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Natural Variability in Projections of Climate Change Impacts on Fine Particulate Matter Pollution

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Key Points:
- Natural variability adds uncertainty to simulations of anthropogenic climate change effects on fine particulate matter pollution
- The use of decadal simulations or ensembles can increase confidence in projections of the impacts on particulate matter
- Regional-scale and climate-stabilization projections may require larger simulation lengths to identify an anthropogenic-forced signal

Supporting Information:
- Supporting Information S1

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Abstract Variations in meteorology associated with climate change can impact fine particulate matter ($PM_{2.5}$) pollution by affecting natural emissions, atmospheric chemistry, and pollutant transport. However, substantial discrepancies exist among model-based projections of $PM_{2.5}$ impacts driven by anthropogenic climate change. Natural variability can significantly contribute to the uncertainty in these estimates. Using a large ensemble of climate and atmospheric chemistry simulations, we evaluate the influence of natural variability on projections of climate change impacts on $PM_{2.5}$ pollution in the United States. We find that natural variability in simulated $PM_{2.5}$ can be comparable or larger than reported estimates of anthropogenic-induced climate impacts. Relative to mean concentrations, the variability in projected $PM_{2.5}$ climate impacts can also exceed that of ozone impacts. Based on our projections, we recommend that analyses aiming to isolate the effect climate change on $PM_{2.5}$ use 10 years or more of modeling to capture the internal variability in air quality and increase confidence that the anthropogenic-forced effect is differentiated from the noise introduced by natural variability. Projections at a regional scale or under greenhouse gas mitigation scenarios can require additional modeling to attribute impacts to climate change. Adequately considering natural variability can be an important step toward explaining the inconsistencies in estimates of climate-induced impacts on $PM_{2.5}$. Improved treatment of natural variability through extended modeling lengths or initial condition ensembles can reduce uncertainty in air quality projections and improve assessments of climate policy risks and benefits.

Plain Language Summary Climate change can worsen air pollution caused by small particles in the atmosphere as it alters temperature, precipitation, and other weather variables. Models have been used to project the effects climate change can have on airborne particle concentrations. However, natural year-to-year and longer-term variations in weather can make it difficult to estimate the impacts specifically caused by human forces. In this study, we use a large set of climate and air quality simulations to assess the effect of natural variability in model-based projections of climate change impacts on air pollution over the United States. Our results show that natural variations in predictions of climate change effects on fine particle levels can be significant. We recommend that projections use longer simulation lengths than typically applied, 10 years or more, in order to filter out this natural variability and better reflect the effect of human-caused climate change on particle pollution. Natural variability can also make it challenging to confidently project human-caused climate impacts in some regions or if efforts are taken to reduce greenhouse gas emissions. By using larger modeling lengths or simulation sets, projections of climate change impacts on air pollution and climate policy benefit analyses can be improved.

1. Introduction

Climate change can exert a large influence on air quality by altering meteorological conditions (Fiore et al., 2015; Jacob & Winner, 2009). As atmospheric ventilation, precipitation rates, atmospheric chemistry, and other key determinants of pollutant concentrations vary, climate change may deteriorate air quality over large regions (Dawson et al., 2014). The impacts on fine particulate matter ($PM_{2.5}$) concentrations are particularly important; ambient $PM_{2.5}$ is the largest risk factor by attributable burden of disease with millions of premature deaths caused by $PM_{2.5}$ pollution each year (Cohen et al., 2017). Multiple modeling studies have projected the impacts of climate change on $PM_{2.5}$ concentrations (Day & Pandis, 2015; Nolte et al., 2018; Trail et al., 2014). However, the effects of variations in climate on $PM_{2.5}$ remain highly uncertain, with significant discrepancies among studies (Fiore et al., 2015). Inconsistencies are especially evident at

regional scales, including differences in the projected direction of climate-induced change (von Schneidemesser et al., 2015).

Natural variability, here defined as the modeled unforced internal variability in the simulated climate system, is partially responsible for the uncertainty in $PM_{2.5}$ projections. To account for natural variability, most modeling studies have relied on simulations covering multiple years. The number of years used has ranged from 1 to 150. A review of 45 prior studies, listed in Table S1, assessing the impact of climate change on $PM_{2.5}$, or particulate matter components, reveals that over half used five years or less of simulated air quality to represent present or future climates and 85% relied on 10 years or less. Such simulation lengths may be insufficient to adequately separate an anthropogenic-forced signal from natural variability. Analyses benefiting from large simulations focused on ozone (O_3) pollution have shown that multidecadal simulations are required to isolate the impact of climate change and may be unable to do so before midcentury (Barnes et al., 2016; Garcia-Menendez et al., 2017). However, the influence of natural variability on $PM_{2.5}$, the pollutant potentially responsible for the majority of health costs associated with the "climate penalty" on air quality (Garcia-Menendez et al., 2015; Silva et al., 2017), has not been specifically assessed. Some recent efforts to project the impacts of twenty-first-century climate change on $PM_{2.5}$ have moved toward larger numbers of modeled years through multidecadal and ensemble simulations (Lacressonnière et al., 2016; Westervelt et al., 2016; Xu & Lamarque, 2018). These highlight the influence natural variability can have on projections of climate change impacts. However, other recent studies, especially those applying regional climate and chemical transport models, have continued to rely on a small number of years to identify an anthropogenic-forced climate signal in $PM_{2.5}$ concentrations, even at midcentury or earlier (Table S1). Shorter simulations are a trade-off that may be necessary to address other sources of uncertainty in projections, such as resolution, emissions, and atmospheric process representations.

Here we weigh the influence of natural variability on estimates of climate change impacts on $PM_{2.5}$ pollution by analyzing the projections of the U.S. Environmental Protection Agency's (EPA) Climate Change Impacts and Risk Analysis project (U.S. EPA, 2015; Waldhoff et al., 2015). The ensemble simulations at the core of the Climate Change Impacts and Risk Analysis projections represent a significant effort to model climate-induced air quality impacts, with over a thousand years of modeled atmospheric chemistry. Based on this ensemble we compare the influence of natural variability on projections of climate change impacts on $PM_{2.5}$ to those for O_3 and recommend a minimum simulation length to provide guidance to future analyses attempting to model anthropogenic-forced, climate-related variations in $PM_{2.5}$ pollution.

2. Methods

We simulate the impacts of climate change on $PM_{2.5}$ pollution under three integrated climate, policy, and economic activity scenarios developed with the MIT Integrated Global System Model linked to the Community Atmosphere Model (MIT IGSM-CAM; Monier et al., 2013). The scenarios project global economic activity, greenhouse gas emissions, and climate under a reference case with no climate change mitigation policy in which total radiative forcing reaches 10 W/m^2 at the end of the century (REF), a climate policy that stabilizes total radiative forcing at 4.5 W/m^2 by 2100 (P45), and a climate policy that stabilizes total radiative forcing at 3.7 W/m^2 by 2100 (P37). Details about the socioeconomic greenhouse gas emission projections are presented in Paltsev et al. (2015). The scenarios have been used to assess climate change impacts and mitigation benefits across a diverse range of sectors in the United States (U.S. EPA, 2015). The ability of the MIT IGSM-CAM model to represent historical atmospheric conditions and variability has been evaluated against station- and model-based observational data sets (Monier et al., 2013). Relative to observational data from 1900 to 2010, the MIT IGSM-CAM realistically simulates major climate variables, including surface air temperature and precipitation, as well as year-to-year climate variability (Monier et al., 2013). A detailed discussion of the MIT IGSM-CAM's climate projections over the United States for the scenarios considered here is included in Monier et al. (2015).

We simulate air quality under each climate policy scenario using the Community Atmosphere Model with Chemistry (CAM-Chem, version 1.1.2; Lamarque et al., 2012). Meteorological fields generated by the MIT IGSM-CAM are used to drive CAM-Chem simulations at 1.9° × 2.5° resolution. In all CAM-Chem atmospheric chemistry simulations, anthropogenic emissions are fixed at start-of-the-century levels (2000) to isolate the effect of climate on air quality. The anthropogenic emissions used are described in Lamarque et al.

(2012) and based on the Precursors of Ozone and their Effects in the Troposphere inventory. The response of biogenic emissions of isoprene and monoterpenes to variations in temperature is modeled; however, the effects of climate on other natural emissions sources, including wildfires and dust emissions, are not included. In CAM-Chem, secondary organic aerosol (SOA) production is represented by a two-product scheme that links SOA formation to oxidation of atmospheric nonmethane hydrocarbons (Lamarque et al., 2012). Here we assess climate-induced impacts on ground-level concentrations of sulfate (SO_4), ammonium nitrate (NH_4NO_3), organic aerosol (OA), and black carbon (BC) particles, and estimate $PM_{2.5}$ mass following Val Martin et al. (2014). CAM-Chem has been previously used to model air quality and its ability to replicate surface concentrations of different aerosol species is evaluated against surface observations in Lamarque et al. (2012). Additional details and discussion about the CAM-Chem simulations and ensemble-mean $PM_{2.5}$ projections used here are included in Garcia-Menendez et al. (2015). Over the United States, the model captures the distribution of major $PM_{2.5}$ components but shows a positive bias for SO_4 and underpredicts observed concentrations of EC and OA. On average, SO_4 and OA are the largest contributors to total modeled $PM_{2.5}$, followed by NH_4NO_3 and a significantly smaller fraction of EC. The simulated annual population-weighted $PM_{2.5}$ concentration at the start-of-the century, 12.6 $\mu g/m^3$, is close to EPA's reported national annual $PM_{2.5}$ concentration averaged across over 400 monitoring sites (mostly urban) in 2000, equal to 13.5 $\mu g/m^3$ (U.S. EPA, 2017).

The analyses described in this study focus on the meteorology-related impacts of climate change on $PM_{2.5}$ pollution. The impact of climate change on ambient $PM_{2.5}$ (i.e., the $PM_{2.5}$ "climate penalty") over the contiguous United States is assessed by estimating the difference between simulated ground-level concentrations under start-of-the-century and future climates. To capture natural interannual variability, we simulate U.S. air quality at the beginning, middle, and end of the twenty-first century using 30-year modeling periods (1981–2010, 2036–2065, and 2086–2115). To further account for multidecadal natural variability within our projections, we model atmospheric chemistry during each period with five different representations of natural variability generated by perturbing initial atmospheric, land, and ocean conditions in the MIT IGSM-CAM climate change simulations (Monier et al., 2013). To evaluate the impact of anthropogenic climate change at midcentury and the end of the century against natural variability within simulated periods, externally forced climate change is controlled by detrending annual-average concentrations within each 30-year interval and centering air quality impacts in 2050 and 2100. Detrending was conducted for each grid cell by computing the least squares fit of a straight line to the data and subtracting the resulting function from the annual-average concentrations. $PM_{2.5}$ pollution under each policy scenario considered and present or future climates is therefore characterized by 150 years of simulated air quality. The ensemble-mean projections of climate-induced changes in $PM_{2.5}$ were used to evaluate health and economic impacts in EPA's Climate Change Impacts and Risk Analysis project (U.S. EPA, 2015). However, the underlying ensemble simulations, which include 1,050 years of simulated air quality, allow for a close inspection of the influence of natural variability in projections of climate change impacts on $PM_{2.5}$. The role of natural variability on U.S. O_3 pollution was assessed in Garcia-Menendez et al. (2017), finding that natural variability significantly affects projections of climate change impacts and recommending a 15-year simulation minimum to adequately identify an anthropogenic-forced signal at a national scale. Uncertainty related to natural variability is compared to that associated with national-scale health and economic impacts in Saari et al. (2019). Here we extend the analysis to explore the role of natural variability in projections of the meteorology-driven impacts of climate change on $PM_{2.5}$ pollution.

3. Results and Discussion

Our simulations of atmospheric chemistry under future climate show a significant penalty on U.S. $PM_{2.5}$ pollution (Figure 1). Ensemble-mean projections estimate a climate-induced increase in U.S. annual population-weighted $PM_{2.5}$ of 0.5 ± 0.1 $\mu g/m^3$ by midcentury and 1.5 ± 0.1 $\mu g/m^3$ by the end of the century under the REF scenario (statistical significance evaluated with a Student's *t* test for 95% confidence). The largest regional penalty is projected over the eastern United States, with lesser increases simulated in the West and small climate-induced decreases in $PM_{2.5}$ anticipated over some areas of the Midwest. The simulated changes reflect multiple pathways through which meteorology influences $PM_{2.5}$ concentrations, including increased SO_2 oxidation and nitrate partitioning to the gas phase under warmer temperatures, higher

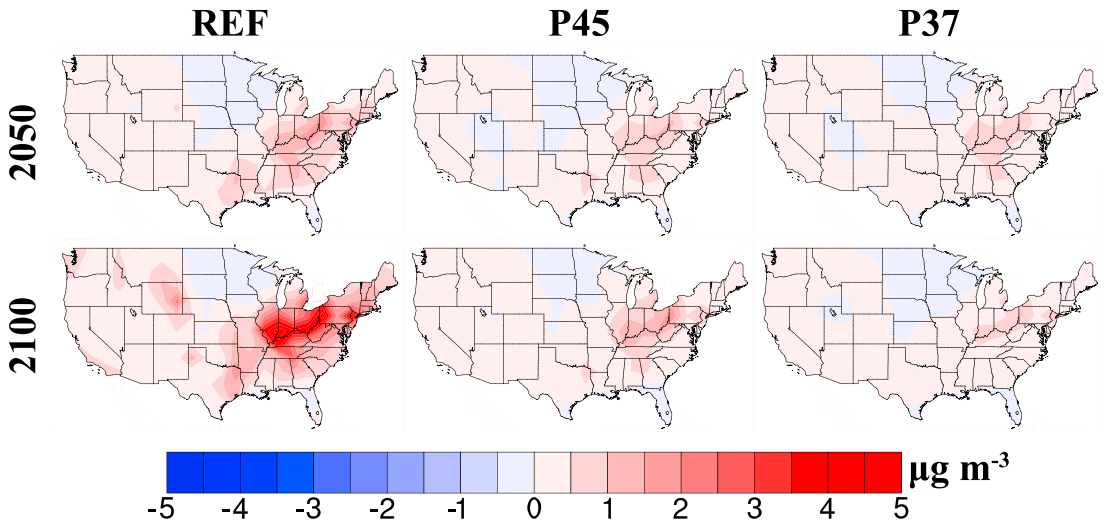

Figure 1. Climate penalty on U.S. $PM_{2.5}$ pollution. Ensemble-mean climate-induced change in annual-average $PM_{2.5}$ from the beginning of the century to 2050 and 2100 under REF, P45, and P37 scenarios.

stagnation, and variations in precipitation, consistent with previous studies analyzing the linkages between climate and air quality (Fiore et al., 2012). The interactions within these ensemble simulations and impacts on different $PM_{2.5}$ components are further discussed in Garcia-Menendez et al. (2015). Although model biases influence predicted $PM_{2.5}$ concentrations, these affect simulations under both start-of-the-century and future climates. Thus, penalties estimated as the difference between future and present air quality account for the biases to the degree that they remain consistent across modeled periods.

Projected $PM_{2.5}$ increases associated with climate change are largely driven by SO_4, particularly in the eastern United States, and to a smaller extent OA. Climate impacts on OA, including SOA, are largest over the regions in Southeast, Northeast, and western United States. While these changes reflect a climate-driven increase in SOA biogenic precursors, SOA summertime production is likely underestimated by the representation of SOA formation in CAM-Chem (Lamarque et al., 2012). These increments are countered by climate driven reductions in NH_4NO_3, which is responsible for the projected drop in $PM_{2.5}$ over areas of the Midwest. The climate penalty on $PM_{2.5}$ is greatly reduced by climate change mitigation policies. Over 80% of the REF-scenario penalty on annual population-weighted $PM_{2.5}$ at the end of the century is avoided under the P37 scenario.

Depending on the region, our projections agree or contrast to varying degrees with recent studies simulating climate change impacts on $PM_{2.5}$. For example, our simulations are consistent with the projections of Nolte et al. (2018) over the southeastern United States, suggesting a climate-induced increase in OA, but differ in the magnitude of the nitrate-driven decrease in concentrations over the Midwest. In contrast, Westervelt et al. (2016) project an end-of-century climate penalty on $PM_{2.5}$ over most of the United States under a high-emission scenario, which, as in our projections, is strongest over the Northeast and Midwest. Similar to our projections, the simulations of Xu and Lamarque (2018) suggest that climate-induced $PM_{2.5}$ changes may be driven by SO_4, with significant impacts over the Northeast. The level of agreement with these studies, and over 40 others listed in Table S1, is expected given the inconsistencies reported in model-based projections of the climate penalty on $PM_{2.5}$ pollution. Large uncertainties associated with climate model response to greenhouse gas and aerosol concentrations can propagate to projections of climate change impacts, including air pollution. Additionally, differences in greenhouse gas scenarios, air pollutant emissions, spatial resolution, time periods, $PM_{2.5}$ components considered, processes simulated, and others can make direct comparisons across projections difficult.

The ensemble-mean projections reflect estimates based on 150 years of underlying simulations representing climate and atmospheric chemistry at the start, middle, and end of the twenty-first century. However, each ensemble-mean representation of present or future air quality encompasses ensemble members exhibiting substantial natural variability. This variability is illustrated in Figure 2, which contrasts climate penalties

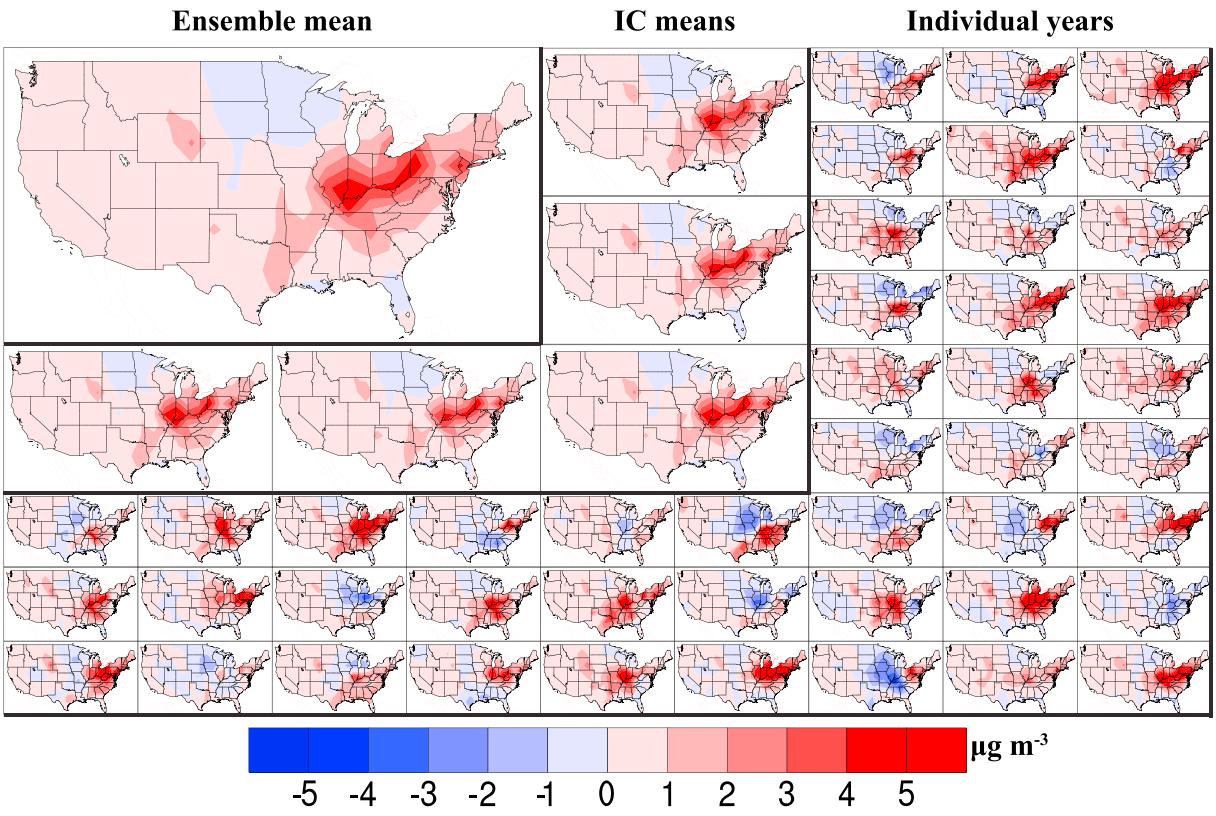

Figure 2. Natural variability in projected $PM_{2.5}$ climate change impacts. The ensemble-mean 2100 climate change impact on annual-average $PM_{2.5}$ estimated under REF scenario is shown in the top left panel. Impacts estimated under each specific climate model initialization and 30-year present and future simulations are shown in the five midsized panels. Samples of projections estimated from one-year present/future simulation pairs are shown in the 45 smaller panels.

on $PM_{2.5}$ in 2100 under the REF scenario estimated from pairwise combinations of individual present and future annual simulations. Depending on the individual years used to assess the influence of climate on $PM_{2.5}$ concentrations, impacts higher than +5 $\mu g/m^3$ or lower than −4 $\mu g/m^3$ may be projected to occur at the same location. The variability in simulated $PM_{2.5}$ climate impacts is largely driven by variability in the SO_4 particulate matter component. Estimating the climate penalty from years with meteorology that is particularly conducive or unfavorable to $PM_{2.5}$ pollution leads to projections that range from a significant increase in concentrations across the entire United States to others predicting a climate-induced reduction over most of the country. Natural variability is especially evident in the eastern United States and Midwest, which, driven by SO_4, have the largest mean climate impacts (+1.9 and +1.1 $\mu g/m^3$, respectively), as well as the greatest interannual variations (standard deviations of 1.2 and 1.0 $\mu g/m^3$, respectively). The anthropogenic-forced signal in air quality can be differentiated from natural variability using multiyear simulations or initial condition ensembles. Figure 2 also shows average climate penalty projections under each of the five model initializations included in our ensemble simulations. When 30 years of atmospheric chemistry are used to represent present and future air quality, projections under all initializations resemble the ensemble-mean climate penalty projection.

We find that confidently identifying an anthropogenic-forced climate change signal in U.S. air quality may be challenging at midcentury or under climate stabilization policies. Relying on a limited characterization of natural variability in present and future air quality can lead to climate penalty estimates that disagree with the ensemble-mean projection. Close to all penalties (>90%) calculated by pairing single present and future annual simulations suggest a climate-induced increase in U.S. pollution by 2100 under the REF scenario. However, only about 70% of the REF-scenario single-year estimates project a $PM_{2.5}$ penalty at midcentury. Although the ensemble-mean projections under the P45 and P37 scenarios suggest an overall increase in $PM_{2.5}$ concentrations driven by climate change, 30% to 40% of the estimates derived from individual years

Table 1
Margin of Error in Projections of Climate Change Impacts on $PM_{2.5}$

	Ensemble-mean climate penalty	Margin of error	Simulation years required
U.S. population-weighted	1.5 $\mu g/m^3$	$\pm$0.5 $\mu g/m^3$	8
		$\pm$0.25 $\mu g/m^3$	29
Northeast	1.9 $\mu g/m^3$	$\pm$0.5 $\mu g/m^3$	23
Midwest	1.1 $\mu g/m^3$	$\pm$0.5 $\mu g/m^3$	16
Southeast	1.0 $\mu g/m^3$	$\pm$0.5 $\mu g/m^3$	9

Note. Simulation years required to achieve a $\pm$0.5- or $\pm$0.25-$\mu g/m^3$ margin of error at 95% confidence in 2100 REF-scenario climate change impacts estimated from this ensemble. Ensemble-mean $PM_{2.5}$ impacts are also listed. Regions included correspond to those defined in the 2018 U.S. National Climate Assessment (Reidmiller et al., 2018).

under these scenarios reflect a climate "benefit" on population-weighted concentrations, which does not reflect the true policy impact.

Separating the climate change signal from natural variability in estimates of the climate penalty on air quality requires an adequate simulation length. The degree to which natural variability must be attenuated will depend on each study's objectives and design. Previously reported estimates of the impact of climate change on $PM_{2.5}$ in the United States are as large as few microgram per cubic meter, frequently close to or smaller than $\pm$1 $\mu g/m^3$ (Fiore et al., 2015). In our ensemble simulations, estimating the REF-scenario end-of-century climate penalty on U.S. population-weighted $PM_{2.5}$ at national scale with a $\pm$0.5-$\mu g/m^3$ margin of error at 95% confidence requires eight present and future years of simulated atmospheric chemistry. At a regional level, a larger number of simulation years can be necessary to attain the same level of confidence in projected regional air quality penalties, with over 20 paired years required for the Northeast. Table 1 lists the number of simulation years required to project climate penalties with a specified margin of error over the U.S. regions most heavily influenced by natural variability, the Northeast, Midwest, and Southeast.

Additionally, a margin of error of $\pm$0.5 $\mu g/m^3$ may be inadequate for projections at midcentury, under climate stabilization scenarios, or regions with smaller effects, where estimated climate change impacts on $PM_{2.5}$ are close to or lower than 0.5 $\mu g/m^3$. Decreasing the margin of error in projections to $\pm$0.25 $\mu g/m^3$ entails a significantly larger number of simulations. For the REF scenario end-of-century penalty on U.S. population-weighted $PM_{2.5}$ pollution, this would require increasing the paired years simulated to nearly 30. Reducing overconfidence in a simulated estimate of a climate penalty can be achieved by increasing the extent of both temporal and spatial averaging to strengthen signal detection under the noise of natural variability (Brown-Steiner et al., 2018).

Based on our results, we recommend using a minimum of 10 years of simulated climate and atmospheric chemistry to constrain natural variability in modeled present and future air quality for analyses attempting to quantify the climate penalty on $PM_{2.5}$ pollution at a national or larger scale. For regional or local projections, our results suggest carefully weighing the degree of natural variability at the relevant scale to ensure the robustness of reported climate penalty estimates. Furthermore, these estimates are derived from a chemical composition of $PM_{2.5}$ that may vary under changing anthropogenic emissions. In our projections, SO_4 and NH_4NO_3 display the strongest responses to climate change. As the fraction of OA in $PM_{2.5}$ increases, the magnitude of the climate penalty may decrease. However, similar coefficients of variation (~35%) for the simulated penalties on population-weighted SO_4, NH_4NO_3, and OA concentrations suggest that an extended simulation length will still be necessary to separate an anthropogenic-forced signal, albeit a smaller one, from natural variability. While this study simulates the impact of climate change on emitted pollutants, it does not project its effect on wildfire and dust emissions, which are sensitive to variations in meteorology and highly susceptible to natural variability (Achakulwisut et al., 2018; Mills et al., 2015; Yue et al., 2013). Considering these natural emission sources would likely increase the amount of modeling required to capture the anthropogenic-forced climate impact on $PM_{2.5}$.

In several efforts to model the climate penalty on air quality, simulations have been used to simultaneously project impacts on both $PM_{2.5}$ and O_3. As previously described, in our ensemble simulations a set of five model initializations across which climate forcings are equal but the simulations' initial state, represented in the ocean, land and atmosphere, is different is used to capture natural variability beyond multidecadal

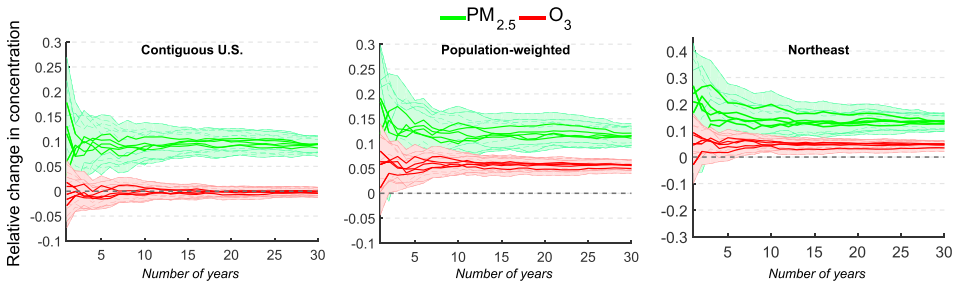

Figure 3. Variability in climate change impact on $PM_{2.5}$ and O_3 pollution. The 2100 REF-scenario climate impact on U.S.-average, U.S. population-weighted, and Northeast-average annual ground-level $PM_{2.5}$ and daily maximum 8-hr O_3, expressed as relative change with respect to start-of-century mean concentrations. Climate impacts are estimated using five climate model initializations (denoted by solid lines) and simulation lengths increasing from 1 to 30 years. Shaded regions indicate the margin of error for each estimate at a 95% confidence level based on the 30-year sample standard deviation.

simulations (Monier et al., 2013). For each initialization, Figure 3 shows how climate penalty estimates vary as the simulation length used to characterize present and future air quality is increased from 1 to 30 years. While the climate penalties on $PM_{2.5}$ pollution projected under each initialization can differ substantially for short model runs, as the simulation length approaches 10 years, mean projections for each initialization converge to a similar anthropogenic-forced impact. Compared to our previous study focused on O_3 pollution (Garcia-Menendez et al., 2017), we find that the variability of $PM_{2.5}$ impacts relative to mean concentrations is larger. Although our recommended minimum simulation length for $PM_{2.5}$ climate impact assessments is lower than our previous 15-year recommendation for impacts on O_3 pollution, the margins of error on which these are based (0.5 $\mu g/m^3$ for $PM_{2.5}$ and 1.5 ppb for O_3) usually represent a larger fraction of the ensemble-mean penalties projected for $PM_{2.5}$ compared to those for O_3.

4. Conclusion and Implications

Even after over a decade of research progress there is still little consistency among projections of the climate penalty on $PM_{2.5}$ (Reidmiller et al., 2018). To identify the causes of the discrepancies and reduce the uncertainty in these estimates, it is critical that simulations adequately consider natural variability in attributing changes in $PM_{2.5}$ concentrations to anthropogenic climate change. While executing large-ensemble simulations with computationally expensive or high-resolution models may be challenging, strategically combining temporal and spatial averaging can add robustness to projections (Brown-Steiner et al., 2018). Our results show that, as with O_3, natural variability has a significant influence on estimates of climate-induced changes in $PM_{2.5}$. Based on our ensemble simulations, we recommend using 10 years or more in efforts to model climate impacts on U.S. $PM_{2.5}$ at a national scale with a $\pm$0.5-$\mu g/m^3$ margin of error. Further modeling was required to meet the same threshold for smaller-scale projections. It is also important to note that the level of variability in climate projections is model-dependent and additional analyses may be necessary to weigh the influence of natural variability for different modeling frameworks. While our 10-year recommendation is drawn from a single model and a specific set of socioeconomic and climate scenarios, we believe that it can add confidence to reported projections and encourage closer inspection of natural variability in future efforts to simulate the climate penalty on air quality.

Additional sources of uncertainty beyond natural variability affect projections of $PM_{2.5}$ under climate change. Our analysis focuses on the effect of climate on $PM_{2.5}$. Future air quality will be determined by the combined effect of climate change and changes in anthropogenic emissions, which are likely to have a larger effect than the penalty associated with variations in meteorology. Emission changes can also impact the chemical composition and spatial distribution of $PM_{2.5}$ pollution, influencing its response to climate and the level of natural variability inherent to the climate penalty on air quality. However, our results support concerns that climate change has the potential to degrade air quality gains from pollutant emission reductions, with significant consequences for human health.

Model uncertainty in climate and atmospheric chemistry simulations is another important contributor to overall uncertainty in $PM_{2.5}$ projections, as evidenced by the significant differences across members of multi-model ensembles (Allen et al., 2016; Lacressonnière et al., 2016; Silva et al., 2017). Unlike model or emission uncertainty, the noise from natural variability can be filtered out with extended modeling, allowing simulations to successfully detect the impact of emission policies. Reducing uncertainty associated with natural variability would also complement modeling efforts targeting other sources of uncertainty in projections of air quality under climate change, such as spatial resolution or atmospheric process representations. Furthermore, the uncertainty in estimates of climate-induced air quality impacts can propagate to projections of health damages and economic costs included in climate policy assessments, where the uncertainties associated with modeling health impacts and their economic valuation may be larger still (Heo et al., 2016; Matus et al., 2012; Saari et al., 2019). The use of decadal or ensemble simulations to better capture natural viability can reduce overall uncertainty in integrated climate change mitigation analyses, allowing them to inform climate policy discussions more effectively.

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