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U.S. air quality and health benefits from avoided climate change under greenhouse gas mitigation

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Abstract

We evaluate the impact of climate change on U.S. air quality and health in 2050 and 2100 using a global modeling framework and integrated economic, climate, and air pollution projections. Three internally consistent socioeconomic scenarios are used to value health benefits of greenhouse gas mitigation policies specifically derived from slowing climate change. Our projections suggest that climate change, exclusive of changes in air pollutant emissions, can significantly impact ozone (O_3) and fine particulate matter ($PM_{2.5}$) pollution across the U.S. and increase associated health effects. Climate policy can substantially reduce these impacts and climate-related air pollution health benefits alone can offset a significant fraction of mitigation costs. We find that in contrast to co-benefits from reductions to co-emitted pollutants, the climate-induced air quality benefits of policy increase with time and are largest between 2050-2100. Our projections also suggest that increasing climate policy stringency beyond a certain degree may lead to diminishing returns relative to its cost. However, our results indicate that the air quality impacts of climate change are substantial and should be considered by cost-benefit climate policy analyses.

Introduction

Air pollution has been identified as the world's largest environmental health risk.[1] Climate and atmospheric pollution are coupled by a series of feedbacks in which climate influences tropospheric concentrations of pollutants, including ozone (O_3) and fine particulate matter ($PM_{2.5}$), and pollutants simultaneously act as climate forcers. Climate change may alter air quality through multiple mechanisms including reaction rates, atmospheric ventilation, pollutant deposition, and natural emissions.[2] These changes can increase pollutant concentrations and lead to a “climate penalty” on air quality, exacerbating health impacts and weakening the effectiveness of abatement measures.

Multiple studies have simulated the climate penalty on air quality using chemical transport models driven by climate fields derived from general circulation models and, more recently, fully coupled global chemistry–climate models. These have been previously reviewed.[2-4] At a global scale, studies agree that background O_3 in the lower troposphere will decrease under a warmer climate.[5-9] However, climate change can lead to increases in ground-level O_3 over polluted and urban areas.[10-14] In the U.S., regional and global simulations consistently project a climate-related O_3 increase over the Northeast, but exhibit less agreement for other regions.[4, 15] Although several studies suggest that climate change will affect $PM_{2.5}$, these impacts remain highly uncertain. There is still little consistency among projections regarding the magnitude of the climate penalty on $PM_{2.5}$ and direction of changes for regional effects.[16] Significant $PM_{2.5}$ changes associated with climate change have been projected over the U.S. by several studies.[17-21] Additionally, a few studies have extended their analysis of climate penalty to air pollution-related impacts on human health.[22-24] Some have aimed to quantify the penalty on U.S. health specifically, generally projecting an increase in premature mortality.[25-29] Only a small number of air quality studies have attempted to monetize these climate-related health impacts.[30, 31] West, et al. [32] compared global costs and benefits of the RCP4.5 scenario considering the effects of climate and co-emitted pollutants, but do not monetize climate-related impacts alone.

Simulations exploring the impacts of climate change on air quality rely on scenarios of future greenhouse gas and aerosol emissions to drive general circulation models. To focus on the climate penalty, the effect of climate on air quality is typically isolated by maintaining anthropogenic emissions in the simulations fixed at present-day levels. The most commonly used emission scenarios are those included in the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (SRES),[33] and the Representative Concentration Pathways (RCPs).[34] Although these scenarios project emissions of climate forcers for multiple futures, there are several restrictions to their use. These scenarios of emissions and concentrations, used by climate modeling groups as part of the Coupled Model Intercomparison Project Phase 3 (CMIP3) and Phase 5 (CMIP5), were developed by different Integrated Assessment Modeling (IAM) groups, with different socio-economic assumptions and different baseline reference scenarios.[35] The differences between scenarios and associated climate change cannot easily be identified as the impact of specific climate policies, with an associated cost. As a result, these scenarios do not provide an ideal framework to identify the impacts, in terms of costs and benefits, of climate policies of different stringencies.

Greenhouse gas mitigation can have significant air quality co-benefits from associated reductions in co-emitted conventional air pollutants. The air quality co-benefits alone may be large enough to offset the cost of climate policy,[36, 37] although recent analyses find that different CO_2 reduction policies may improve or deteriorate U.S. air pollution depending on the mitigation strategy followed.[38] Several studies have explored the change in co-emitted pollutants under climate policy, but did not consider the impact of a changing climate on air quality.[39] We investigate the complementary approach, considering the effect of climate change on air quality exclusive of emissions reductions. Comparing these air quality benefits of climate policy is important; while co-benefits from reduced pollutant emissions will be near-term and diminish with policy stringency, we hypothesize that benefits associated with a reduction in the climate penalty on air quality may grow with time and policy stringency. As a result, the benefits gained by reducing the effect of climate change on air pollution could offset a greater share of climate policy costs as mitigation efforts are increased over time.

Consistent and comparable estimates of avoided damages across multiple policy scenarios have been used in several evaluations of climate impacts on sectors other than air quality. The Climate Change Impacts and Risk Analysis (CIRA) project, led by the U.S. Environmental Protection Agency (EPA), is a comprehensive effort to estimate benefits of greenhouse gas mitigation and inform policy decisions.[40] The project relies on scenarios based on integrated socioeconomic and climate projections to assess physical and economic benefits of climate policy across multiple sectors. Under the CIRA framework, these scenarios have been systematically applied to explore different impacts, including water resources, infrastructure, and health.[41-43]

We examine the effect of climate change and climate policy on U.S. air quality and its associated health risks using the scenarios developed under the CIRA project for consistent analyses of climate impacts. Our modeling framework includes an integrated assessment model, a global atmospheric chemistry model, and a health and economic benefits model. We simulate air quality in 2050 and 2100 under three consistent projections of climate change. By using an internally consistent modeling framework, we are able to compare air quality projections that reflect the response to policy and evaluate two climate policies of differing stringency relative to a business-as-usual case. We then calculate pollution-related U.S. health and economic impacts of global climate policy following methods used in regulatory analysis. Finally, we compare the benefits attained from the avoided climate penalty on air quality under each policy to estimates of policy cost. As such, this study presents the first end-to-end analysis of air pollution and health benefits from avoided climate change using integrated economic, climate, and air quality projections.

Methods

Climate change and policy scenarios

Greenhouse gas emissions and climate projections are generated with the Massachusetts Institute of Technology Integrated Global System Model linked to the Community Atmosphere Model (MIT IGSM-CAM).[44] The MIT IGSM has two main coupled components, an Earth system model of intermediate complexity and a human activity model. The Earth system component includes representations of the atmosphere, ocean, sea-ice, carbon and nitrogen cycles, and terrestrial water, energy, and ecosystem processes. The IGSM simulates zonal-mean atmospheric dynamics and physics,[45] chemistry for 33 climate-relevant gas and aerosol species,[46] and a three-dimensional dynamical ocean based on the MIT ocean general circulation model.[47] The IGSM-CAM framework uses greenhouse gas concentrations, aerosol loadings, and sea surface temperature from the IGSM to drive the National Center for Atmospheric Research Community Atmosphere Model version 3,[48] and generate three-dimensional climate fields with 2° × 2.5° resolution and 26 vertical layers. In addition, the IGSM-CAM is designed to allow the evaluation of different emissions, climate parameters (e.g. climate sensitivity, aerosol forcing), and representations of natural variability.[49] A climate sensitivity of 3°C is used for all simulations in this study.

The human activity component of the IGSM is the MIT Emissions Predictions and Policy Analysis (EPPA) model, a computable general-equilibrium model of the world economy.[50] The EPPA model projects economic activity and related emissions of climate-relevant gas and aerosol species for 16 global regions and 25 economic sectors. It relies on fundamental assumptions about population and labor productivity growth, land and energy use, technology availability and cost, and policy constraints to determine gross domestic product (GDP) growth for each world region and policy scenario. Associated emissions from energy production and use, industrial processes, agricultural activities, and waste processing are used to drive the IGSM's Earth system component.

We simulate atmospheric pollution under three greenhouse gas emissions scenarios: (1) a "no-policy" reference scenario (REF) that assumes no mitigation efforts, continued economic growth, and unconstrained emissions with total radiative forcing of 10 W m^{-2} by 2100; (2) a stabilization 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 stabilization scenario that targets a total radiative forcing of 3.7 W m^{-2} by 2100 (POL3.7) and likewise assumes implementation of a worldwide tax on emissions. Additional information on the design of these scenarios is provided in Paltsev, et al. [51]. Under the reference scenario the concentration of CO_2 in the atmosphere is projected to rise to 830 ppm in 2100, while implementation of climate policy limits the increase to 500 ppm and 460 ppm under the POL4.5 and POL3.7 scenarios respectively. Global mean surface temperature is projected to rise by approximately 6 ˚C throughout the 21st century in the absence of climate policy, while increases smaller than 1.5 ˚C are projected under the stabilization scenarios. Additional details on the climate projections over the U.S. are available in Monier, et al. [49].

Global atmospheric chemistry and air quality

To simulate U.S. air quality, we use the global Community Atmosphere Model with atmospheric chemistry (CAM-Chem)[52] within the Community Earth System Model framework (CESM version 1.1.2). CAM-Chem includes an extensive tropospheric chemical mechanism with over 100 gas and aerosol species. A bulk aerosol scheme is used to simulate atmospheric concentrations of sulfate, ammonium nitrate, primary carbonaceous aerosols, secondary organic aerosols, dust, and sea salt. Process representations for photolysis, dry and wet deposition, and biogenic emissions are also included. CAM-Chem's chemistry-specific parameterizations are largely based on the Model for Ozone and Related chemical Tracers (MOZART-4).[53] In addition, we apply the optimized dry deposition scheme developed by Val Martin, et al. [54] that couples leaf and stomatal vegetation resistances to the leaf area index. Simulations are carried out at 1.9˚ x 2.5˚ resolution using 26 vertical levels reaching a height of approximately 40 km.

CAM-Chem has been used to simulate air quality in several studies.[21, 55, 56] The model's ability to replicate surface concentrations of O_3 and different aerosol species was evaluated in Lamarque, et al. [52]. Here, meteorological fields generated with the IGSM-CAM are used to drive CAM-Chem simulations using the model's offline configuration. Atmospheric emissions are described in Lamarque, et al. [52], largely based on the POET (Precursors of Ozone and their Effects in the Troposphere) emissions inventory.[57] We analyze the climate penalty on air quality across the contiguous U.S. by projecting changes in concentrations of ground-level O_3 and sulfate (SO_4), black carbon (BC), organic aerosol (OA), and ammonium nitrate (NH_4NO_3) particles, all $PM_{2.5}$ components of concern to human health. $PM_{2.5}$ mass is estimated following Val Martin, et al. [21] To isolate the impact of climate change on air pollution, anthropogenic emissions are set at year-2000 levels in all simulations. The concentrations of greenhouse gases, including those with dual roles as short-lived climate forcers and significant components of air pollution, are also held constant in our chemical mechanism. We use 30-year simulations to characterize air quality under present (1981-2010) and future (2036-2065 and 2086-2115) climates. In addition, 5-member ensembles of different climate variability representations, generated by modifying the IGSM-CAM's initialization, are used to capture long-term natural variability.[49] As a result, each scenario's projection of air quality under 2000, 2050, and 2100 climates is obtained from 150 years of underlying simulations to robustly evaluate the role of greenhouse gas mitigation. Statistical significance is evaluated through a Student's *t*-test for a 95% confidence level. The range in reported concentration changes represents the confidence interval at 95% for the difference in ensemble means.

Health and economic impacts assessment

To assess the impact climate policy would have on U.S. health by reducing the climate penalty on air quality, we estimate the change in mortality risk associated with ozone and fine particulate matter in 2050 and 2100 for each stabilization scenario. Estimates of mortalities avoided and years of life gained under policy follow EPA's Regulatory Impact Analysis methodology,[58] with details described in the SI. The Environmental Benefits Mapping and Analysis Program (BenMAP) version 4.0.67 is used to relate projected concentration changes to health incidences through multiple concentration-response functions.[59] Ensemble-mean air quality projections are used along with county-level census population data to quantify exposure differences between REF and policy scenarios. Mortality changes are estimated by applying the differences in May-September daily-maximum 8-hour O_3 (8-hr-max O_3) and daily average $PM_{2.5}$ to the concentration response functions. The range of reported mortality changes reflects the 95% confidence interval in concentration response functions.

Health impacts and corresponding monetized benefits are based on projections consistent with future population and GDP per capita in each policy scenario[51] and future mortality incidence rates following West, et al. [32] (details included in the SI). Climate-related air quality benefits associated with each policy are estimated as the value of reduced mortality risk due to reduced air pollution in 2050 and 2100. Reduced mortality risks are valued using two methodologies: 1) projecting the estimate for the Value of a Statistical Life (VSL) used by the EPA, which is based on 26 value-of-life studies with a distribution mean of $7.4 million (2005$),[60] and 2) valuing years of life saved (YLS) by projecting the 2005 U.S. national median annual household income ($50,000).[61] The costs of climate policy implementation are estimated as the loss in GDP relative to the REF scenario projected in 2050 and 2100. Additional details, projected values, and sensitivity analyses of the valuations are described in the SI.

Results

Climate change impact on O_3

Ensemble-mean projections show a climate change impact on ground-level O_3 throughout the U.S. At national scale, annual-average O_3 concentration is projected to decrease. Under the REF scenario, simulated annual O_3 concentrations averaged across the contiguous U.S. drop 0.7 ± 0.2 ppbv by 2050 and 1.3 ± 0.2 ppbv by 2100. However, projected changes differ regionally. Regional impacts are also stronger for daily-maximum concentrations. Figure 1 shows the simulated impact of climate change on annual-average 8-hr-max O_3 in 2100 under different scenarios. U.S.-average 8-hr-max O_3 is expected to remain unchanged in 2100 under the REF scenario (Table S4). However, increases as large as 10 ppbv are projected at specific locations. The simulations indicate that climate change will exacerbate O_3 pollution over large areas in the Northeast, South, Midwest, and Southwest. In contrast, a climate-related decrease in 8-hr-max O_3 is projected over the Northwest and a portion of the Midwest. Climate-driven O_3 increases are especially substantial during summer months (the climate penalty on U.S. ozone-season concentrations is shown in Figure S1); a climate penalty of +4.7 ± 0.5 ppbv on June-August U.S.-average 8-hr-max O_3 is projected by the end of the century.

The impact of climate change on O_3 is significantly diminished by greenhouse gas mitigation. The change in U.S.-average annual O_3 concentration by 2100 under the REF scenario is nearly halved in the POL4.5 and POL3.7 scenarios. Most of the increases in O_3 simulated over the eastern U.S. in the REF scenario become smaller than 1 ppbv or statistically insignificant under climate policy (Figure 1). The difference in simulated penalties on U.S.-average summertime 8-hr-max O_3, +4.7 ± 0.5 and +0.8 ± 0.5 ppbv by 2100 for the REF and POL4.5 scenarios respectively, is of note. In addition, at national scale no significant gains in O_3 pollution are attained by 2100 under the more stringent POL3.7 mitigation scenario compared to POL4.5.

Climate change impact on $PM_{2.5}$

Ensemble-mean results also show a climate penalty for $PM_{2.5}$ pollution. Annual U.S.-average $PM_{2.5}$ (SO_4+BC+OA+NH_4NO_3) concentrations are projected to increase under the REF scenario by 0.3 ± 0.1 and 0.7 ± 0.1 μg m^{-3} in 2050 and 2100 respectively. Regional variations are significant. Figure 1 shows projected changes in ground-level $PM_{2.5}$ from 2000 to 2100. Under the REF scenario, $PM_{2.5}$ is projected to increase over the most of the U.S., with penalties as large as +3.0 μg m^{-3} in the East. A decrease in ground-level $PM_{2.5}$ is anticipated over parts of the Midwest. $PM_{2.5}$ enhancement is especially significant during the summer; June-August concentrations are projected to increase over most of the country, while a decrease in winter-time $PM_{2.5}$ (December-February) is projected over a large fraction of the eastern U.S. (seasonal changes are included in Figure S2).

Implementation of climate policy notably reduces simulated impacts on ground-level $PM_{2.5}$. Additional reductions are achieved by implementing a tighter stabilization strategy under the

POL3.7 scenario. The penalty on annual U.S.-average $PM_{2.5}$ projected at +0.7 ± 0.1 μg m^{-3} in 2100 under the REF scenario, falls to +0.2 ± 0.1 μg m^{-3} in the POL4.5 scenario and is not statistically significant for POL3.7. As shown in Figure 1, many of the regional impacts projected in the absence of climate policy are rendered insignificant by greenhouse mitigation efforts.

Impacts of climate policy on U.S. air quality and health

In our simulations greenhouse gas mitigation largely curbs climate impacts on air pollution and health. Figures 2 shows U.S.-average population-weighted annual 8-hr-max O_3 and $PM_{2.5}$ concentrations projected under each scenario in 2000, 2050, and 2100, considering climate impacts alone without accounting for changes in emissions. Corresponding climate penalties under each scenario for these health-relevant metrics are included in Table 1. Under the REF scenario, the penalty on population-weighted O_3 is projected at +0.8 ± 0.3 and +3.2 ± 0.3 ppbv in 2050 and 2100 respectively. Population-weighted O_3 penalties are considerably higher than un-weighted estimates, as climate-induced increases occur over populated regions. Although climate change still exerts a negative effect on O_3 pollution under the policy scenarios, the penalty on population-weighted concentrations is reduced by over 50% and 80% in 2050 and 2100 respectively. Penalty reductions attained under POL4.5 and POL3.7 with respect to REF are included in Table 2. Projected penalties and policy impacts on summertime O_3 are considerably larger. Similarly, REF scenario penalties on population-weighted annual $PM_{2.5,}$ +0.5 ± 0.1 μg m^{-3} in 2050 and +1.5 ± 0.1 μg m^{-3} in 2100, are cut by over 40% and 70% respectively by implementing a mitigation policy. The largest gains in avoided air quality penalty under stabilization scenarios are anticipated to occur during the second half of the 21st century. In the SI, Figure S4 shows how projected policy impacts on population-weighted $PM_{2.5}$ and O_3

concentrations are greater during the second half of the 21st century. As previously described, air quality benefits are larger under the POL3.7 scenario than POL4.5 for $PM_{2.5}$, but no additional improvements in O_3 pollution are projected for the more stringent policy.

Health benefits associated with climate change mitigation by reducing the climate penalty on O_3 and $PM_{2.5}$ are listed in Table 2. Compared to the REF scenario, over 10,000 (4,000-22,000) premature U.S. deaths are prevented in 2050 under climate policy. The projections grow to greater than 50,000 (19,000-95,000) avoided deaths in 2100. Mean estimates of annual U.S. life years saved under policy exceed 550,000 by 2050 and 1,300,000 by 2100. Reductions in $PM_{2.5}$ largely drive the change in mortality. However, the contribution of O_3 to these estimates increases towards the end of the century and accounts for 40% of projected life years saved by 2100. Individual estimates for each pollutant are included in the SI.

The mean value of benefits associated with avoided mortality under POL4.5 with respect to REF is approximately \$150 billion and \$1.3 trillion (2005\$) in 2050 and 2100 respectively using the VSL. Under POL3.7 the mean value of these benefits is nearly \$180 billion and \$1.4 trillion (2005\$). VSL-based values correspond to over \$120 per ton of CO_2 equivalent (tCO_2e) (\$45 tCO_2e^{-1}-\$209 tCO_2e^{-1}) in 2100. The mean value of YLS for both POL4.5 and POL3.7 compared to the REF scenario is approximately \$60 and \$150 billion (2005\$) in 2050 and 2100 respectively. Values based on lost income and YLS correspond to \$13 tCO_2e^{-1} (\$2 tCO_2e^{-1}-\$25 tCO_2e^{-1}) in 2100. All valuations are listed in Table S7 of the SI. Compared to REF, average global GDP growth rate is reduced by 0.3-0.5% per year under climate policy (detailed economic projections are presented in Paltsev, et al.[47]). Figure 3 shows the costs of climate policies and value of climate-related air quality benefits as a fraction of projected REF scenario U.S. GDP. Benefit valuations estimated with the VSL based on avoided mortalities and lost income based on YLS are shown and compared to U.S. policy costs in the years 2050 and 2100. While the annual costs of greenhouse gas mitigation in 2050 and 2100 under POL3.7 are approximately 30% larger than POL4.5, the associated increase in projected benefits for the more stringent policy is smaller. Valuation of health impacts using the VSL yields significantly higher estimates than the income-based approach. Additionally, while VSL-derived benefits grow significantly as a fraction of U.S. GDP over time, YLS-based values are consistent, within uncertainties, over time and across policies. Health benefits attained by reducing the climate penalty on U.S. air quality are projected to offset 1%-9% of climate policy costs in 2050. By 2100 the mean VSL-based value of avoided premature deaths under POL4.5 offsets close to 15% of policy costs with an upper limit estimate of nearly 25%.

Discussion

Climate change affects ground-level O_3 in our simulations through several mechanisms. Globally, a climate-induced drop in O_3 is caused by increased atmospheric water vapor under a warmer climate. Higher humidity shortens the atmospheric lifetime of O_3 in low-NOx conditions by enhancing its conversion to hydroxyl radicals through reactions sensitive to water vapor concentration.[4] Reductions in simulated ground-level concentrations over the West and Midwest are largely driven by this decline in background O_3. However, the sensitivity of O_3 to water vapor is altered under polluted atmospheres, and climate change is projected to increase O_3 concentrations across much of the U.S. Different factors contribute to this. Enhanced photochemistry and tropospheric ozone formation, reflected in higher concentrations of nitrogen oxides and hydrogen oxide radicals and lower peroxyacetyl nitrate across the U.S. in the future climate simulations, are associated with temperature changes.[15] Simulations also reveal an increase in climate-sensitive emissions of biogenic volatile organic compounds, particularly over the Southeast. In addition, greater stagnation, as evidenced by an increase in modeled ground-level CO, further contributes to higher O_3 concentrations.

Several of the pathways through which climate change impacts O_3 also influence $PM_{2.5}$. However, climate-related effects vary among different $PM_{2.5}$ components. Higher temperature and water vapor increase SO_4 concentration by enhancing SO_2 oxidation, while a drop in nitrate PM results from greater partitioning into the gas phase at higher temperature.[4] Increased temperature can also shift partitioning of OA further to the gas phase, while simultaneously intensifying emissions of biogenic precursors.[3] Changes in atmospheric ventilation have a stronger effect on $PM_{2.5}$ than O_3. In addition, variations in precipitation affect $PM_{2.5}$ concentrations by altering wet deposition. Estimates of climate-induced impacts on $PM_{2.5}$ depend on the components considered. Here, projected $PM_{2.5}$ increases are largely driven by a rise in SO_4, especially in the eastern U.S. The increment is countered by reductions in NH_4NO_3, largest over the Midwest (projected changes to SO_4 and NH_4NO_3 are shown in Figure S3). A lesser increase in OA is also is also projected across the U.S., in particular over several areas in the Northeast, Southeast, and West. A small rise in BC, concentrated over the West, reflects higher stagnation and the decrease in precipitation projected over the region.

Our ensemble-mean projections agree with the robust finding of prior studies that climate change will negatively impact O_3 over the Northeast.[3] Climate-induced O_3 reductions in the West and Midwest have also been reported by several of the regional- and global-scale simulations included in EPA's assessment of climate change impacts on ground-level O_3.[15] Although the projections of Val Martin, et al. [21] and Pfister, et al. [56] also show a significant penalty on O_3 over the eastern U.S., they report increased concentrations throughout most of the country including the West. However, these estimates include the effect of rising CH_4 levels on background O_3

concentrations and, for the summertime regional-scale simulations in Pfister, et al. [56], future-level chemical initial and boundary conditions. Comparisons of climate penalty projections for $PM_{2.5}$ across studies are often complicated by differences in the components and processes included in each analysis. Furthermore, $PM_{2.5}$ projections often disagree on the expected direction of change. Our ensemble-mean results agree with those reported by Fang, et al. [22], projecting enhanced $PM_{2.5}$ pollution throughout the U.S., higher increases in the East, and a rise in SO_4 and OA concentrations due to 21st century climate change. These findings contrast with those of Val Martin, et al. [21] which only project a few areas, mostly over the Midwest, with statistically significant climate-induced reductions in $PM_{2.5}$ by 2050.

In interpreting these results, several air quality modeling assumptions must also be considered. By maintaining greenhouse gases at present-day levels in future atmospheric chemistry simulations, we neglect O_3 formation from rising methane (CH_4) along each scenario's concentration pathway. The choice allows our analyses to focus on meteorology-related impacts, whereas the benefits of CH_4 emissions controls have been previously examined from a policy perspective.[62, 63] Simulated penalties on O_3 are significantly higher considering the projected increase in global CH_4 concentration (240% by 2100 under REF), largely negating climate-related reductions over some U.S. regions described in Results (Figure S5). The impact of CH_4 on U.S. O_3 in these simulations, 1-5 ppbv by 2050 under REF, is comparable to the 4-8 ppbv increase reported by Gao, et al. [64] for the RCP 8.5 scenario. The effect of future CH_4 concentrations on $PM_{2.5}$, from which most monetary impacts are derived, is smaller, increasing REF scenario U.S.-average annual concentration in 2100 by 2%. By retaining anthropogenic emissions at year-2000 levels, it is possible that climate penalties may be high relative to estimates obtained under lower future pollutant emissions and concentrations. In addition, our estimates do not consider the effect of CO_2 inhibition on biogenic isoprene emissions, which may be substantial but has not been included in most analyses of climate impacts on air quality.[65] The influence of climate change on dust, sea salt, and wildfire emissions is not simulated, but may be especially significant for $PM_{2.5}$.[66-68] Changes in land cover and land use associated with climate, which impact pollutant emissions and deposition,[21] are not modeled. In a comparison of global- and regional-scale simulations, Pfister, et al. [56] find that coarse-grid models, while unable to fully resolve local-scale impacts, capture the main drivers of climate-induced changes in U.S. O_3. Still, coarse resolution simulations may not capture concentrations at densely-populated urban locations.

Significant uncertainties are also associated with our health and economic estimates. These rely on simplifying assumptions to represent pollutant exposure, health impacts, economic valuations, population, economic growth, and technology costs. Projected population growth is considered in the estimates, but distribution across the U.S. is assumed to remain unchanged. Health impacts are derived from ensemble-mean changes in concentrations, neglecting significant variability in air quality projections. Reported ranges for avoided mortalities and YLS are solely based on the spread in concentration response functions. Concentration response functions are assumed to remain valid throughout the 21st century. Valuations are based on willingness-to-pay or income-based measures, rather than being represented in the economic model, which is shown to affect economic estimates.[36] The sensitivity of valuations to uncertainty in income elasticity and discount rate is tested in the SI. It is important to note that health benefits projected in this study only partially cover the total impact of climate policy on human health, and represent only a fraction of the benefits of avoiding damages from climate change. Firstly, the benefits of slowing climate change are quoted for the years 2050 and 2100, but will extend beyond this analysis period. As previously noted, important health benefits stem from reductions of co-emitted pollutants under greenhouse gas mitigation. In addition, our estimates only consider health benefits associated with O_3 and $PM_{2.5}$ reductions and do not include avoided impacts on morbidity. Beyond air quality, climate change mitigation is expected to benefit many sectors, including ecosystems, infrastructure, agriculture, and others.[69]

Large uncertainties are associated with projections of climate policy costs in economic models, which are sensitive to assumptions about the details represented in the models, technology costs and availability. A wide range of cost estimates has been reported for climate policy in the U.S.,[70] and this source of uncertainty is not accounted for here. Lower cost estimates would change the ratio of climate-related air quality benefits relative to mitigation costs. Our projections are, despite these uncertainties, intended to provide insight into the significance of climate-related air quality benefits. In addition, our treatment of health and economic impacts is consistent with previous literature on climate policy co-benefits for air quality.

Implications for Benefits Assessments

We evaluated the impact of greenhouse gas mitigation policies on air quality and health in the U.S. by reducing the climate penalty on air pollution. In contrast to prior studies based on scenarios that disallow cost and benefit comparisons, we used a consistent modeling framework to provide integrated economic, climate, and air quality projections. We further tested the hypotheses that climate-related benefits may increase over time and with policy stringency. Additionally, we used 150-year simulations to robustly account for climatic variability in characterizations of present and future air quality. Although large-scale greenhouse gas reductions will be inevitably tied to a decrease in co-emitted pollutants, by modeling air quality impacts solely due to variations in climate, estimated benefits are directly attributable to climate change mitigation.

The influence of climate change and policy on U.S. air quality in our simulations is substantial; modeled reductions in annual-average population-weighted $PM_{2.5}$ and 8-hr-max O_3 are over 1 $\mu g\ m^{-3}$ and 2.5 ppbv by 2100. Our projections also reveal several policy-relevant insights. Similar to reported co-benefits from co-emitted pollutant reductions, we observe diminishing returns with increasing policy stringency from climate benefits, as added climate stabilization achieved under a more stringent policy comes at a higher cost. Our estimates suggest that intensifying policy stringency from POL4.5 to POL3.7 could raise costs nearly 30% by 2100, yet increase mortality benefits less than 6%. Unlike near-term co-benefits from reduced emissions, the largest benefits attained by slowing climate change may not occur until decades after mitigation efforts begin. These policy impacts are largely concentrated over urban locations in the East and California.

Isolating the influence of climate on air quality in our analysis enables comparisons with prior studies exploring the co-benefits of climate policy. We project climate policy benefits in the U.S due to a reduction in climate-induced mortality with a mean value of \$8-25 tCO_2e^{-1} in 2050 and \$13-125 tCO_2e^{-1} (2005\$) in 2100, depending on policy stringency and valuation method. Our estimates are significantly lower than the emissions-related co-benefits reported by Thompson, et al.[35] for U.S. policies targeting a 10% reduction in CO_2 emissions by 2030. They are also lower than those projected for the RCP4.5 scenario by West, et al. [32], which include both emissions and climate-related effects (\$30-600 per ton CO_2). However, our monetized benefits of reduced climate change alone are within the \$2-196 per ton CO_2 range of 37 air quality co-benefits studies surveyed by Nemet, et al. [39] that only consider co-emission reductions, suggesting the need to include the effect of climate in benefits assessments. Importantly, while these studies project air quality co-benefits that decrease with time, our climate-specific estimates grow substantially towards 2100. Furthermore, the magnitude of our projected impact of climate policy on avoided mortality is similar to that estimated, for example, for extreme temperature mortality using the same policy and climate scenarios under EPA's CIRA project.[41] These findings demonstrate that climate-specific air quality impacts can significantly contribute to the value of benefits associated with climate change mitigation and should be considered in decisions concerning climate policy.

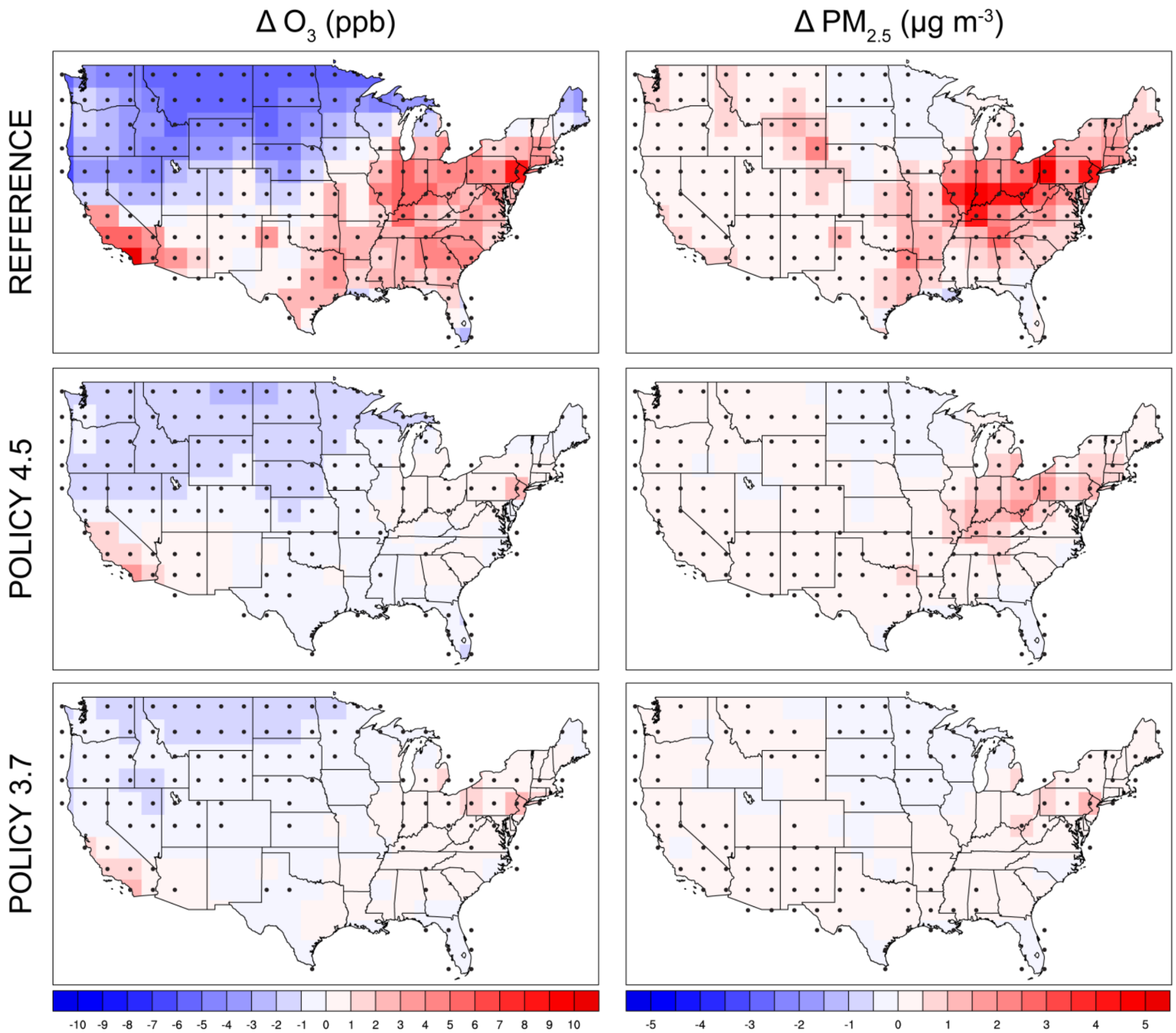

Figure 1. Ensemble-mean climate-induced change in annual-average ground-level 8-hr-max O_3 and $PM_{2.5}$ from 2000 to 2100 under the REF, POL4.5, and POL3.7 scenarios. Changes identified as statistically significant are indicated by black dots.

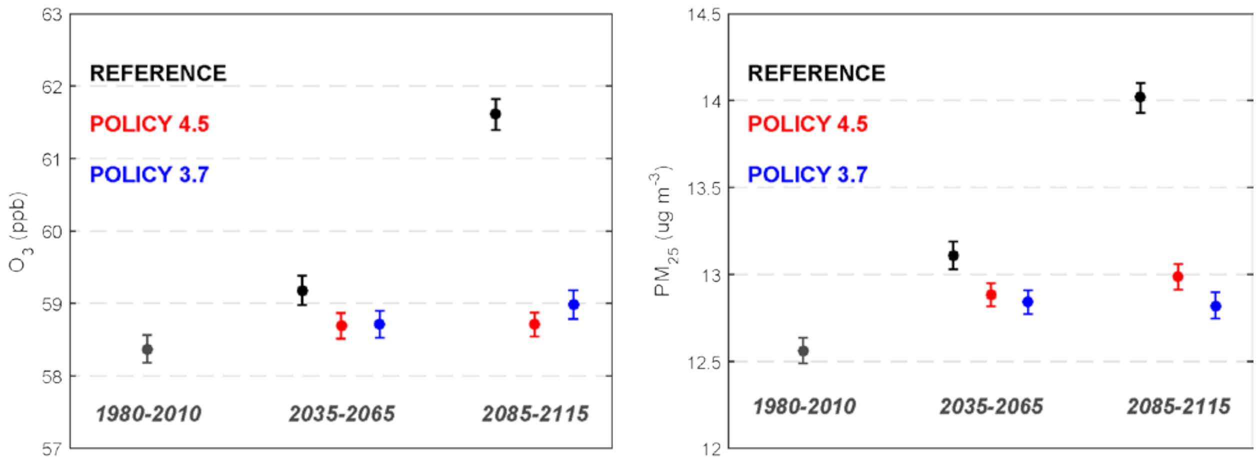

Figure 2. Ensemble-mean U.S.-average population-weighted annual 8-hr-max O_3 and $PM_{2.5}$ in 2000, 2050, and 2100 under REF, POL4.5, and POL3.7 scenarios.

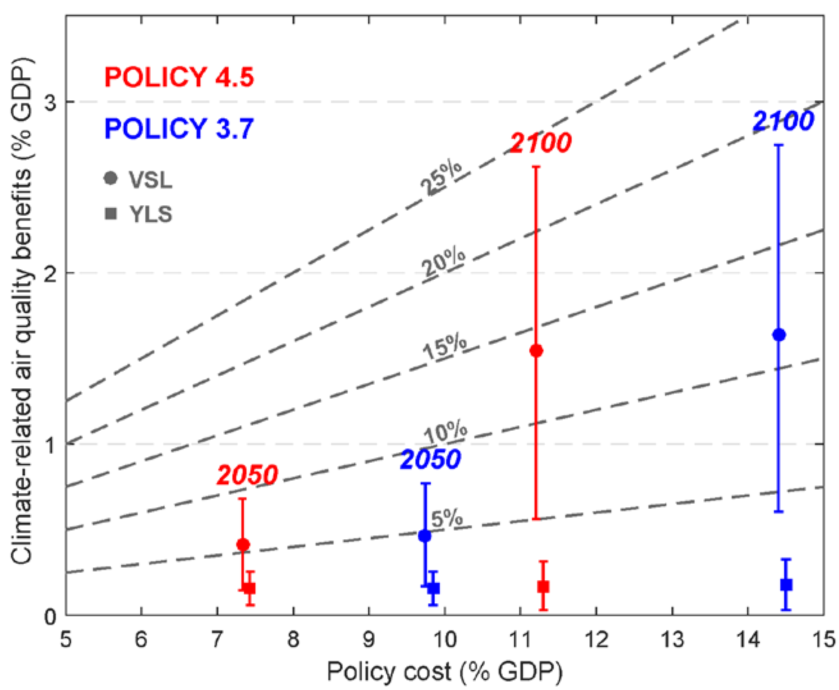

Figure 3. Cost of climate policy and value of mortality-related benefits from reduced climate penalties on O_3 and $PM_{2.5}$ expressed as fraction of REF scenario U.S. GDP. Valuations based on avoided mortalities (VSL) and years of life saved (YLS) are shown. Dashed lines indicate the percentage of climate policy costs offset by health benefits.

Table 1. Ensemble-mean climate penalties on U.S.-average population-weighted annual 8-hr-max O_3 and $PM_{2.5}$ from 2000 to 2050 and 2100.

		8-hr-max O_3 (ppbv)	$PM_{2.5}$ ($\mu g\ m^{-3}$)
REF	*2000 → 2050*	0.8 ± 0.3	0.5 ± 0.1
	2000 → 2100	3.2 ± 0.3	1.5 ± 0.1
POL4.5	*2000 → 2050*	0.4 ± 0.2	0.3 ± 0.1
	2000 → 2100	0.4 ± 0.2	0.4 ± 0.1
POL3.7	*2000 → 2050*	0.3 ± 0.3	0.2 ± 0.1
	2000 → 2100	0.6 ± 0.3	0.2 ± 0.1

Table 2. Avoided climate penalties under POL4.5 and POL3.7 relative to REF for U.S.-average population-weighted annual 8-hr-max O_3 and $PM_{2.5}$ in 2050 and 2100. Resulting avoided deaths and life years saved also included.

		8-hr-max O_3 (ppbv)	$PM_{2.5}$ ($\mu g\ m^{-3}$)	Avoided deaths	Life years saved (thousands)
REF → POL4.5	*2050*	-0.5 ± 0.3	-0.2 ± 0.1	11,000 (4,000-19,000)	570 (210-940)
	2100	-2.9 ± 0.3	-1.0 ± 0.1	52,000 (19,000-87,000)	1,300 (240-2,500)
REF → POL3.7	*2050*	-0.5 ± 0.3	-0.3 ± 0.1	13,000 (4,800-22,000)	620 (230-1,000)
	2100	-2.6 ± 0.3	-1.2 ± 0.1	57,000 (21,000-95,000)	1,400 (240-2,600)

ASSOCIATED CONTENT

Supporting Information. Further information on health impacts methods, climate policy air quality and health benefits, sensitivity analyses for benefits valuations, and the influence of methane in simulations. This material is available free of charge via the Internet at http://pubs.acs.org

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Notes

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