# U.S. Air Quality and Health Benefits from Avoided Climate Change under Greenhouse Gas Mitigation*

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# U.S. Air Quality and Health Benefits from Avoided Climate Change under Greenhouse Gas Mitigation

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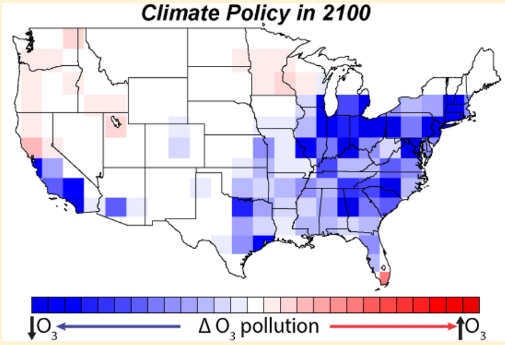
*Supporting Information*



**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 cobenefits from reductions to coemitted pollutants, the climate-induced air quality benefits of policy increase with time and are largest between 2050 and 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 coemitted 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 Con-

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centration 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 socioeconomic 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 cobenefits from associated reductions in coemitted conventional air pollutants. The air quality cobenefits 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 coemitted 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 cobenefits 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 $2° \times 2.5°$ 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 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]

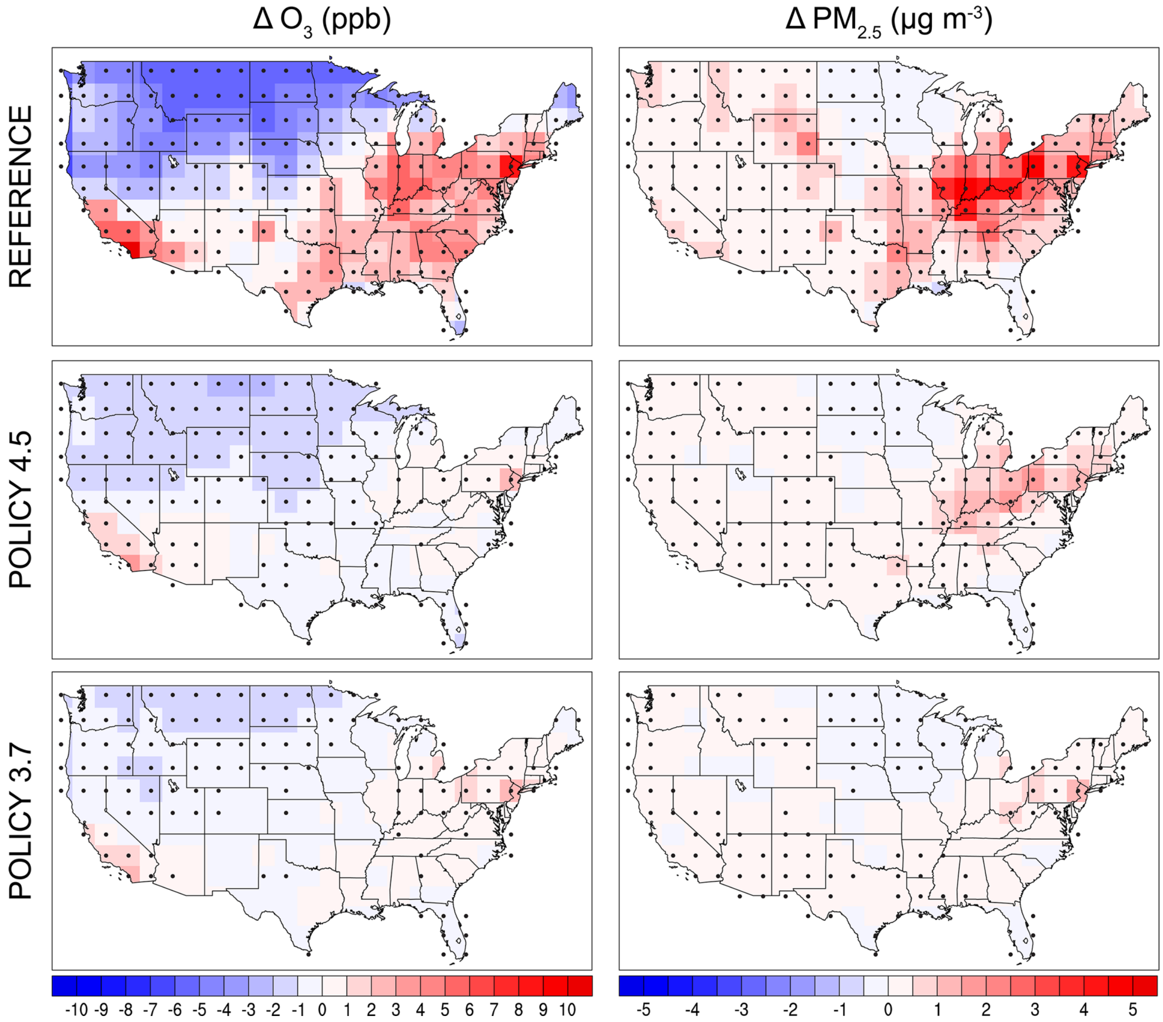

**Figure 1.** Ensemble-mean climate-induced change in annual-average ground-level 8-h-max $O_3$ and $PM_{2.5}$ from 2000 to 2100 under the REF, POL4.5, and POL3.7 scenarios. Changes identified as statistically significant are indicated by black dots.

**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 parametrizations 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° × 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]

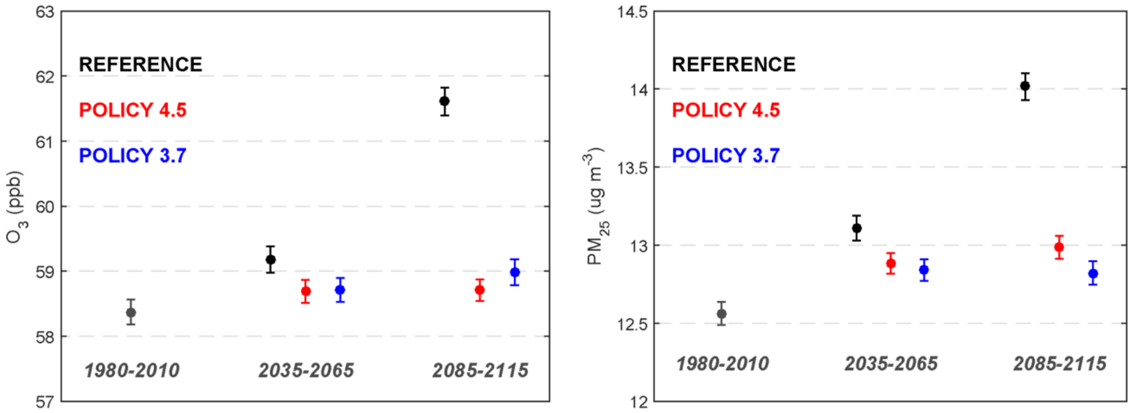

**Figure 2.** Ensemble-mean U.S.-average population-weighted annual 8-h-max $O_3$ and $PM_{2.5}$ in 2000, 2050, and 2100 under REF, POL4.5, and POL3.7 scenarios.

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-h $O_3$ (8-h-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-h-max $O_3$ in 2100 under different scenarios. U.S.-average 8-h-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-h-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-h-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-h-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 $\mu g\ m^{-3}$ 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 most of the U.S., with penalties as large as +3.0 $\mu g\ m^{-3}$ 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 $+0.7 \pm 0.1\ \mu g\ m^{-3}$ in 2100 under the REF scenario falls to $+0.2 \pm 0.1\ \mu g\ m^{-3}$ 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. Figure 2 shows U.S.-average population-weighted annual 8-h-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 8-h-max $O_3$ is projected at $+0.8 \pm 0.3$ and $+3.2 \pm 0.3$ ppbv in 2050 and 2100, respectively. Population-weighted $O_3$ penalties are considerably higher than unweighted 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 $PM_{2.5}$, $+0.5 \pm 0.1\ \mu g\ m^{-3}$ in 2050 and $+1.5 \pm 0.1\ \mu g\ m^{-3}$ 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.

**Table 1. Ensemble-Mean Climate Penalties on U.S.-Average Population-Weighted Annual 8-h-max $O_3$ and $PM_{2.5}$ from 2000 to 2050 and 2100**

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

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 toward 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

**Table 2. Avoided Climate Penalties under POL4.5 and POL3.7 Relative to REF for U.S.-Average Population-Weighted Annual 8-h-max $O_3$ and $PM_{2.5}$ in 2050 and 2100[a]**

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

[a] Resulting avoided deaths and life years saved also included.

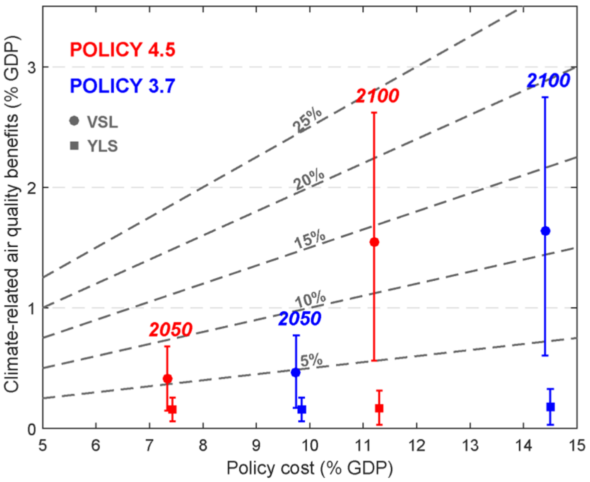

**Figure 3.** Cost of climate policy and value of mortality-related benefits from reduced climate penalties on $O_3$ and $PM_{2.5}$ expressed as fraction of REF scenario U.S. GDP. Valuations based on avoided mortalities (VSL) and years of life saved (YLS) are shown. Dashed lines indicate the percentage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

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 $PM_{2.5}$ 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, estimates for the summertime regional-scale simulations in Pfister et al.[56] include the effect of rising $CH_4$ levels on background $O_3$ concentrations and 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. First, 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 coemitted 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 cobenefits 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 coemitted 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-h-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 cobenefits from coemitted 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 cobenefits 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 cobenefits 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 cobenefits 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 cobenefits studies surveyed by Nemet et al.[39] that only consider coemission reductions, suggesting the need to include the effect of climate in benefits assessments. Importantly, while these studies project air quality cobenefits that decrease with time, our climate-specific estimates grow substantially toward 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.

## ■ 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. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01324.

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

### Notes

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