR = 1 + a\{1 - \exp[-b(X - X_0)^P]\}} \qquad [\mathbf{1}]$$

where RR is the relative risk for air pollution related diseases: Ischemic heart disease (IHD), Cerebrovascular disease (stroke), obstructive pulmonary disease (COPD) and Lung cancer (LC). a, b, p are coefficient parameters, X is the $PM_{2.5}$ concentration, and X0 is the counterfactual concentration randomly drawn from a uniform distributed range of concentrations below which there is no health risk. We derived 95% confidence intervals for RR estimates based on 1000 Monte Carlo simulations for each disease per age group. RR estimates are then applied to estimate the change in mortality due to $PM_{2.5}$ for each grid, using the following equation:

$$\Delta Mortality = y_0 * \frac{RR - 1}{RR} * Population \quad [2]$$

Where y_0 is the baseline incidence rate for each disease category per age group. Baseline incidence rate at year 2000 from World Health Organization Statistical Information System Mortality Database (World Health Organization 2012) is used and assumed as constant in 2050 and 2100. China's Population for 2000 at 0.5x0.5 resolution was obtained from XXXX(ask Mingwei) and regridded to 1.9x2.5 resolution to match the concentrations of air pollutants from CAM-Chem. We used the total population projections from the United

Nations Department of Economic and Social Affairs/Population Division70 (http://esa.un.org/unpd/wpp) and applied a linear scaling factor to each grid population in 2050 and 2100. In the sensitivity scenario, population was held constant at 2000 level. We estimated the number of deaths attributable to LC and COPD for the entire population and Stroke and IHD for adult population greater than 30 years old. By summarizing all the mortality changes for each disease category under multiple greenhouse gas mitigation scenarios, we are able to infer the overall health impacts due to climate-related air pollution. We assume that uncertainty in mortality estimates only comes from uncertainty in RRs. Uncertainty associated with population and baseline incidence rate are not included. Detailed GBD IER Model methodology and parameter outputs are available at The Institute for Health Metrics and Evaluation (IHME).

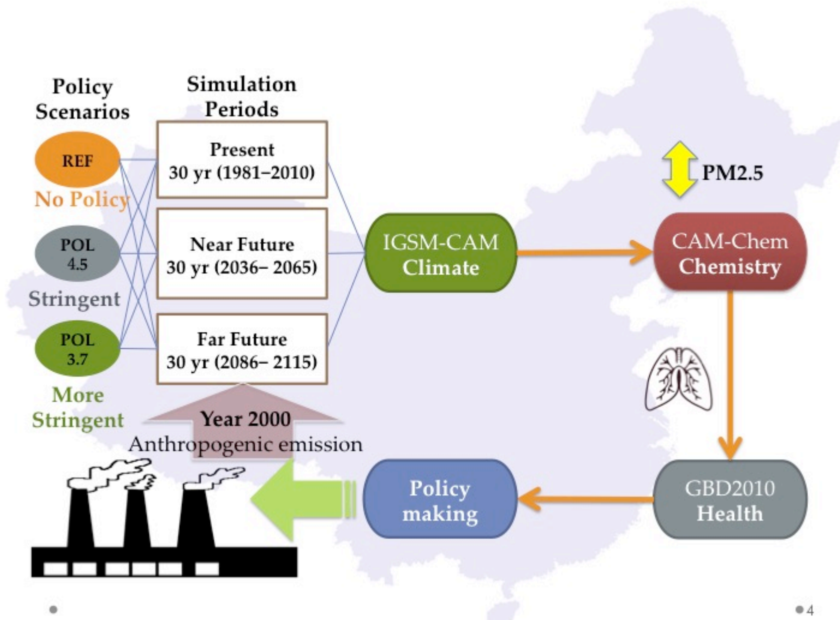

Figure 1: Summary of the integrated multi-model approach used in the study. By keeping anthropogenic GHG emissions at year 2000 level in all simulations, we evaluate climate impact on $PM_{2.5}$ under three climate policy scenarios (REF, POL4.5 and POL3.7) at present, near future and far future using a Climate-Chemistry-Health modeling framework.

3 Results

3.1 Model Validation

CAM-Chem has only been previously systematically evaluated in North America and Europe (Lamarque et al. 2012; Val Martin, Heald, and Arnold 2014). Extending the application of MIT IGSM-CAM model to China requires careful model validation. Unfortunately, CAM-Chem validation on China is difficult due to the lack of observation data in 2000. Unlike United States and Europe, continuous large-scale monitoring of air pollution has just recently started in China. Although not ideally comparable, sulfate, ammonium nitrate, black carbon and organic carbon in REF2000 were compared with previous literature data available (2006-2013) to gauge our confidence in the model. (Zhang et al. 2013; Jiang et al. 2013; He et al. 2012; Zhao et al. 2013; L. Yang et al. 2007)Observation concentrations are linearly adjusted using SO2. NOX, NH3 emissions from Regional Emission inventory in Asia (REAS Ver.2) (Kurokawa et al. 2013). Since CAM-Chem uses a bulk aerosol model that does not specify other ammonium or nitrate species except for ammonium nitrate, total nitrate and total ammonium species for the model are assumed to be the ammonium and nitrate species in the ammonium nitrate. **Figure 2** shows generally good agreement with observed sulfate (r=0.79), nitrate (r=0.68) and ammonium (r=0.81). Total sulfate, after linearly adjusted for emission differences, shows only 6% Normalized mean bias (NMB) between the model observations sites. Emission-adjusted NMB for nitrate is -27%. Ammonium is significantly underestimated (NMB=-80%) possibly due to the low NH3 emissions in 2000 and availability of non-NH_4NO_3 ammonium. Although more validation work will be needed, CAM-Chem is capable of reproducing the spatial distribution of China's $PM_{2.5}$ SNA species.

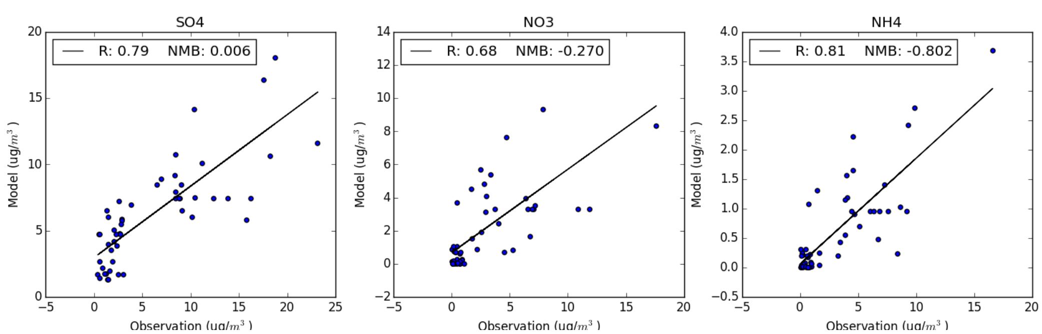

Figure 2. Correlation between annual modeled REF2000 SNA species and annual observation data (2006-2013). Modeled total nitrate shown is a fraction of ammonium nitrate. Sulfate, ammonium and nitrate correlate well with observation (R=0.68-0.81). Large bias exists for nitrate and ammonium.

3.2 Climate Change Impact on China's $PM_{2.5}$

Regional variability in China-average annual anthropogenic $PM_{2.5}$ change (including SO_4, NH4 NO3, BC and OA) are projected to be greater in magnitude under a changing climate. Under the REF scenario, Greater Beijing and Central China (See boundary specification for the regions in **Figure A1**), experience significant increases in $PM_{2.5}$ in 2100 while $PM_{2.5}$ in coastal regions such as Southern China, Northeastern and East China decreases.

As shown in **Figure 3**, Regional $PM_{2.5}$ change ranges from 6.01 μg/m^3 increase in Sichuan Basin area to 2.99 μg/m^3 decrease in Southern China. Under POL4.5 and POL3.7, the two stringent climate mitigation scenarios, regional differences are similar but smaller. Almost all regional climate impacts are statistically significant.

At national scale, surface $PM_{2.5}$ decreases in all scenarios except for REF2100. Under MITIGATION scenario POL4.5, national-average population-weighted $PM_{2.5}$ is expected to decrease 0.36 ± 0.12 μg/m^3 in 2050 and 0.55+0.11 μg/m^3 in 2100. Decrease in $PM_{2.5}$ under the most stringent scenario POL3.7 in 2050 is not as significant compared POL4.5 (-0.29 ± 0.11), but decreases most in 2100, by a significant 0.76 μg/m^3. National-average changes under an unconstrained climate under REF are not statistically significant, yet the probability density function of $PM_{2.5}$ under REF 2000 and 2100 (**Figure 4**) suggests a greater probability of having high $PM_{2.5}$ national levels beyond 34 μg/m^3 if climate is not sufficiently mitigated in the long term.

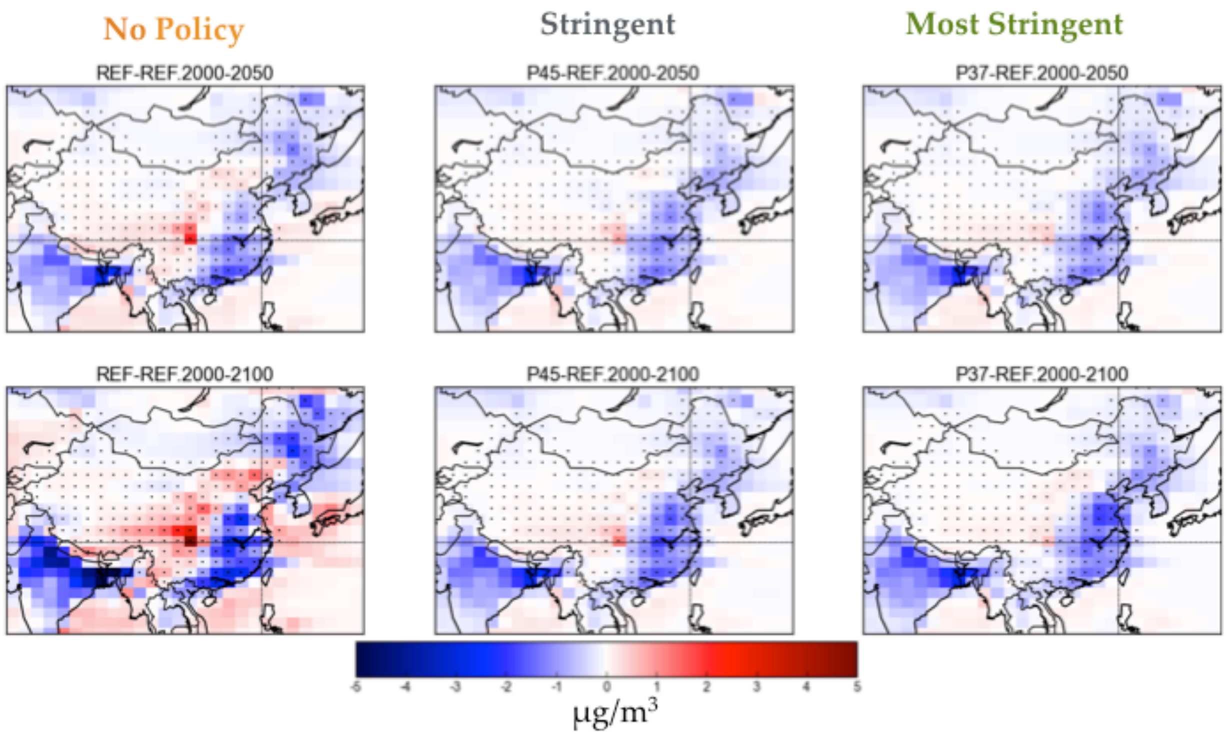

Figure 3. Ensemble-mean climate-induced change in annual average surface $PM_{2.5}$ from 2000 to 2050 and 2100 under the REF, POL4.5, and POL3.7 scenarios. Black dots indicate statistically significant changes.

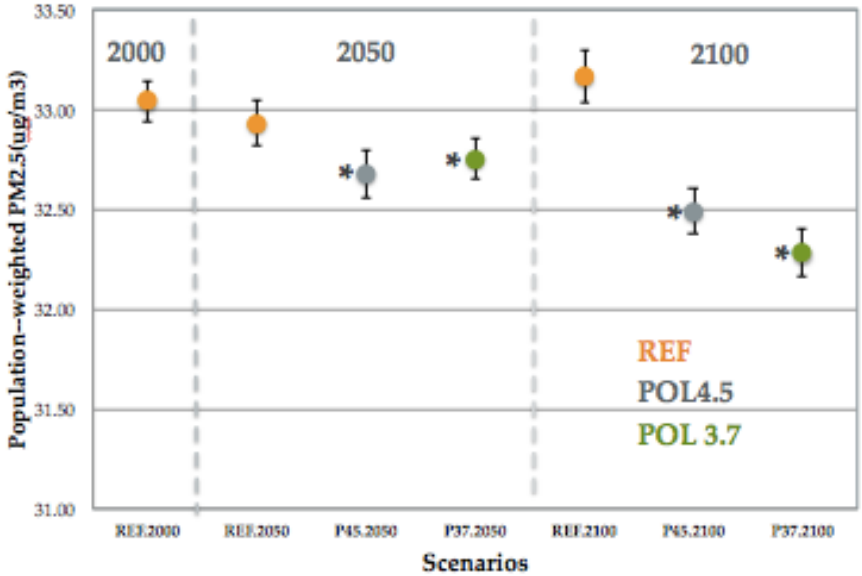

Figure 4. Ensemble-mean national-average population-weighted annual $PM_{2.5}$ in 2000, 2050, and 2100 under REF, POL4.5, and POL3.7 scenarios. Asterisks suggest significant statistical difference from REF2000 $PM_{2.5}$ with 95% confidence.

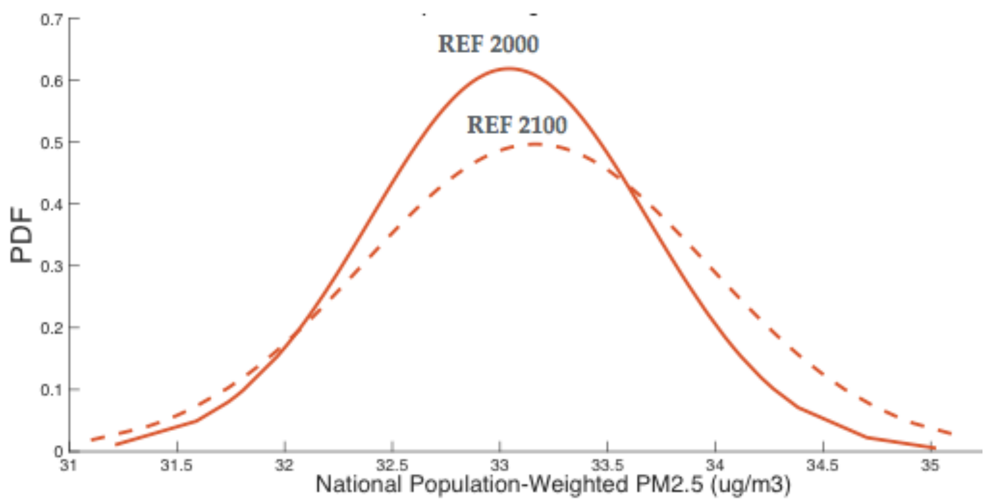

Figure 5. Probability density function of national-average population-weighted $PM_{2.5}$ in REF 2000 and 2100 using 150 annual $PM_{2.5}$ simulations, assuming a Gaussian distribution.

3.3 Meteorological drivers for SNA Changes

Meteorological changes from base year 2000 are significant. As shown in **Figure 8,** temperature increases in all seasons by approximately 6.5K in 2100. Precipitation percent change generally increases in summer, but varies greatly by regions in winter, decreasing 53% in the south while increasing nearly 40% in northeastern China. National average boundary layer height increases by 12% in winter. South China exhibits over 10% increase in boundary height in all seasons, with the highest percent increase (14%) in summer among all regions. Percent changes in surface wind speed and relative humidity are smaller. Surface wind speed increases by 10% in summer South China, and by 9% in Northeastern China in winter. Relative humidity is enhanced by 8% in Northeastern China but decreases in almost all regions in winter (+1% to -18%). In summer, relative humidity in BJ and NE increases by 3.3% and 7.9% respectively.

We evaluate the simulated seasonal sulfate and ammonium species change, with a focus on summer (June-August) and winter (December-February) changes under the REF 2100 scenario, in which SNA percent changes are most significant. Seasonal percent changes for SNA species and total $PM_{2.5}$ in REF2100 are shown in **Figure 6**. The difference in percent change of $PM_{2.5}$ and its species varies widely by season. In summer, $PM_{2.5}$ concentrations are enhanced by 3-18% in most parts of China except the South (-19%). In winter, $PM_{2.5}$ decreases in all regions (BJ, CC, NE, EC, SC). Summer $PM_{2.5}$ increase is mostly driven by the sulfate percent increase, particularly in greater Beijing where the percent change in sulfate could be as high as +48%. (**Figure 7**) Winter $PM_{2.5}$ percent decreases are mostly driven by both sulfate and ammonium nitrate percent decreases. Sulfate decreases in winter across China by 12%, with significant 25% decrease in Northeastern region. Ammonium nitrate decrease in all seasons, especially in summer with regional averages ranging from -61% (BJ) to -89%(SC). Ammonium nitrate percent decreases are smaller in winter, ranging from -6%(CC) to -41% (SC).

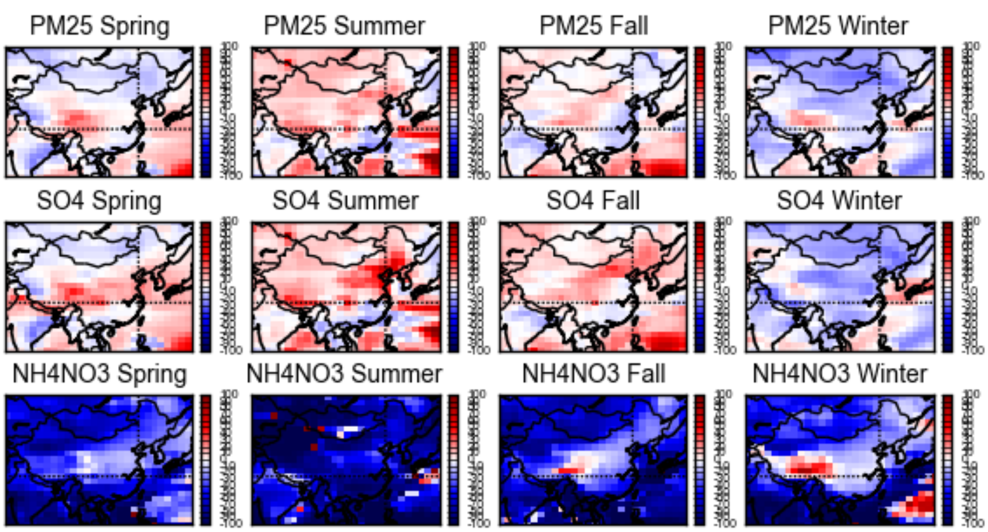

Figure 6. Ensemble-mean climate-induced seasonal percent change in surface $PM_{2.5}$, sulfate and ammonium nitrate from 2000 to 2100 under the REF scenario.

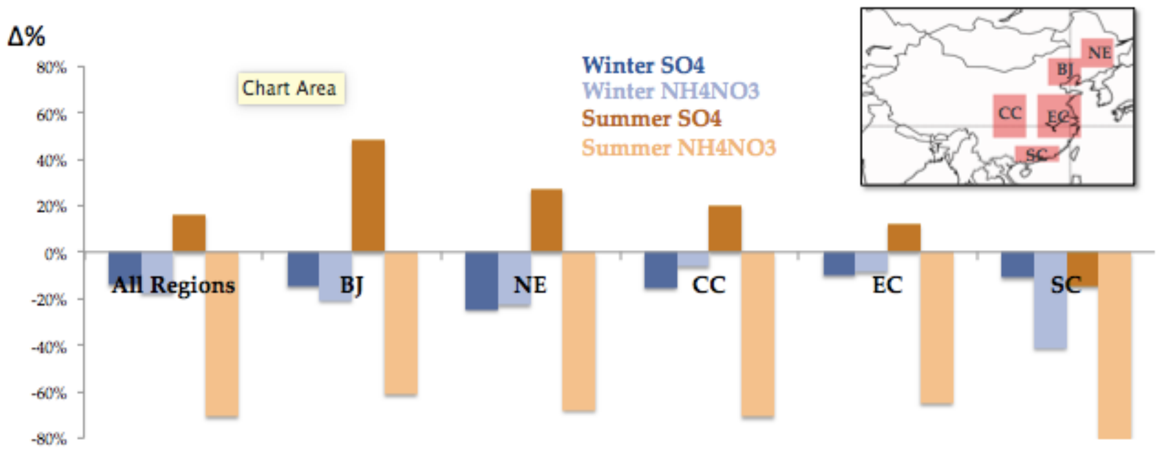

Figure 7. Regional SNA percent changes in Greater Beijing (BJ), Northeastern (NE), Central (CC), Eastern (EC) and South China (SC)

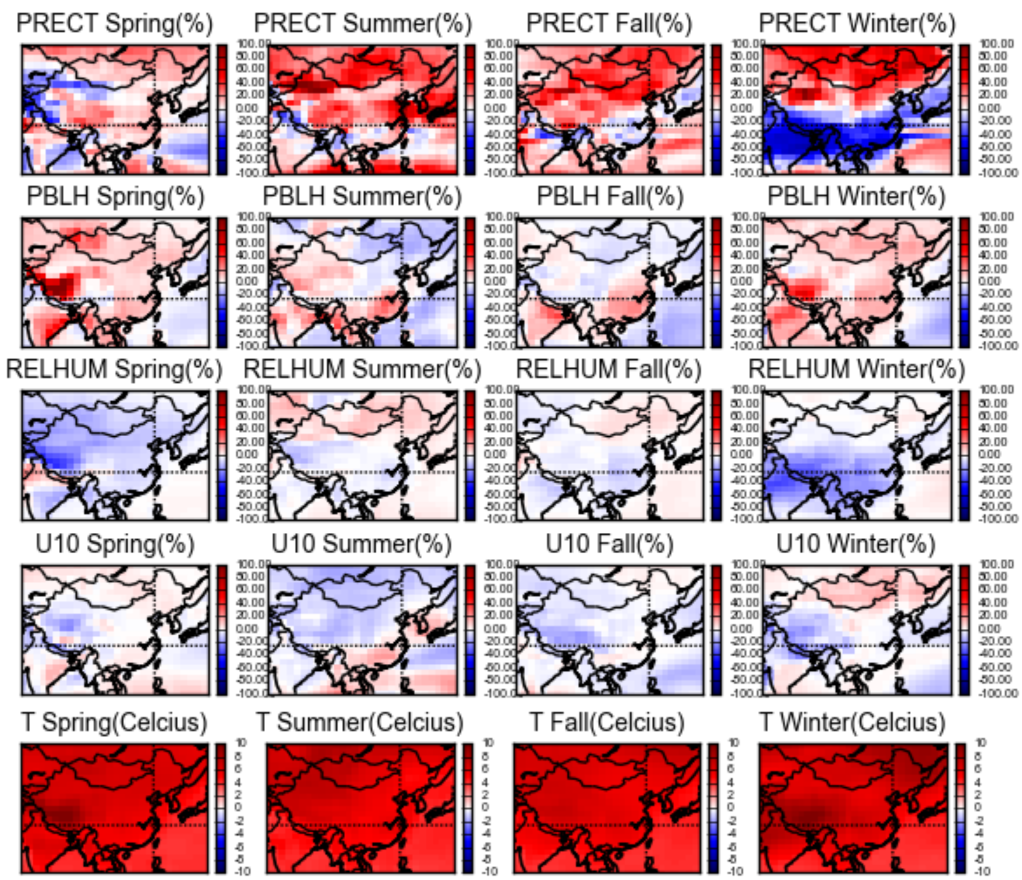

Figure 8. Ensemble-mean climate-induced seasonal change in surface meteorology from 2000 to 2100 under the REF scenario. Total Precipitation (PRECT), boundary layer height (PBLH), Relative humidity (RELHUM) and surface wind speed (U10) are shown as percent change. Absolute change in temperature (T) is shown.

3.4 Climate impact on Air Pollution Related Health

Based on REF2000 ground-level $PM_{2.5}$ concentrations, premature mortality due to air pollution is estimated to be 981,000(485,000-1,380,000) (**Table 1**) which is consistent with previous studies (Lelieveld et al. 2015; G. Yang et al. 2013). Mortality is highest in Greater Beijing, eastern China, and several densely populated areas across China (**Figure 9**). Under all scenarios, $PM_{2.5}$-related mortality is projected to decrease from the year 2000 level assuming no change in population (**Figure 10**). Differences from REF2000 $PM_{2.5}$-related mortality ranges from over 8,000 deaths in REF2050 to 14,000 deaths under POL3.7 in 2100, indicating varying degrees of health benefits in response to stringency of the climate policy.

However, significant regional differences exist in mortality change. As shown in Figure 9, mortality responds to changes in national-average Population-Weighted Annual $PM_{2.5}$ in each target year. Central China and Greater Beijing experience substantial increase in mortality while there are huge climate-induced health benefits in regions such as Southern China. Under REF2100, the disparity in mortality change between Central and Southern China could as large as 6000 people. Similar but weaker patterns are observed under the POL3.7 and POL4.5 scenarios. Increase in mortality in Central China diminishes, which creates an overall larger health benefits at national scale.

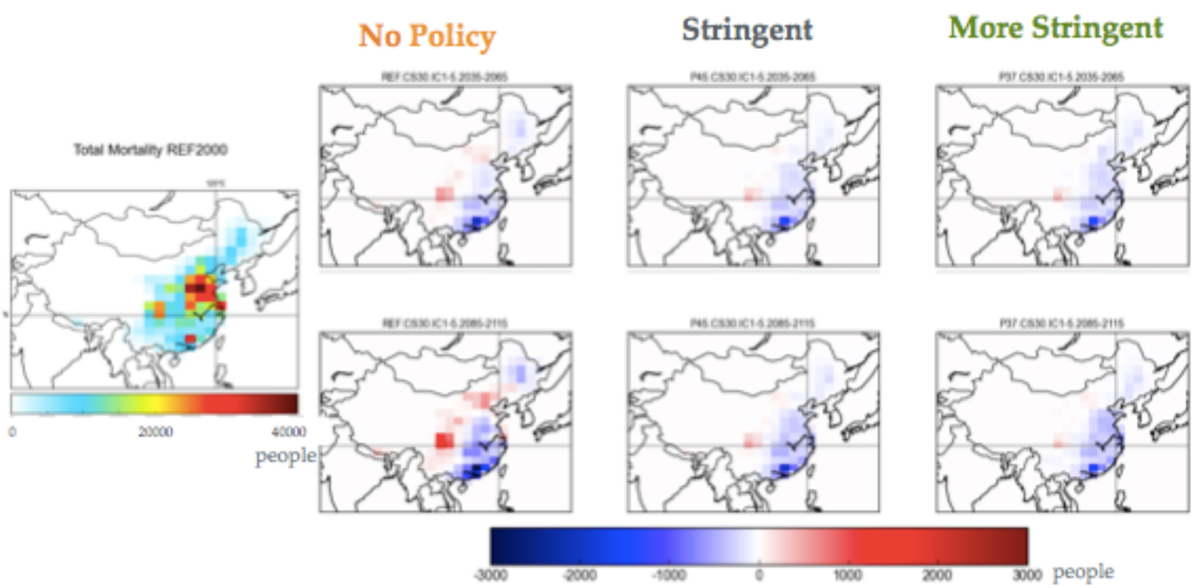

Figure 9. Total $PM_{2.5}$-related premature mortality in 2000 (Left) and Changes in total $PM_{2.5}$-related premature mortality under REF, POL4.5 and POL3.7 scenarios in 2050 (top row) and 2100 (bottom) based on ensemble-mean climate-induced change in annual average surface $PM_{2.5}$ shown in Figure 1.

Table 1. Annual premature mortality and uncertainty associated with $PM_{2.5}$ under REF, POL4.5 and POL3.7 in 2000, 2050,2100. (a) Sensitivity scenario in which population is kept constant at year 2000. (b) Population is linearly scaled to match United Nations population projection for 2050 and 2100.

(a) Population Yr 2000	Mortality	Uncertainty
2000-REF	981,000	485,000 - 1,380,000
2050-REF	973,000	481,000 - 1,370,000
2050-P45	971,000	479,000 - 1,370,000
2050-P37	970,000	479,000 - 1,370,000
2100-REF	971,000	480,000 – 1,370,000
2100-P45	968,000	478,000 - 1,370,000
2100-P37	967,000	477,000 - 1,360,000
(b) Changing Population	**Mortality**	**Uncertainty**
2000-REF	981,000	443,000 - 1,370,000
2050-REF	1,030,000	465,000 - 1,440,000
2050-P45	1,030,000	463,000 - 1,440,000
2050-P37	1,030,000	463,000 - 1,440,000
2100-REF	768,000	346,000 - 1,070,000
2100-P45	765,000	344,000 - 1,070,000
2100-P37	764,000	343,000 – 1,070,000

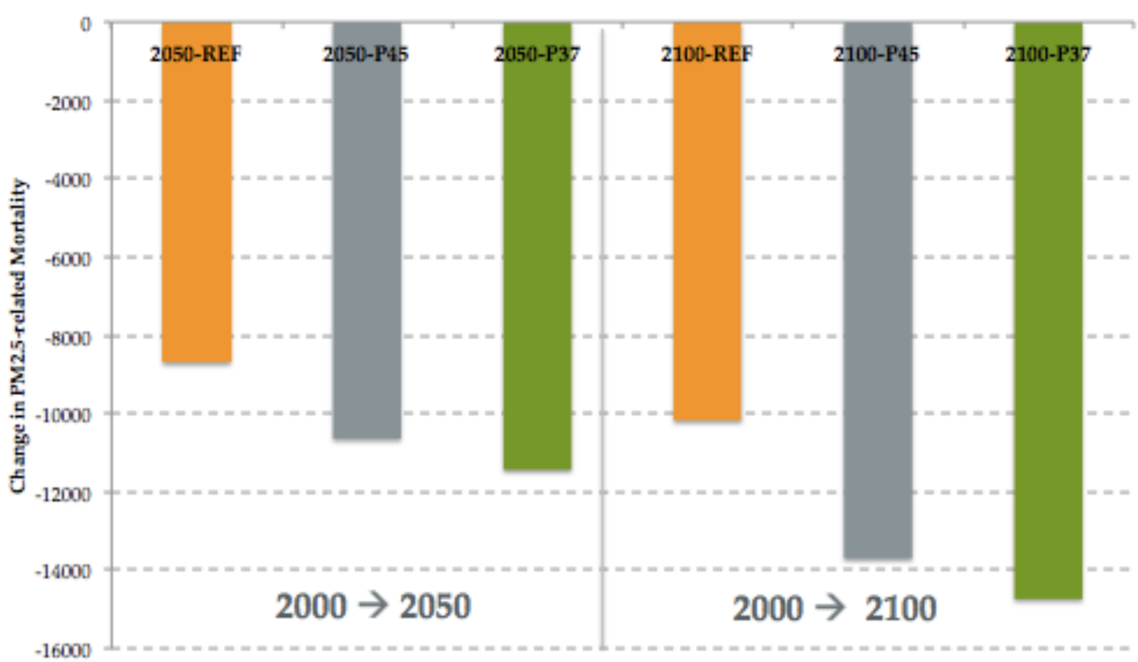

Figure 10. Changes in total $PM_{2.5}$-related premature mortality under REF, POL4.5 and POL3.7 scenarios for national-average Population-Weighted Annual $PM_{2.5}$ in 2050 and 2100.

4 Discussion

4.1 Implications of Climate Change on $PM_{2.5}$

Climate-induced $PM_{2.5}$ changes vary significantly by region. We observed mixed climate benefits (NE, EC, SC) and penalties (CC, BJ) across China under our reference scenario. This finding is in contrast with recent climate-related $PM_{2.5}$ projections in the United States, where $PM_{2.5}$ is expected to increase in across the continental United States (Garcia-Menendez et al. 2015; Fang et al. 2013). Our result suggests that although $PM_{2.5}$ increases are driven by increases in SO_4, the effect of decreasing NH_4NO_3 due to increasing temperature is also significant and drives $PM_{2.5}$ decreases along coastal regions. Our results report the same magnitude of $PM_{2.5}$ changes as in Jiang et al. 2013 (despite small disagreements due to different resolution, model and climate scenario), but disagree with the signs, spatial distribution, and $PM_{2.5}$ species. REF scenario in this study demonstrates that faster changing climate could accentuate regional differences in changes in total $PM_{2.5}$ and SNA species. Stringent climate policy could mitigate the impact of climate as regional disparities decrease with less climate penalties in some polluted regions and less benefits in others in the same time.

4.2 Relationships between meteorological drivers and $PM_{2.5}$

As the major components of anthropogenic $PM_{2.5}$, Sulfate and ammonium nitrate concentrations can be significantly perturbed by meteorological changes. Here we analyze how climate-induced changes in temperature, total precipitation, boundary layer height, relative humidity and surface wind speed may drive SNA changes only, not their relative contribution to percent change in $PM_{2.5}$. First of all, increasing temperature across China has a major effect on summertime sulfate and ammonium nitrate in both seasons. A hotter climate enhances SO2 oxidation, particularly summer greater Beijing and Northeastern China. A high temperature in BJ and NE may also correspond to a higher relatively humidity percent change**,** which favors higher HOx production, catalyzes H2O2 formation, and leads to more aqueous-phase formation of sulfate. Overall 40% increase in tropospheric H2O2 concentration across China suggests that temperature enhances SO2 oxidation primarily through increases in oxidant concentrations. (Figure A4) With a high temperature, semi-volatile NH_4NO_3 are more likely to partition into its gas phase due to its low vapor pressure, which explains the national-wide decrease in NH_4NO_3 in all seasons.

Changes in ventilation (wind speed, mixing depth, stagnation) and wet deposition (precipitation) can significantly affect SNA species in all regions during winter and summertime South China and. In winter, both sulfate and ammonium nitrate decrease across China, which could due to a higher boundary layer height. General increases in PBL height across China promote atmospheric ventilation and prevent accumulation of $PM_{2.5}$ species. In summer, South China is the only region that experiences sulfate decreases along with NH_4NO_3 while sulfate in all other regions are increasing through temperature-enhanced oxidation. Summertime south China is also associated with the significantly increased PBL height and surface wind speed that favors particulate matter removal, which suggests temperature increase in this already hot and humid tropical region plays a less important role as compared to other parts of China, and wet deposition and ventilation become the principle drivers for sulfate decrease. Analysis on meteorological and air quality changes under the most stringent POL3.7 scenario also shows similar climate-SNA relationships. Because of the smaller magnitude change in meteorological drivers under a slower changing climate, sensitivity of $PM_{2.5}$ species to climate change are also smaller, demonstrating the effectiveness of using climate mitigation strategies to minimize the climate impact on $PM_{2.5}$.

4.3 Implications of Climate Change on health

Using GBD2010 EIR model, we found large regional differences in changes in $PM_{2.5}$-related premature mortality, which corresponds to climate impact on $PM_{2.5}$ concentrations. Decreases in national $PM_{2.5}$-related premature mortality among all climate mitigation scenarios suggest overall benefits of climate change to human health in China. A slower changing climate, such as in the ones in POL3.7 and POL4.5, could yield more health benefits. This is very different from U.S mortality estimates where climate penalty on health is observed across all scenarios. Mortality differences among the climate scenarios are relatively small compared to the U.S. By implementing POL3.7, 4,500 deaths could be avoided in China by 2100 compared to mortality under REF2100, while avoided deaths in the U.S. could be 57,000 (Garcia-Menendez et al. 2015).

Considerable uncertainty exists for our mortality estimates, due to our low confidence in the relative risk values. We also do not consider the uncertainty within $PM_{2.5}$ concentrations by only taking the ensemble-mean annual averages as the input of the health assessment model. As shown in **Table 1**, if we take population projections into account, a short-term increasing and long-term declining population results in ~1.03M in all scenarios in 2050, and a low ~765,000 mortality in 2100. The significant effect of changing population on future mortality estimates shows that even with decreased $PM_{2.5}$ concentrations in certain regions due to climate benefits, a growing population can exceed the current burden, which is particularly alarming for developing countries with high population growth. Vice versa, a declining population, as the case in 2100, can also offset climate penalty on $PM_{2.5}$. Additionally, base year incidence rate are also held constant. Future changes in people's vulnerability to air pollution related diseases could also drive the future air pollution related mortality (Silva et al. 2013)

4.4 Air Quality Co-benefits from emissions and Climate impact

Climate mitigation policy, if implemented, could have a profound improvement on future air quality through two pathways: (i) reduction of co-emitted air pollutant and its precursor gases and (ii) a slower-changing climate. Because human activities emit greenhouse gases (GHGs) and conventional air pollutants from shared sources, a stringent climate policy would reduce common greenhouse gas emissions as well as emissions directly related to air pollutant formation, such as nitrogen oxides (NOx) and sulfur dioxide (SO2) (West et al. 2013).

We found that the impact of climate alone on air quality are still significant as compared to decreases in $PM_{2.5}$ due to reduction of co-emitted pollutants. West et al. 2013 found 0-9 $\mu g/m^3$ decrease in annual average $PM_{2.5}$ in China by 2100 under the POL4.5 scenario due to reduced emissions and 0-1 $\mu g/m^3$increase due to meteorology. Our study shows a different projection of the climate impact, in which $PM_{2.5}$ in China in fact decreases by 0-2 $\mu g/m^3$ in coastal regions of China. Although avoided deaths and economic benefits associated with reduced emissions can be much greater, meteorological contributions to $PM_{2.5}$ changes, considering the inherent climate uncertainty and significant regional differences when climate change is not properly contained in time, should be carefully incorporated in the climate policy making process.

4.5 Future Work

For future research, we hope to center our simulations at a more recent base year, so that the climate impact could be more relevant to our current state of emissions. More model validation is also needed in China to build our confidence in the results and awareness on the model limitations. Additional to comparing with seasonal and monthly averages abundant in existing literature, we could look into monitoring data that is becoming more and more available in China. Secondly, critical non-anthropogenic $PM_{2.5}$ species such as wildfire (black carbon) emission and dust could be included in the model to further understand the climate impact on all $PM_{2.5}$ species by improving existing model or developing linkages between IGSM-CAM and GEOS-Chem. Also, only five meteorological parameters were considered in this paper, parameters such as cyclone frequency, convective flux and cloud cover could all potentially influence PM concentrations. An in-depth climate driver study should be conducted based on more complete set of important meteorological information. Lastly, advanced statistical analysis such as step-wise multi-linear regression, quantile regression have been proven effective in elucidating non-linear relationships between climate and chemistry (Porter et al. 2015). We hope to apply these statistical methods to understand climate impact in the future.

5 Conclusion

This paper provides a systematic, multi-model analytic approach to quantify the impact of climate in China's air quality and $PM_{2.5}$-related premature mortality. We evaluate how meteorological changes influence $PM_{2.5}$, sulfate and ammonium nitrate, and assess the associated health impacts under three climate policy scenarios, REF, POL4.5 and POL3.7.

We found that climate change results in a overall decrease in national-average population-weighted $PM_{2.5}$ in two stringent policies and a unconstrained climate, results in a higher likelihood of more extreme national averages for $PM_{2.5}$. At the regional scale, changes in $PM_{2.5}$ from the base year level vary significantly, with increases in Central China and greater Beijing and decrease in coastal regions. Stringent climate controls can slow down climate change and effectively mitigate the regional differences.

Our meteorology driver analysis on SNA aerosols shows that a rising temperature may drive sulfate summer increase through enhanced oxidant concentration. A hot climate also results in NH_4NO_3 loss to gaseous phase in all seasons. Changes in ventilation, transport and deposition are also important in across all regions in winter and summertime South China. Climate mitigation is able to slow down the changes in meteorological parameters that lead to smaller response from sulfate and ammonium nitrate species.

We estimated the $PM_{2.5}$-related premature mortality in 2000 to be 981,310. Mortality decreases from base year, which shows climate change can positively contribute to national-level air quality. Largest climate impact on health occurs under POL3.7 in 2100, which helps us understand the health benefits in stopping climate change. However, some regions such as Central China and Greater Beijing exhibit increases in mortality as well, which correspond to regions with increased $PM_{2.5}$. Our mortality estimates are subject to uncertainties in relative risk and $PM_{2.5}$ change. They can also be largely driven by baseline incidence rates and changing population.

As China just signed the Paris Climate Treaty in vow to combat climate change in April this year, designing appropriate climate mitigation strategies for the future has now become an urgent task for China. Identifying appropriate stringency and the corresponding air quality and health impacts of climate policies are increasingly crucial. By gaining a better understanding of PM2.5 responses to meteorological changes, we are able to resolve some of the uncertainties in climate policy policies. Our study shows that climate, if not constrained, is going to change significantly over the next decades and will impact regional PM concentrations and human exposure in the future.

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7 Appendix

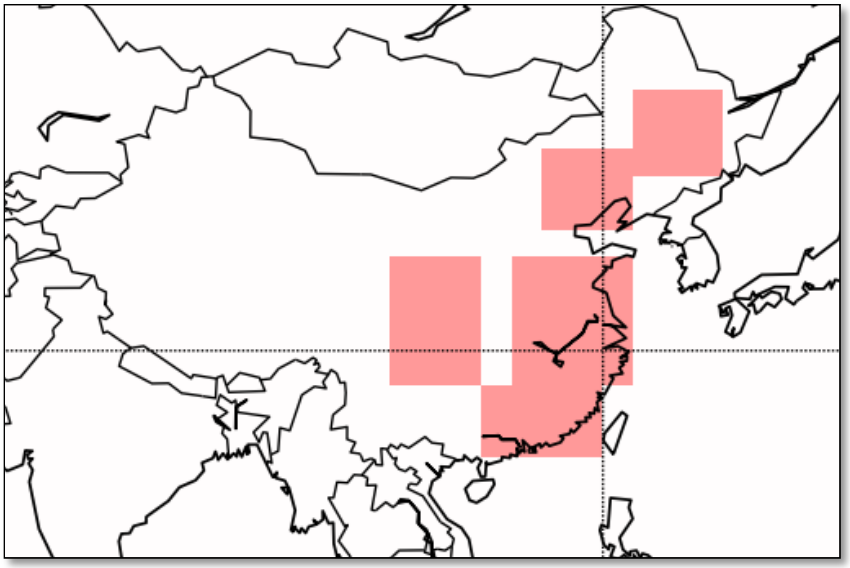

Figure A1: Regions of Interest (Northeast, NE; Greater Beijing area, BJ; East China, EC; Southern China, SC and Central China, CC)

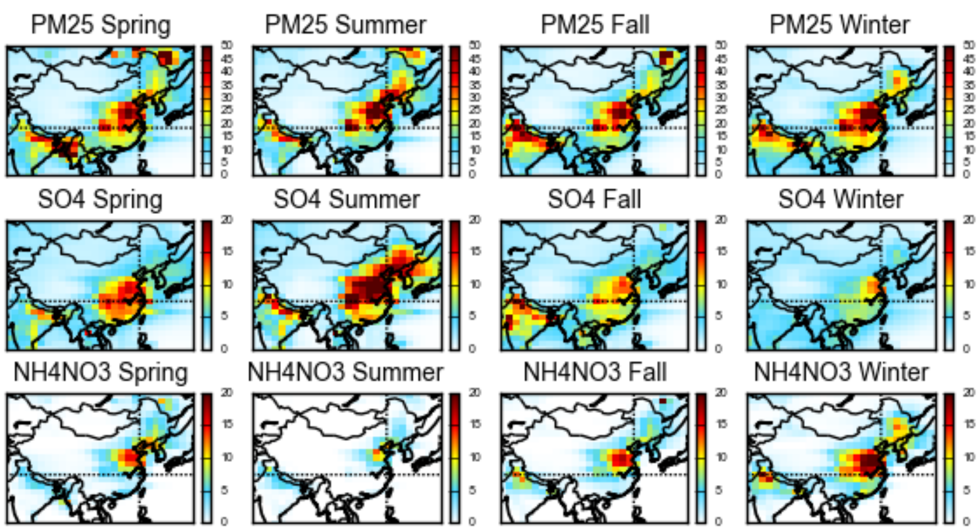

Figure A2: Seasonal average $PM_{2.5}$, SO_4 and NH_4NO_3 concentrations at REF2000

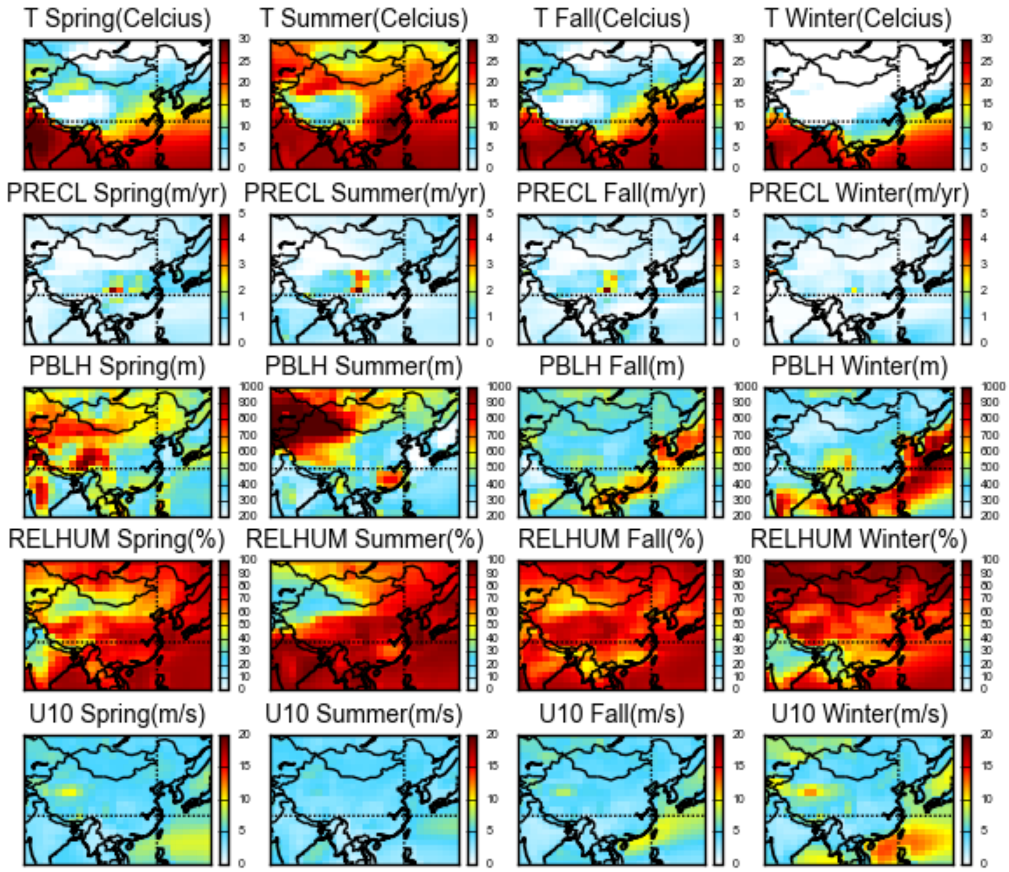

Figure A3: Seasonal average meteorology in REF2000.

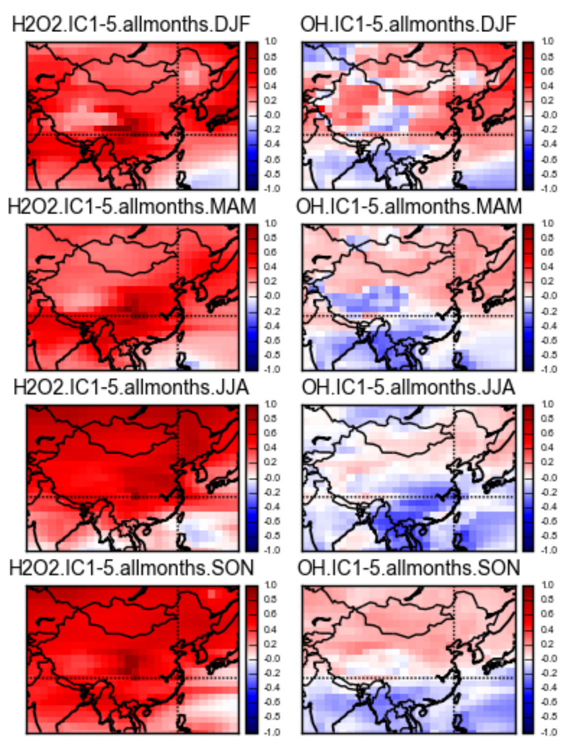

Figure A4: Ensemble-mean climate-induced seasonal change in tropospheric H2O2 nad OH from 2000 to 2100 under the REF scenario. Legend shows % change in decimal format.

	Winter					Summer				
	T(Δ°C)	Precipitation (Δ%)	PBLH (Δ%)	RH (Δ%)	U10 (Δ%)	T(Δ°C)	Precipitation (Δ%)	PBLH (Δ%)	RH (Δ%)	U10 (Δ%)
China	7.0	3.7%	11.6%	-9.3%	-0.9%	6.0	27.3%	2.9%	0.4%	-3.8%
All Regions	6.4	-14.3%	12.2%	-10.2%	0.4%	5.3	22.8%	3.8%	-0.4%	1.6%
BJ	6.4	23.4%	9.6%	-1.3%	1.8%	5.3	16.2%	-6.2%	3.3%	-3.4%
NE	8.0	39.6%	15.5%	1.1%	8.9%	5.0	32.2%	-12.0%	7.9%	-2.8%
CC	6.8	-17.4%	10.9%	-18.1%	-1.1%	5.5	14.7%	-1.1%	-1.4%	-3.9%
EC	6.1	-30.2%	12.6%	-10.3%	-2.5%	5.6	37.0%	12.6%	-4.4%	5.0%
SC	5.4	-52.7%	12.5%	-15.0%	-0.6%	4.9	7.1%	14.7%	-1.8%	10.0%

Table A1: Percent change in Temperature, Precipitation, boundary layer and surface wind speed in REF2100. Summarized by regions (All China, All selected regions, BJ, NE,CC, EC and SC) and seasons (Winter and Summer)

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