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Effect of Health-Related Uncertainty and Natural Variability on Health Impacts and Cobenefits of Climate Policy

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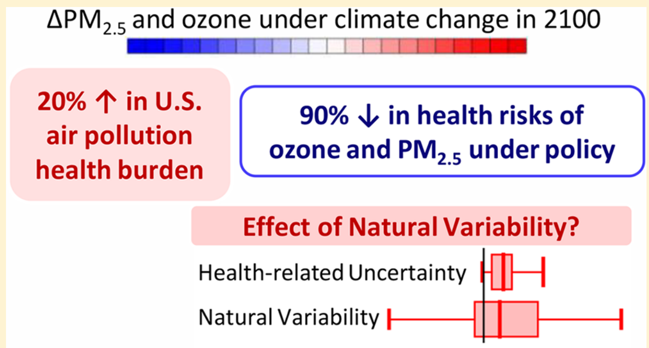
Supporting Information

ABSTRACT: Climate policy can mitigate health risks attributed to intensifying air pollution under climate change. However, few studies quantify risks of illness and death, examine their contribution to climate policy benefits, or assess their robustness in light of natural climate variability. We employ an integrated modeling framework of the economy, climate, air quality, and human health to quantify the effect of natural variability on U.S. air pollution impacts under future climate and two global policies (2 and 2.5 °C stabilization scenarios) using 150 year ensemble simulations for each scenario in 2050 and 2100. Climate change yields annual premature deaths related to fine particulate matter and ozone (95CI: 25 000−120 000), heart attacks (900−9400), and lost work days (3.6M-4.9M) in 2100. It raises air pollution health risks by 20%, while policies avert these outcomes by 40−50% in 2050 and 70−88% in 2100. Natural variability introduces "climate noise", yielding some annual estimates with negative cobenefits, and others that reach 100% of annual policy costs. This "noise" is three times the magnitude of uncertainty (95CI) in health and economic responses in 2050. Averaging five annual simulations reduces this factor to two, which is still substantially larger than health-related uncertainty. This study quantifies the potential for inaccuracy in climate impacts projected using too few annual simulations.



■ INTRODUCTION

Climate change and air pollution are public health challenges linked in ways that affect policy outcomes. Climate change increases health risks due to air pollution.[1−3] This "climate penalty"[4] on air quality affects adaptation, vulnerability, and preparedness.[5,6] Mitigating climate change could yield health-related air quality cobenefits that offset policy costs,[7−12] though most studies focus on health cobenefits due to reducing coemitted pollutants only, and do not consider the effect of climate change. This is partly due to the fact that climate-related improvements in air quality ("climate cobenefits") are considered small compared to those of coemitted pollutants, and partly due to the added computational complexity of simulating climate change, which is obscured by natural (or internal) variability. Most studies that do simulate the effect of climate change on pollutant concentrations address natural variability by averaging five years or less of simulations, though there is evidence that more years may be needed.[13] No studies have yet considered the adequacy of this typical approach for health impact analysis. The well-known uncertainty in relationships between concentrations and health responses may preclude the need for more precise concentrations, or may, by comparison, reveal the significance of uncertainty introduced by natural variability. Here, we quantify air pollution-related health risks from climate change, and isolate the effect of natural variability on climate cobenefits of stringent global policies that avert those risks. By comparison with health-related uncertainty, we assess the public health and policy relevance of addressing natural variability, and test the adequacy of current practice to address this source of uncertainty in projections of climate impacts.

Climate change can affect air pollutant concentrations, including ozone and fine particulate matter ($PM_{2.5}$), through multiple mechanisms, such as enhancing pollutant formation at higher temperatures or via reduced atmospheric ventilation.[14] Climate policy improves air quality by directly reducing the effect of climate change on air pollution (the "climate cobenefit"[15]), and by reducing coemitted air pollutants. Many studies estimate health cobenefits of climate policy

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Table 1. Experimental Design to Isolate the Effect of Natural Variability on Climate Cobenefits[a]

Framework	Variables	Simulations	Output
Policy (EPPA) Climate (MESM- CAM) Air Quality (CAM-Chem) Health & Valuation (BenMAP)	**Constant** Anthropogenic pollutant emissions Population age/spatial distribution **Varying** Population growth Economic growth Baseline mortality incidence rates GHG emissions Climatic conditions Pollution concentrations	**Scenarios** Reference, Policy 4.5, Policy 3.7 **Years of Interest** 2000, 2050, 2100 **Annual simulations** 30-year periods: 1986-2015; 2036-2065; 2086-2115 5 initializations 150 annual simulations per scenario and year of interest	**Impacts due to fine particulate matter and ozone exposure (multiple CRFs)** - All-cause mortality - Morbidity including: - acute myocardial infarction, - hospital admissions (respiratory, cardiovascular, emergency), - respiratory symptoms (upper respiratory symptoms, asthma exacerbation, acute bronchitis), - lost productivity (work loss days, school loss days, minor restricted activity days) - Economic valuation of benefits

[a]EPPA = MIT Economic Projection & Policy Analysis. MESM = MIT Earth System Model. CAM-Chem = Community Atmosphere Model with Chemistry. BenMAP = environmental Benefits Mapping and Analysis Program. CRF = concentration−response function.

related to air pollution;[16,17] however, most use constant meteorological inputs, focusing only on coemitted pollutants. Cobenefits from coemitted pollutants are likely larger than climate cobenefits.[15] However, climate cobenefits may increase over time, as pollutant emissions are reduced through air quality measures, and as the climate responds to greenhouse gas reductions. Garcia-Menendez et al.[18] found climate cobenefits of \$8−42/tCO_2e in 2050 rose to \$45−207/tCO_2 by 2100.[18] Still, few studies include climate cobenefits,[7,19−23] and few isolate this effect.[15,18,24] Those that do isolate climate cobenefits find significant annual impacts, up to thousands of deaths avoided and trillions of dollars in benefits offsetting up to one-quarter of annual policy costs.[15,18,23]

Despite their significance,[25] human health cobenefits lack traction in climate policy analysis.[16] This is due, in part, to a variety of methods[25] and uncertainties[26] that limit general conclusions.[17] Previous studies assessed uncertainties, including emissions scenarios,[27] demographics,[28,29] model selection[24,28] and resolution,[30−33] exposures,[34,35] and health-related uncertainty. Health-related uncertainties include the shape of the concentration−response function (CRF)[36,37] (relation of air pollution exposure to health risk), thresholds,[24] baseline incidence rates,[8,24] confounding, and effect modification.[38,39] In United States air quality policy analysis, the most commonly quantified health-related uncertainty[40] is the confidence interval in the CRF associated with individual studies, such as those for $PM_{2.5}$-related mortality from the American Cancer Society study[41] and the Harvard Six Cities study.[42] Capturing uncertainty related to the health impacts of climate change or climate policy, therefore, requires an assessment of multiple end points (mortality and morbidity) using multiple CRFs.

While recent reviews[1−3] present estimates of projected health burdens of air pollution due to climate change, policymakers need a better understanding of future mortality and morbidity risks, and associated uncertainties. Many U.S. studies address only ozone-related mortality[23,28,43−46] and morbidity.[23,47] However, $PM_{2.5}$ is a leading cause of disease burden in the US[48] and globally.[49] There is some intermodel agreement that $PM_{2.5}$ increases in many locations under climate change,[50] yielding higher $PM_{2.5}$-related U.S. mortality by 2100.[24] Existing studies of the entire U.S. include mortalities in 2050[28,45,18,27,51,52] and 2100[24] due to $PM_{2.5}$ and ozone; however, only one[27] includes morbidities, such as heart attacks and hospitalizations, needed for public health preparedness[3] and uncertainty assessment.

Quantifying uncertainties helps to assess their policy relevance, and to inform more consistent methods. For example, previous studies found the choice of climate change-air quality modeling system yielded the greatest uncertainty in ozone-related mortality under climate change, compared to population projections and concentration−response functions.[28] Different climate change-air quality modeling systems yield deaths due to climate change that differ by 3000 deaths for ozone in 2050[28] and 28 000 deaths for $PM_{2.5}$ in 2100.[24] Other work[27] suggests that uncertainty in climate projections may have a comparable effect on health impacts. One study[27] estimated the effect of uncertainty in future climate projections on ozone- and $PM_{2.5}$-related deaths, using the 0.5th and 99.5th percentiles of a probabilistic distribution of meteorological variables derived from the MIT Integrated Global System Model (MIT IGSM). The difference in estimates across these variables was 2600 ozone-related deaths and 9300 $PM_{2.5}$-related deaths in the U.S. in 2050 under RCP8.5. While this suggests uncertain climate projections may be as significant as intermodel differences for future public health, the effect of natural variability on climate cobenefits has not been quantified.

Natural climate variability can introduce "noise"[53] into climate projections that obscures estimates of the future health burden of air pollution. Natural variability is the unforced fluctuation resulting from the chaotic nature of the climate system,[53] including nonlinear interactions, feedbacks, and varying response times among climate system components.[54] Consequently, in one year the reference simulation might be warm and dry, and the policy simulation cool and wet, yielding differences due to natural variations in meteorology that are incorrectly attributed to policy.[13] This yields large uncertainty in climate projections, including projections of the climate penalty,[14] which can be evaluated using multiple initial condition ensembles of climate simulations.[55]

To date, however, the implications of natural variability for health impacts of air pollution remain unclear.[56] This is primarily due to computational intensity[14] of many required simulations of climate, air quality, and human health responses

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across multiple pollutants and health outcomes. Unlike uncertainty in CRFs, the effect of natural variability can be filtered out with sufficient simulations.[13] Most (e.g., 29 of 41 studies on ozone[13]) air quality projections average less than five years of simulations.[13] Recent findings suggest more simulations may be needed—perhaps more than 10-year averages—to achieve sufficient precision in future pollutant concentrations.[13,57,58] Since this finding exceeds current practice for health impact assessment, potentially introducing further computational burden, the significance of natural variability should be assessed in the context of other significant and well-quantified sources of uncertainty, such as in CRFs.

Here, we employ a large multidecadal, multiple initial condition ensemble to assess the effect of natural variability and uncertain human health responses on U.S. mortality, morbidity, and economic impacts of future climate and two global climate policies. We use constant pollutant emissions to isolate the effect of climate change on $PM_{2.5}$ and ozone. We employ self-consistent, coupled models of the economy, climate, air quality, and human health at midcentury and end-of-century. Our scenarios include a reference case (REF) and two policies—Policy 4.5 (P4.5) and Policy 3.7 (P3.7)—designed to stabilize global temperature rise at 2.5 and 2.0 °C from preindustrial, respectively, by 2100.[59] We apply 30-year averages across five climate model initializations, a total of 150 annual simulations per policy and target year, to filter out natural variability and estimate the future health burden of air pollution due to climate change. We quantify the influence of natural variability and health-related uncertainty on climate cobenefits and policy selection. We compare their relative influence versus policy cost. Finally, we assess the effect of the common practice of using five-year averages to address natural variability.

■ MATERIALS AND METHODS

Integrated Modeling Approach. We examined two global climate policies described elsewhere[59] using an internally consistent modeling framework, developed in Garcia-Menendez et al.,[18] depicted in Table 1. It employs the MIT Integrated Global System Model (IGSM),[60,61] an integrated assessment model that couples the MIT Economic Projection & Policy Analysis (EPPA)[62,63] model of the world economy to the MIT Earth System Model (MESM)[64] of intermediate complexity. EPPA is a multiregion multisector computable general equilibrium model that projects economic activity and associated emissions of greenhouse gases, aerosols, and other climate-relevant species under policy constraints by determining prices that balance supply and demand across five-year periods, 25 sectors and 16 world regions.[62,63] We use the MIT IGSM-CAM framework,[65] which links the IGSM to the National Center for Atmospheric Research (NCAR) Community Atmosphere Model (CAM) to provide three-dimensional climate variables used to simulate global atmospheric chemistry with the Community Atmosphere Model with Chemistry (CAM-Chem)[66] at a 1.9° × 2.5° horizontal resolution, an approach balancing accuracy and computational efficiency needed for uncertainty analysis.

CAM-Chem predictions of ground-level ozone and $PM_{2.5}$ concentrations have been evaluated.[66−68] Emissions are based on the Precursors of Ozone and their Effects in the Troposphere (POET) inventory.[66] Health and economic impacts of ozone and $PM_{2.5}$ are estimated with the environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP-CE v1.0814).[69,70] MIT IGSM-CAM-Chem-BenMAP framework is used here to estimate global policy costs, U.S. health outcomes, and economic impacts across three scenarios.

Health Outcomes and Valuation of Climate-Induced Air Quality Impacts. We used CRFs included in Supporting Information (SI) Table S1. The selection and pooling of CRFS and valuations followed regulatory analyses by the U.S. Environmental Protection Agency (EPA),[71,72] to estimate health outcomes as

$$\Delta\text{outcomes} = y_0 \times \text{pop} \times (1 - \exp(-\beta \times \Delta x))$$

Where y_0 is the baseline cause-specific incidence rate, pop is population size, β is the risk coefficient for the health end point of interest, and Δx is the change in pollutant concentration between two scenarios. We applied no lower concentration threshold. While some CRFs had different functional forms, all depended on the change between two scenarios in daily mean $PM_{2.5}$ or May-through-September daily maximum 8 h average ozone. We used two CRFs for $PM_{2.5}$ (Krewski et al.[41] and Lepeule et al.[42]) and ozone (Zanobetti and Schwartz[73] and Smith et al.[74]) to estimate all-cause mortality. Morbidity end points included nonfatal myocardial infarction, hospital admissions, and other symptoms (Table 1). Incidences were valued per SI Table S1.

Reference and Policy Scenarios. Three scenarios of economic activity, greenhouse gas emissions and climate change were developed for U.S. EPA's Climate Change Impacts and Risk Analysis (CIRA) project,[75] and used to assess impacts across U.S. sectors,[76] presented elsewhere[18,59,77] and the SI. REF has unconstrained emissions, CO_2 reaching 830 ppm, and global mean surface temperature increasing by 6 °C in 2100. Policies implement a global tax on carbon emissions to stabilize total radiative forcing at 4.5 W/m^2 (for P4.5) or 3.7 W/m^2 (for P3.7) by 2100.[77] They avoid 8 and 9 billion tons of U.S. CO_2 emissions in 2100 under P4.5 and P3.7, respectively, and limit CO_2 levels to 500 ppm (P4.5) and 460 ppm (P3.7) and temperature rise to 2.5 °C (P4.5) and 2.0 °C (P3.7) from preindustrial.

To assess the public health burden, we isolate climate-induced changes in ozone and $PM_{2.5}$ at the middle and end of the 21st century relative to their start-of-century levels (details in Garcia-Menendez et al.[18]). We consider only climate cobenefits, and not coemissions cobenefits. To do this, we isolate climate-induced effects with constant year 2000 anthropogenic pollutant emissions, and constant natural emissions. The response of biogenic emissions to temperature is simulated, but other effects of climate change on natural sources, including dust and wildfires, are not modeled. $PM_{2.5}$ changes include sulfate, black carbon, organic aerosol, and ammonium nitrate particles.[18,78] Under REF, U.S. population-weighted annual 8-h-max ozone increases by 0.8 ± 0.3 and +3.2 ± 0.3 ppbv and population-weighted annual $PM_{2.5}$ increases by 0.5 ± 0.1 μg/m^3 and 1.5 ± 0.1 μg/m^3 in 2050 and 2100, respectively (see SI). Drivers of ozone change include greater stagnation, enhanced photochemical formation, and higher emissions of biogenic precursors. Climate-induced effects on $PM_{2.5}$ vary by component, with meteorological variations affecting oxidation, gas-particle partitioning, and atmospheric ventilation. Policies reduce penalties by over 80% for ozone and 70% for $PM_{2.5}$ in 2100.

Start-of-century population, demographics, and baseline incidence rates were derived from BenMAP-CE. Future

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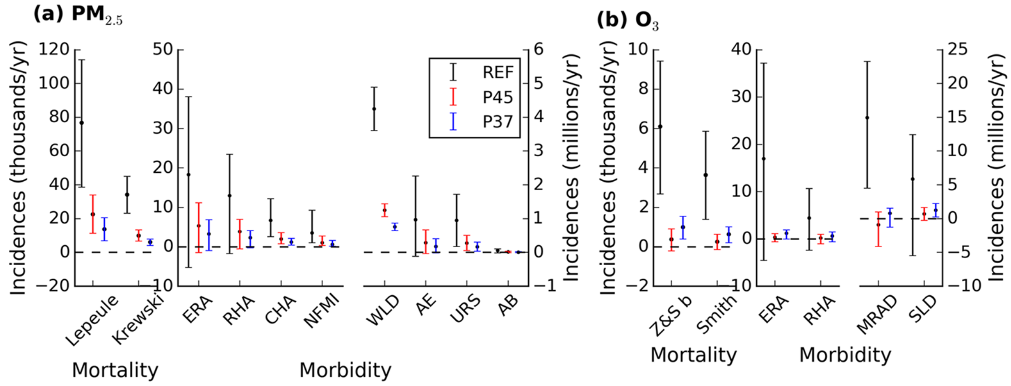

Figure 1. Change in U.S. premature mortality and morbidity at end-of-century relative to start-of-century related to (a) $PM_{2.5}$ and (b) ozone under the REF, P4.5, and P3.7. The ranges are 95th confidence intervals due to health-related uncertainty, after natural variability is filtered out using ensemble-mean concentrations. Lepeule = estimated with Lepeule et al.[42] Krewski = estimated with Krewski et al.[41] Z &S = mortality estimated with Zanobetti and Schwartz.[73] Smith = mortality estimated with Smith et al.[74] ERA = Emergency Room visits for asthma; RHA = respiratory hospital admissions; CHA = cardiovascular hospital admissions; NFMI = nonfatal myocardial infarction. WLD = work loss days; AE = Asthma exacerbation; URS = upper respiratory symptoms; AB = Acute bronchitis; MRAD = minor restricted activity days; SLD = school-loss days.

Table 2. Future Health Impacts Avoided by Policy in 2050 and 2100

	health outcomes avoided annually (95% confidence interval)			
	P4.5		P3.7	
end point group	2050	2100	2050	2100
Adult Mortality				
Lepeule et al. (2012)	11 000[a] (5000, 17 000)	59 000[a] (29 000, 89 000)	13 000[a] (5800, 20 000)	68 000[a] (33 000, 100 000)
Krewski et al. (2009)	5200[a] (3200, 7300)	29 000[a] (18 000, 39 000)	6200[a] (3800, 8500)	32 000[a] (21 000, 44 000)
work loss days	570 000[a] (480 000, 660 000)	3 000 000[a] (2 600 000, 3 500 000)	680 000[a] (570 000, 800 000)	3 500 000[a] (3 000 000 4 000 000)
cardiovascular hospital admissions	860[a] (270, 1600)	4700[a] (1800, 8700)	1000[a] (320, 2000)	5500[a] (2100, 10 000)
upper respiratory systems	130 000[a] (15 000, 240 000)	680 000[a] (120 000, 1 200 000)	150 000[a] (15 000, 290 000)	790 000[a] (140 000, 1 400 000)
acute myocardial infarction, nonfatal	470[a] (130, 1300)	2500[a] (910, 6700)	570[a] (150, 1600)	3000[a] (1100, 7800)
minor restricted-activity days	2 500 000[a] (550 000, 4 400 000)	17 000 000[a] (5 800 000, 28 000 000)	2 400 000[a] (470 000, 4 300 000)	16 000 000[a] (4 600 000, 26 000 000)
school-loss days	890 000 (−22 000, 2 500 000)	6 400 000[a] (1 200 000, 17 000 000)	860 000 (−52 000, 2 400 000)	5 700 000[a] (560 000, 15 000 000)

[a]Significant at $p < 0.05$. (School-loss days in 2050 are significant at $p < 0.07$) Annual avoided premature mortality and morbidity in 2050 and 2100 under P4.5 and P3.7 relative to REF due to reducing the climate penalty on ozone and $PM_{2.5}$. The ranges are 95th confidence intervals due to health-related uncertainty, after natural variability is filtered out by using ensemble-mean concentrations. Mortality estimates include those related to ozone as estimated by taking the median of Zanobetti and Schwartz[73] and Smith et al.[74]

population was projected (growing 50% by 2050 and 75% by 2100 relative to 2005).[59] Baseline mortality incidence rates were projected as in Garcia-Menendez et al.,[18] based on cardiopulmonary mortality for $PM_{2.5}$ (12% increase in 2050, −8% in 2100, relative to 2008) and respiratory mortality for ozone (24% in 2050, 64% in 2100). Migration and demographic shifts were not modeled. Valuations were projected using GDP per capita growth (80−100% by 2050 and 240−250% by 2100, relative to 2005). We applied a 0.4 income elasticity (central estimate in BenMAP-CE[79]), assuming most benefits are due to reduced mortality risk.

Isolating Uncertainty from Natural Variability and Health Responses. We characterized interannual variability with 30 year simulations covering start-of-century (1981−2010), midcentury (2036−2065), and end-of-century (2085−2115). We captured multidecadal variability by modeling each 30 year period with five perturbations of conditions in the MIT IGSM-CAM.[65] To simulate average conditions in 2050 and 2100, we detrended concentrations within each future 30-year period using least-squares linear regression at each grid cell. We applied GDP, baseline mortality incidence, and population values in the year 2050 or 2100.

To filter out natural variability, we calculated ensemble mean concentrations yielding 150 year averages for each scenario and pollutant as input to BenMAP. To quantify the effect of annual natural variability on climate cobenefits, we compared each annual simulation under policy to REF. In total, we simulated health impacts for 1200 years (two pollutants, two policies, two 30 year periods, and five initializations). To assess common practice, we averaged five years of impacts to partially filter out natural variability, which we do around each year within the respective 30 year periods (details in SI).

Health and economic uncertainty is the 95% confidence interval (95CI) obtained from 5000 Monte Carlo simulations of pooled CRFs and economic impacts. The choice of the CRF is assessed using two CRFs for $PM_{2.5}$-related mortality. We likely underestimate this uncertainty because other CRFs are unchanged, other sources of uncertainty are not quantified (e.g., valuation methods,[18] shape of CRF,[80] and there remains significant epistemic uncertainty (see SI).

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RESULTS AND DISCUSSION

Future Health Burden of Climate Change and Health Benefits of Reducing Climate Penalty. Compared to start of the century, climate change increases U.S. air pollution-related risks, yielding annual premature deaths (95CI: 40 000–120 000 using Lepeule et al.[42]), nonfatal heart attacks (940–9400), and lost work days (3.6–4.9 M) in 2100 (Figure 1 and SI Table S2). Figure 1 compares future conditions to start-of-century, including climate change and projected population. Natural variability was filtered out using the 30 year average of annual atmospheric chemistry simulations across the five model initializations (i.e., 150 years averaged) for each scenario. The effect of climate change is not always significant at 95CI for each health end point (details in SI). Global policies consistent with 2 and 2.5 °C warming targets reduce these risks across all end points in Figure 1 by 40–60% in 2050 and 70–88% in 2100.

Policies avoid thousands of annual premature deaths and illnesses in the U.S. Table 2 compares policies to the reference case in 2050 and 2100, respectively, for the same future populations. By midcentury, P4.5 prevents 11 000 (5000–17 000) premature deaths (using Lepeule et al.[42]), 470 (130–1300) nonfatal heart attacks, and 570 000 (480 000–660 000) lost work days annually. The more ambitious P3.7 reduces these risks by an additional 15% at midcentury for $PM_{2.5}$-related end points. By end-of-century, 59 000 (29 000–89 000) premature deaths are avoided annually (using Lepeule et al.[42]), also 2500 (910–6700) heart attacks and 3 million (2.6–3.5 million) lost workdays under P4.5. P3.7 avoids an additional 40% of $PM_{2.5}$-related outcomes.

Controlling natural variability yields consistent estimates of relative and absolute values of policies. Mean climate cobenefits of both policies are positive, offsetting a fraction of costs increasing from 2 to 6% in 2050 to 6–16% in 2100. The more stringent P3.7 has higher costs and higher mean cobenefits.[18] Annually, it yields $10 billion more than P4.5 in 2050 and $30 billion more in 2100 using Krewski et al.[41] (or, using Lepeule et al.:[42] $30 billion more in 2050; $100 billion more in 2100).

Uncertainty in Climate Cobenefits from Improved Air Quality under Two Global Policies. When natural variability is not filtered out, it obscures relative and absolute climate cobenefits. Figure 2 depicts a multitrillion dollar range of climate cobenefits in the U.S. under two global policies and constant pollutant emissions. The spread represents uncertainty due to natural variability, health impacts, and valuation. Some individual estimates (e.g., negative estimates) do not reflect true policy impacts. Climate cobenefits in Figure 2 span from −4 to 3.5 trillion USD per year around 2050, to −6 to 13 trillion USD annually around 2100. Policies cost $9–11 trillion annually in 2100[59] (all USD in year 2000 currency). Thus, when climate cobenefits are obscured by these two factors, they can seem comparable to policy costs, appearing to offset over 100% of annual climate policy costs in some simulations at the end of the century (further details in SI).

Natural variability and uncertain health responses have comparable effects on climate cobenefits, especially at midcentury. Figure 3 shows the fraction of U.S. annual climate policy costs offset by climate cobenefits in 2050 and 2100. Health and economic uncertainty is estimated by pooling multiple health and economic studies for various health outcomes (SI Table S1). For those estimates, natural variability

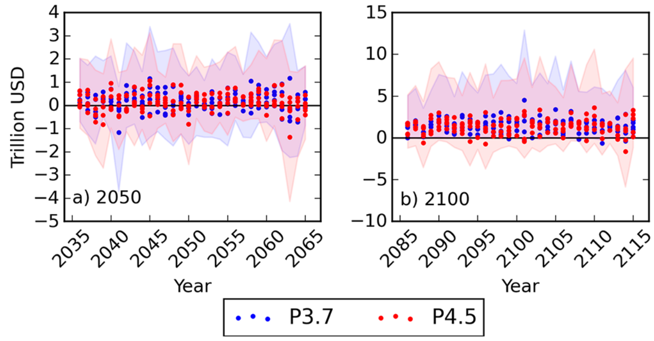

Figure 2. Annual health cobenefits from reducing the climate penalty on U.S. air quality by policies P4.5 (red) and P3.7 (blue) for a 30 year period around (a) 2050 (b) 2100. The shaded regions indicate the 95th confidence intervals given uncertainty in health impacts and economic benefits, while the dots represent the mean cobenefits for each annual simulation. There are five initializations per policy per year. The variation between dots of the same color represents the effect of natural variability. Cobenefits include reduced mortality and morbidity for $PM_{2.5}$ and ozone. Adult mortality from $PM_{2.5}$ estimated using Lepeule et al.[42] (results using Krewski et al.[41] in SI). Currency is year 2000 USD.

is filtered out using ensemble mean (across 150 years) pollutant concentrations in 2050 and 2100. Uncertainty due to CRF selection is represented using CRFs for $PM_{2.5}$–related mortality in Krewski et al.[41] and Lepeule et al.[42] Uncertainty due to natural variability is represented by the variation in mean health and economic estimates across 150 years. Remaining uncertainty across five initializations is shown after applying the common practice of using five-year averages health and economic impacts (details in SI).

In estimating climate cobenefits at midcentury, natural variability has a larger impact than health-related uncertainty. Compared to the 95CIs associated with health and economic uncertainty, those representing natural variability are three to four times larger (Figure 3(a)). Using Lepeule et al.[42] instead of Krewski et al.[41] increases the size of the 95CI, but this type of health-related uncertainty is still less than the effect of natural variability. Averaging five years' of simulations to estimate cobenefits reduces this uncertainty, but it remains commensurate with health-related uncertainty. The resulting 95CI is 1.1–1.6 times that of health and economic uncertainty for a given CRF, and 0.8 times the spread across CRFs. The 95CI is −$54 to 80/$tCO_2e$ due to natural variability alone (using Krewski et al.[41]), −$15 to 43/$tCO_2e$ due to natural variability after applying five-year averaging (using Krewski et al.[41]), and −$1 to 75/$tCO_2e$ due to health-related uncertainty (across health and economic uncertainty and two CRFs).

By end-of-century, CRF selection carries greater weight than natural variability (Figure 3(b)). As the climate responds to greenhouse gas mitigation measures, the signal of policy becomes stronger compared to the noise of natural variability, and health-related uncertainty begins to dominate. Using a different CRF (Lepeule et al.[42] instead of Krewski et al.[41]) doubles the mean and more than doubles the size of the 95CI for policy cost offset. Conversely, natural variability remains equal in its 95CI to that of health and economic uncertainty. Averaging improves this, with five year averages shrinking uncertainty due to natural variability to about one-third (33–36%) of health and economic uncertainty.

Spurious negative impacts appear in our ensemble. This occurs primarily when an annual simulation of the climate

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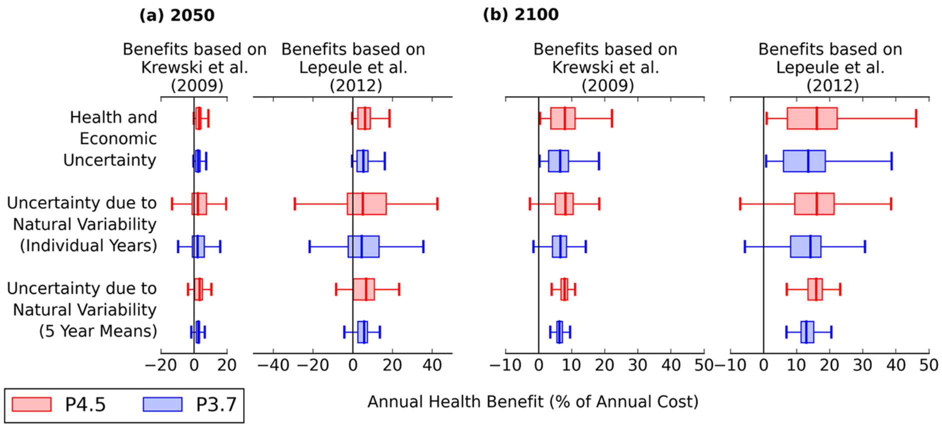

Figure 3. Effect of uncertainties on percent of policy costs offset by reducing health risks from climate penalty in (a) 2050 and (b) 2100. Range depicts 95th confidence interval. In "Health and Economic Uncertainty", natural variability is removed with the entire relevant ensemble (five initializations over 30 years). "Natural Variability" shows the variability across the ensemble (five initializations over 30 years). Reflecting typical practice, five year averages are then used to partially filter out natural variability. Benefits include reduced mortality and morbidity for $PM_{2.5}$ and ozone. Adult mortality from $PM_{2.5}$ estimated using either Lepeule et al.[42] or Krewski et al.[41]

under a policy leads to higher pollutant formation than the reference, that is, "noise" from natural variability overwhelms policy benefits.[13] At midcentury, in Figure 3(a), a small (<5%) portion of annual costs offset by cobenefits is negative due to health and economic uncertainty. Contamination by natural variability yields negative impacts in about one-third of annual midcentury simulations (Figure 3(a)), but in less than 10% of end-of-century simulations (Figure 3(b)). Some initializations yield negative impacts unless a minimum of 10−17 years of simulation are averaged at midcentury (see SI). Thus, five-year averages are insufficient to remove negative impacts from natural variability at midcentury, but they do reduce them to less than 10% of simulations. By end-of-century, conversely, an average of only two to three years are needed. These spurious negative results suggest caution in using only a few years of simulation to estimate climate cobenefits.

Simulations incorrectly yield higher cobenefits for the less stringent policy (P4.5) in nearly half of the midcentury simulations (47% using either Krewski et al.[41]or Lepeule et al.[42]). By end-of-century, this fraction drops slightly (41% of simulations using Krewski et al.[41] and 37% for Lepeule et al.[42]). For P4.5, natural variability introduced a standard deviation of $175 billion in 2050 and $370 billion in 2100 using Krewski et al.,[41] and $390 billion in 2050 and $900 billion in 2100 using Lepeule et al.[42] After removing natural variability, the mean difference in cobenefits between policies is $10−$30 billion in 2050, which is small compared to these standard deviations. Coefficients of variation due to natural variability alone are over 200% in 2050, and around 50% in 2100 across policies and CRFs. Thus, natural variability significantly obscures the difference between these two stringent policies' climate cobenefits, especially at midcentury.

Implications for Health Burden of Air Pollution. These findings are relevant to policy-makers concerned with the effects of climate change on illness prevention, treatment, and costs. Climate change implies a 2% (0.6−3%) increase in mortality (across Krewski et al.[41] and Lepeule et al.[42]) and 0.1−3.5% increase in mean morbidity risks from 2000 by 2100 (details in SI). This is an increase of 20% (10−30%) in the public health burden from air pollution, based on an attributable risk of 5% of all deaths in 2010[81] from PM_2 (using Krewski et al.[41]). This represents nearly half the gains from air quality improvements from 1990 to 2010.[82] The mean estimated burden increase would be 3−5% under global policies consistent with a 2 to 2.5 °C target (risk reduction of 70−88% compared to reference).

Our 2050 U.S. ozone-related premature mortality due to climate change agrees with previous estimates. We use CRFs from Zanobetti and Schwartz[73] (1200 (360−1900) and Smith et al.[74] (730 (180−1300)). These agree with 1200 (−820 to 3200) under RCP8.5 in Alexeeff et al.,[45] which also held anthropogenic pollutant emissions constant, but, unlike this study, held population and baseline mortality rates constant. Our estimates agree within errors with Stowell et al.,[52] which used statistical downscaling to estimate 47 (±525) deaths under RCP8.5 and projected population and baseline mortality rates, and with Tagaris et al.,[27] which estimated 300 (100−500) deaths from ozone with constant pollutant emissions and population under A1B. Finally, they agree within errors with others who cite combined effects of climate change and pollutant emission reductions under RCP8.5.[83,28,51] In 2100, we estimate 6100 (2700−9400) deaths with Zanobetti and Schwartz[73] and 3700 (1400−5900) with Smith et al.[74] These are contained within the multimodel spread of −1820 to 27 012 deaths in the U.S. in Silva et al.[24] under RCP8.5 with projected population and baseline mortality rates.

Fewer studies estimate U.S. health effects of $PM_{2.5}$ under climate change. Our estimates are generally higher due to different methodologies and aims. We use two CRFs, Lepeule et al.[42] (25 000 (12 000−38 000) in 2050; 77 000 (38 000−120 000) in 2100) and Krewski et al.[41] (11 000 (7300−15 000) in 2050; 34 000 (23 000−45 000) in 2100). Two previous estimates[24,51] of U.S. $PM_{2.5}$-related mortality include pollutant emissions reductions under RCP8.5, so their combined effect on mortality is lower than our effect of climate change alone. One study that reports values for the entire U.S. and also keeps pollutant emissions constant is Tagaris et al.,[27] estimating climate-induced premature deaths (3700 using Pope et al.,[84] a predecessor to Krewski et al.[41]) and morbidity in 2050 under A1B with constant population and baseline mortality rates. Our mortality estimates are nearly 200% higher, which is reduced to less than 15% after adjusting for differences in population, baseline mortality rates, and

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CRFs, despite remaining differences in socioeconomic scenarios, models, and resulting concentrations.

In contrast to previous estimates of the public health burden, this work uses a multidecadal, multiple initial condition perturbation ensemble to filter out natural variability. We also quantify the uncertainty it introduces in health impacts. Others have explored significant uncertainties, including modeling choice. Post et al.[28] cites differences of 3000 ozone-related deaths in 2050 between seven climate change−air quality modeling systems, five population projections, and 3 CRFs. In our work, natural variability alone lead to ozone-related deaths in 2050 that differ by 20 000 deaths using Zanobetti and Schwartz.[73] In 2100, Silva et al.[24] cites differences of 28 000 $PM_{2.5}$-related premature deaths across nine models. Our 95CI across health-related uncertainty in 2100 is 16 000−95 000, or a range of 79 000 $PM_{2.5}$-related deaths. Our 95CI due to natural variability alone is −8700 to 57 000 (using Krewski et al.[41]), or a difference of 65 700 deaths. While we cannot infer the importance of natural variability with this comparison, we recommend it be considered in health impact assessment of the climate penalty at midcentury, noting that health-related uncertainty potentially dominates by end-of-century.

Implications for Climate and Air Quality Policy Analysis. Natural variability leads to a wide spread in annual impacts that, when not addressed, may obscure potential future health risks and climate cobenefits. The combined effect of natural variability and health and economic uncertainty yields maximum economic impacts spuriously exceeding 100% of climate policy costs in 2100. On a marginal basis, we find a 95CI of -\$1 to \$85/tCO2e (year 2005 USD) of climate cobenefits in 2050 across two policies and two CRFs when natural variability is filtered out. When it is not, it induces a 95CI of −\$61 to 90/tCO_2e due to interannual variability alone, which is almost twice that of the health-related 95CI. It introduces negative impacts in one-third of simulations, which do not reflect the ensemble mean or the true impact of the policy. While the common practice of five-year averaging narrows the 95CI to an estimated −\$17 to 49/tCO_2e due to natural variability, it remains nearly as large as the health-related 95CI. Neglecting this source of uncertainty may produce inconsistent estimates of the absolute or relative value of climate cobenefits, thereby ignoring potential gains, facing unforeseen harms, or encouraging a less valuable policy.

Following Garcia-Menendez et al.,[18] this is the second study to cite a range of U.S. climate cobenefits, and the first to do so across multiple health end points and epidemiologic studies. Our mean estimates of marginal cobenefits are \$28 and \$144/tCO_2e (in 2005 US\$) for P4.5 using Lepeule et al.[42] in 2050 and 2100, respectively, slightly higher than Garcia-Mendez et al.[18] due to the inclusion of morbidity. Other studies that include climate cobenefits do not isolate them. Zhang et al.[15] estimates climate cobenefits to be <4% of total air quality cobenefits of \$137/tCO_2 (\$87−187/tCO_2) under RCP4.5 in 2050. After filtering out natural variability, we estimate climate cobenefits of \$20 (-\$1 to \$85/tCO2e) under P4.5 in 2050. Our lower mean is in line with Zhang et al.[15]'s finding that climate cobenefits are a small fraction of total cobenefits, though study differences preclude direct comparisons between our work and others, such as Zhang et al.[15] and West et al.[8]

Our health impacts under climate policy are in line with previous literature, given differing study aims and methods. West et al.[8] estimates higher mortality by including coemissions, and Fann et al.[23] has lower estimates due to its earlier year (2030) and less stringent policy (RCP6.0). Zhang et al.[15] builds on West et al.[8] but isolates health estimates for climate change, specifically, 300 (200−400) $PM_{2.5}$−related and 500 (200−700) ozone-related annual deaths avoided in 2050 in the U.S. under RCP4.5. Our results for ozone-related mortality using Smith et al.[56] are similar (500 (200−800) deaths avoided in 2050) after filtering out natural variability. Our estimates for $PM_{2.5}$ are higher, for example, 4600 (1600−11 000) using Krewski et al.[41] This follows from our differing climate effects of P4.5 for each pollutant, which are similar for ozone but higher for $PM_{2.5}$ (see SI). Significant discrepancies persist among $PM_{2.5}$ projections,[14,85] and our mortality differences are smaller than intermodel differences examined elsewhere.[24,28] Finally, accounting for differences in CRFs, our mortality estimates are in line with those in 2055 for a 50% CO_2 cap vs 2005 (our equivalent reduction in CO_2 emissions is 60%) which includes coemissions under both regulated and unregulated scenarios.[22]

Implications for Modeling Climate Impacts. These results, combined with literature including coemissions, suggest that more robust simulations are needed to yield consistent estimates of the absolute and relative values of policies. Commonly, simulations used to model the climate penalty on air pollution are not sufficient to address the potential contamination of health impacts by natural variability.[13,14] Here, we find the effect of natural variability on projected climate cobenefits is larger than the uncertainty for health and economic impacts at midcentury. Climate cobenefits are likely smaller than coemissions cobenefits, based on studies that estimate both (e.g., Zhang et al.[15]); however, their variability can lead to estimates of equal or greater magnitude at midcentury when too few years are simulated. This variation spuriously yielded damages instead of benefits in one-third of our midcentury simulations for global policies consistent with 2 and 2.5 °C warming from preindustrial. Averaging one to two decades of simulations was needed at midcentury to eliminate apparent negative impacts. By end-of-century, only two years were needed, consistent with current practice. However, additional averaging is required to obtain robust estimates of cobenefits, beyond the correct sign. By end-of-century, health-related uncertainty (specifically, selection of CRFs between Krewski et al.[41] and Lepeule et al.[42]) dominates the effect of natural variability on climate cobenefits, suggesting diminishing returns of additional simulation years for risk and benefits analysis of 2100. While the precise number of simulation years required for a given degree of accuracy will depend on the timing and strength of the policy in question, these results motivate the need for large ensembles to filter out this source of uncertainty, including for policies and timings in line the Paris Agreement on climate change.

Encouraging consistency across studies of health cobenefits could increase policy traction by allowing comparisons and general conclusions to be drawn.[17] This work shows that comparability could be increased by reporting results for mutltidecadal simulations or ensemble simulations with perturbed initial conditions, especially for near-term policy years like 2030 and 2050. It also reinforces the importance of consistent health impact estimation, as the choice of health study remained the dominant uncertainty by end-of-century. Finally, it highlights the importance of capturing the effects of a changing climate on air quality for cobenefits analysis, which is included in many studies (e.g., refs 8, 15, 19, 20, and 22) but

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not those with constant meteorology (e.g., refs 9, 10, and 86) or with reduced-form relationships between emissions and air quality (e.g., ref 87).

This study focuses on the effect of natural variability and uncertainty due to health and economic valuation; the former can be partly addressed through extended simulations (to the extent that models can capture natural variability), while the latter requires further research. Preliminary comparisons to other estimates of the health burden and policy cobenefits suggest that the combined effect of these factors is significant compared to some of the factors considered elsewhere, including population projections and modeling systems. These U.S. findings may not apply everywhere. Others have shown geographic variation in aspects of uncertainty in climate cobenefits, including the magnitude of natural variability[53] and health-related uncertainty.[80] Other important uncertainties, including emissions scenarios (as estimated by different models),[27] model resolution,[30−33] demographics,[29] incidence rates,[8,24] and different specifications of health response relationships (including, e.g., thresholds and shape of the response)[24] have been explored elsewhere. Many important additional uncertainties have not been considered in this analysis, including uncertainty in economic modeling,[9] and the application of valuations and CRFs to future populations with potentially different preferences, susceptibility, vulnerability, and confounding conditions (e.g., housing, healthcare, and pollutant mixtures).[25] Additional limitations of this framework are discussed in previous work.[13,18,65,77] Future work is needed on how to best estimate the health impacts of climate policy and inform decisions.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b05094.

Provides information on methods (integrated modeling framework, health and economic impacts, policy costs, and cobenefits), and additional results (concentrations, numerical cobenefits, negative impacts, public health burden, and overall ranges) (PDF)

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Author Contributions

R.K.S., F.G.M., and E.M. formulated the study. E.M. developed IGSM simulations to drive CAM-Chem. F.G.M. simulated air pollutant concentrations with CAM-Chem. Y.M. performed initial health impacts modeling. R.K.S. performed additional health impacts modeling and developed the health, economic, and uncertainty analyses. All contributed to manuscript preparation, and all approved it.

Notes

The authors declare no competing financial interest.

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