

HEALTH AND CLIMATE POLICY IMPACTS ON SULFUR EMISSION CONTROL

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[1] Sulfate aerosol from burning fossil fuels not only has strong cooling effects on the Earth's climate but also imposes substantial costs on human health. To assess the impact of addressing air pollution on climate policy, we incorporate both the climate and health effects of sulfate aerosol into an integrated-assessment model of fossil fuel emission control. Our simulations show that a policy that adjusts fossil fuel and sulfur emissions to address both warming and health simultaneously will support more

stringent fossil fuel and sulfur controls. The combination of both climate and health objectives leads to an acceleration of global warming in the 21st century as a result of the short-term climate response to the decreased cooling from the immediate removal of short-lived sulfate aerosol. In the long term (more than 100 years), reducing sulfate aerosol emissions requires that we decrease fossil fuel combustion in general, thereby removing some of the committed carbon emissions and leading to a reduction in global warming.

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1. INTRODUCTION

[2] Sulfate aerosol has strong cooling effects on the Earth's climate, which partially cancel out the warming caused by CO₂ and other greenhouse gases [*Ramaswamy et al.*, 2001]. *Wigley* [1991] explored the impact on temperature of a simultaneous cut in CO₂ and sulfur emissions, as might result from curbing fossil fuel use. That study showed that because the atmospheric residence times of sulfate aerosol and CO₂ were very different, a cut in fossil fuel emissions (and hence both CO₂ and sulfur emissions) by 2% per year starting in 1990 would give rise to a net warming effect for a few years (through approximately 2012). Beyond that point the net cooling effect would dominate. Sulfate aerosol is a major urban and regional air pollutant that has detrimental effects on human health [*Hall et al.*, 1992]. *Wigley* [1991] noted that separate controls targeting sulfate aerosol would prolong the period of net warming.

[3] The fossil fuel emission path considered by *Wigley* [1991] was representative of fairly stringent climate control, but it was not derived from a systematic policy analysis. As a commonly used cost-benefit analysis tool for studying policy options to deal with anthropogenic influence on the climate, the dynamic integrated climate-economy (DICE)

model [*Nordhaus*, 1992] incorporates the forcing effects of a fixed path of projected changes in sulfate (and other) aerosols. However, it does not incorporate the inherent linkage between CO₂ and sulfur emissions as both are mainly from fossil fuel burning, and thus it is not suitable for studying the potential feedbacks between CO₂ and sulfur control policies. Nor does it address the implications for climate of direct sulfur controls to deal with health concerns.

[4] To address this subject in the present paper, we extend the DICE model structure (as updated by *Nordhaus and Boyer* [2000]) by adding to the control on fossil fuel emissions a new control on the sulfur content of those emissions. We also modified the climate module of the DICE model to incorporate the cooling effect of sulfate aerosol explicitly. In the original DICE and our modified version, policy is derived from optimizing the weighted total of the "utility" (a measure of happiness or satisfaction) gained from per capita consumption of goods or services over a time horizon. Because the same amount of utility for a person currently alive is valued higher than that for a person in the future, utilities are discounted on the basis of historical economic behavior to render them comparable. The annual discount rate starts at 3% in 1995 and gradually decreases to 2.3% in 2100 [*Nordhaus and Boyer*, 2000]. Economic growth is subject to constraints such as model-predicted health effects of sulfate aerosol in the atmosphere, climate effects of sulfate aerosol and CO₂, and control costs

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of both in the modified DICE model. By solving the optimization problem, the total utility is maximized through adjusting the “control variables” (i.e., rates of reinvestment, fossil fuel, and sulfur controls), and the resulting values of these variables are customarily described as “optimal” in the literature. In this study, we simulated the “optimal paths” of fossil fuel and separated sulfur controls for different policy scenarios and compared the short- and long-term climate effects.

2. MODEL DESCRIPTION

[5] The framework for both the economic optimization and the simplified climate box model was provided by DICE-99, a version of the model close to that presented by Nordhaus [1992]. That model, which is focused on the accumulation of CO₂ in the atmosphere, includes a carbon cycle to predict the atmospheric concentration of CO₂ that results from the fossil fuel use associated with economic activity, as modified by control policies. The global mean temperature is determined via a climate model driven by the sum of radiative forcing exerted by heightened CO₂ concentration and a prescribed trajectory of forcing by other greenhouse gases and sulfate aerosol. The latter is parameterized to track the *Intergovernmental Panel on Climate Change (IPCC) [2000] Special Report on Emission Scenarios (SRES) B2* scenario of economic and social development.

[6] We modify DICE-99 to treat sulfur emissions as an adjustable variable that is determined both by the level of fossil fuel use and by dedicated sulfur emission control. In addition to fossil fuel control costs and climate damage (economic loss incurred because of adverse climate impact) already considered by DICE-99, sulfur control costs and human health damage (economic losses associated with sickness or death) are also taken into account.

2.1. Output Determination

[7] Net output (goods and services from the world’s economy available for consumption or investment at time t , $Q(t)$, is gross output, $Q_G(t)$, less climate damage, $D_C(t)$, fossil fuel control costs, $A_F(t)$, health damage, $D_H(t)$, and sulfur control costs, $A_S(t)$,

$$Q(t) = Q_G(t) - D_C(t) - A_F(t) - D_H(t) - A_S(t).$$

Gross output depends on the production function in technology, $A(t)$, as well as the inputs of labor, $L(t)$, and capital, $K(t)$:

$$Q_G(t) = A(t)K(t)^\gamma L(t)^{1-\gamma},$$

where the capital elasticity (a measure of how easily capital is replaced by labor), γ , is 0.3 [Nordhaus and Boyer, 2000]. Net output can be divided between consumption, $C(t)$, and investment, $I(t)$:

$$Q(t) = C(t) + I(t).$$

The investment at time t , $I(t)$, which depreciates at an annual rate of 10%, provides the capital available at time $t + 1$, $K(t + 1)$. Driven over time by the cycle of production and investment, economic growth as modeled here has been calibrated using historical data [Nordhaus and Boyer, 2000].

2.2. Emissions

[8] In the DICE-99 model, emissions from burning fossil fuels are identified as carbon. We find it helpful to introduce a distinction between general emissions from fossil fuel, $E_F(t)$, and emissions of carbon, $E_C(t)$, and sulfur, $E_S(t)$. The three emissions levels are

$$\begin{aligned} E_F(t) &= \theta_F(t)[1 - \mu_F(t)]Q_G(t), \\ E_C(t) &= \theta_C(t)E_F(t), \\ E_S(t) &= [1 - \mu_S(t)]\theta_S(t)E_F(t), \end{aligned}$$

where μ_F is the fossil fuel control rate and μ_S is the sulfur control rate. Here $\theta_F(t)$, the fossil fuel intensity of output (tons fossil fuel per 1000 dollars), $\theta_C(t)$, the carbon intensity of fossil fuel emissions (tons C per ton fossil fuel), and $\theta_S(t)$, the sulfur intensity of fossil fuel emissions (tons S per ton fossil fuel), vary through time. In principle, all these coefficients are affected by the world’s energy structure and could be expected to change as prices of fuels and taxes on emissions vary. Nonetheless, they are assumed to follow prescribed trajectories in the simulations we consider. In particular, as in the original DICE specification, the carbon emissions intensity of production (tons C per 1000 dollars), denoted by $\sigma(t)$ and equal to the product $\theta_C(t)\theta_F(t)$ in our specification, declines monotonically through time following

$$\sigma(t) = \sigma(t - 1)/[1 + g(0)\exp(-\delta_1 t - \delta_2 t^2)],$$

where δ_1 and δ_2 are constant parameters. Carbon emissions are thus related to gross output by

$$E_C(t) = \sigma(t)[1 - \mu_F(t)]Q_G(t).$$

[9] Sulfur emissions are, in turn, related to the carbon emissions by

$$E_S(t) = [1 - \mu_S(t)][\theta_S(t)/\theta_C(t)]E_C(t),$$

where the sulfur-to-carbon ratio of fuel usage $\theta_S(t)/\theta_C(t)$ is parameterized to follow the projected energy structure of the SRES B2 scenario. Because of the increased use of natural gas and low-sulfur coal (fuel switching) the projected sulfur-to-carbon ratio declines from 0.011 in 1990 to 0.008 in 2070 and thereafter increases again to 0.012 in 2100. The use of alternative energy sources such as renewable energy

as well as carbon sequestration technology produces neither CO₂ nor sulfate aerosol, so their use as a control strategy does not affect this ratio. In our model the annual anthropogenic emissions of carbon and sulfur for 1990 are initialized to 6.18 Gt C [Wigley, 1991] and 0.071 Gt S [Wigley and Raper, 1992].

2.3. Concentrations and Impacts

[10] The Earth's carbon cycle and climate dynamics are mimicked with a three-box model (namely, the atmosphere and upper and deep oceans) [Nordhaus and Boyer, 2000]. The carbon cycle is driven by time-dependent carbon emissions, which play an important role in determining the atmospheric carbon concentration, $M(t)$. As a result of the long lifetime of CO₂ in the atmosphere (~ 100 years), present-day carbon emissions have a far-reaching influence on the future carbon concentration [Nordhaus and Boyer, 2000]. The climate and health effects of sulfur emissions depend on the concentration of sulfate aerosol in the atmosphere. Because of its very short lifetime (a matter of days) compared to the time step of 10 years in DICE, we model the concentration of sulfate aerosol as directly proportional to sulfur emissions.

[11] Climate change is the result of the cumulative influence of the trajectory of radiative forcing, $F(t)$, measured in W m⁻², defined as the perturbation of net top of the atmosphere radiative flux from its preindustrial equilibrium level. DICE distinguishes two sources of forcing: the increase in the concentration of CO₂ in the atmosphere and "other." "Other forcing," $O(t)$, results from the changes in the concentration of greenhouse gases other than CO₂ and of sulfate aerosol. The time series of $O(t)$ is prescribed on the basis of the SRES B2 scenario, starting from -0.2 W m⁻² in 1990 and increasing monotonically to 1.2 W m⁻² by 2100 [Nordhaus and Boyer, 2000].

[12] We amend this picture by subtracting the forcing associated with sulfate aerosol as projected in the SRES B2 scenario from the prescribed other forcing trajectory $O(t)$ to yield "other except sulfate," $O_{ES}(t)$, and adding the forcing effect of sulfate aerosol concentration, which is proportional to sulfur emissions as an adjustable variable of the model. With this redefinition of "other forcing" the total forcing becomes

$$F(t) = 4.1 \frac{\ln\{[M(t) + 590]/590\}}{\ln 2} + O_{ES}(t) - 0.3 \frac{E_S(t)}{0.071} - 0.8 \frac{\ln\left(1 + \frac{E_S(t)}{0.042}\right)}{\ln\left(1 + \frac{0.071}{0.042}\right)}.$$

The radiative forcing of CO₂ is a function of the increase in atmospheric carbon concentration from its preindustrial level of 590 Gt C. The direct radiative forcing of sulfate aerosol is calculated as a linear function of sulfur emissions with initial 1990 forcing of -0.3 W m⁻² [Wigley, 1991]. A logarithmic function is used to simulate the indirect radiative forcing of sulfate aerosol initialized as -0.8 W m⁻² in 1990 [IPCC, 1997]. These values are within the

uncertainty ranges of direct forcing (-0.1 to -1 W m⁻²) and of indirect forcing (0 to -2 W m⁻²) [Ramaswamy et al., 2001]. Although the geographical distributions of sulfate aerosol and resulting climate effects concentrate over the source regions as a result of short lifetimes, the model is designed to treat the entire atmosphere as one grid box. Thus the model has made the simplifying assumption that all forcings are globally homogeneous and linearly additive in the model, which is appropriate only for small perturbations of a stable system.

2.4. Damages and Control Costs

[13] The health damage resulting from the increase in mortality caused by particulate matter (PM), of which sulfate aerosol is a significant component, is represented as

$$D_H(t) = r_M P(t) b_{DR} PM_{2.5}(t) VOSL(t),$$

where r_M is the average mortality rate (0.9%), $P(t)$ is the total population, $PM_{2.5}(t)$ is a measure of the concentration of PM (mass concentration of ambient suspended particles with diameter less than 2.5 μm), and $VOSL(t)$ is the average value of a statistical life (the monetary value of avoiding a mortality). To model the impact of the variation in the concentration of PM on the number of deaths in a year, we employ a dose-response function constant, b_{DR} , of 1.8% increase in mortality for every $1 \mu\text{g m}^{-3}$ increase in PM 2.5 concentration [Pearce and Crowards, 1996; E. H. Pechan & Associates, 1997]. Because its lifetime (days) is much shorter than the time step used in this model (10 years), PM is removed in a single time step. The concentration of PM is modeled as proportional to sulfur emissions [Pearce and Crowards, 1996] using a 1990 population-weighted concentration of $6.2 \mu\text{g m}^{-3}$ [E. H. Pechan & Associates, 1997]

$$PM_{2.5}(t) = \frac{E_S(t)}{E_S(0)} PM_{2.5}(0).$$

Note that the conversion from gas-phase sulfur to sulfate aerosol occurs mainly through oxidation within clouds. Therefore possible changes in cloud cover in future climate scenarios could affect the relationship between sulfur emissions and sulfate aerosol concentrations. However, this simplified model is not able to capture this subtlety. The burning of fossil fuels and biomass also gives rise to carbonaceous aerosols (i.e., black carbon and organic aerosol) that occupy a significant fraction of PM, especially over the areas dominated by biomass burning such as central Africa and South America. By scaling PM concentrations with sulfur emissions the model implicitly accounts for changes in PM originating from burning fossil fuels but not those from burning biomass.

[14] The value of a statistical life (VOSL) used in these calculations is based on how much, on average, a person would be willing to pay to avoid a mortality. Estimates of the 1990 VOSL for the United States range from \$1.2 million to \$10.7 million [World Bank Group, 1998]; \$4 million is often used [Ottinger et al., 1990]. To obtain a worldwide average VOSL, we adjust the U.S.

TABLE 1. Simulated Scenarios^a

Simulation	Simulation Description
IPCC	Assumes no fossil fuel control; sulfur control set to match the SRES B2 emission levels (so the radiative forcing of sulfate aerosol is as in DICE-99); investment optimized, taking into account climate damage and sulfur control costs. Health damage is subtracted from consumption.
DICE	Optimizes fossil fuel control to serve climate objective only (so optimization treats health damage as zero); sulfur control set to match the SRES B2 emission levels (so the radiative forcing of sulfate aerosol is as in DICE-99); investment optimized, taking into account climate damage and fossil fuel and sulfur control costs. Health damage is subtracted from consumption.
Health Only	Optimizes fossil fuel and sulfur controls to serve health objective only (so optimization treats climate damage as zero); investment optimized, taking into account health damage and sulfur and fossil fuel control costs. Climate damage is subtracted from consumption.
Climate and Health	Optimizes fossil fuel and sulfur controls to serve both health and climate objectives; investment optimized, taking into account climate and health damages and sulfur and fossil fuel control costs.

^aDefinitions are IPCC, Intergovernmental Panel on Climate Change; SRES, Special Report on Emission Scenarios; and DICE, dynamic integrated climate-economy model.

figures by the ratio of the world average per capita gross domestic product (GDP) to the per capita GDP in the United States [Markandya, 1994; El-Fadel and Massoud, 2000]. The calculated world average VOSL is \$0.62 million in 1990. The future VOSL is also adjusted by per capita GDP

$$\text{VOSL}(t) = \text{VOSL}(0) \frac{Q_G(t)}{P(t)} \frac{L(0)}{Q_G(0)}.$$

[15] As a measure of the approximate cost to world aggregate GDP of increased global mean temperatures and associated regional changes in ecosystems, microclimates, precipitation, etc., the climate damage is expressed as

$$D_C(t) = Q_G(t) / [1 - 0.0045T(t) + 0.0035T(t)^2],$$

where $T(t)$ is the deviation of the global average surface temperature from its preindustrial level [Nordhaus and Boyer, 2000]. Note that DICE-99 includes an assumption that modest warming is beneficial for the world economy and thus increases net output.

[16] While part of “climate damage” is a result of climate impacts on health associated with the spread of disease and other weather-related health problems, here we use the term “health damage” to denote the chronic and acute conditions caused specifically by PM inhalation. Both types of damage are translated into dollar values, and in that sense both can be described as “economic.”

[17] The fossil fuel control costs are

$$A_F(t) = [1 - b_1(t)\mu_C(t)^{b_2}] Q_G(t),$$

where the coefficients $b_1(t)$ and b_2 are the model parameters used for calculating the fractional cost to

gross output [Nordhaus and Boyer, 2000]. The sulfur control costs are

$$A_S(t) = \mu_S(t) [\theta_S(t) / \theta_C(t)] E_C(t) P_S(t).$$

The unit sulfur control cost, $P_S(t)$, derived from the least cost curves of sulfur abatement for desulfurization technologies used in European countries [Halkos, 1994] is

$$P_S(t) = 355 / [1 - \mu_S(t) / 0.85]^2.$$

Reflecting the need to resort to successively more expensive abatement options, the marginal abatement cost rises monotonically with sulfur control rate and increases rapidly at around 80%.

3. POLICY EXPERIMENTS

[18] We consider four policy scenarios, distinguished by variations in the abatement instruments used and policy objectives. In all cases the rates of capital investment and available controls are set to maximize the total utility. The resulting paths of economic development and control policy are compared in section 4. Note that this investment optimization is based on a mistaken view of the world in some cases in the sense that it does not include unforeseen climate damage or health damage or both. In these cases the unanticipated damage is subtracted from that period’s consumption at the end of each 10-year time step.

[19] The four cases are named and described in Table 1. The “IPCC” scenario is obtained through optimizing the investment rate with no controls on emissions and corresponds to the business-as-usual (BAU) case of the original DICE. By contrast, the “DICE” scenario allows for control of fossil fuel use and is similar to the optimal case of DICE. The “Health Only” and “Climate and Health” scenarios

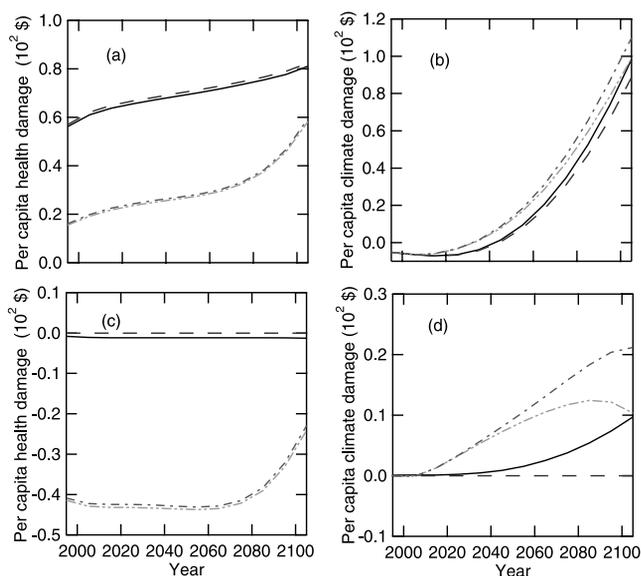


Figure 1. Trajectories of (a) per capita health and (b) climate damage in four scenarios (IPCC, black solid curve; DICE, blue dashed curve; “Health Only,” pink dashed-dotted curve; and “Climate and Health,” green dashed-dotted-dotted curve) and (c) per capita health and (d) climate damage differences from the DICE scenario. See color version of this figure in the HTML.

result from optimizing with respect to investment and controls on both fossil fuel use and sulfur emissions, the first with a single-minded focus on health damage and the second taking into account both the climate and health damages.

4. RESULTS

[20] This paper highlights the policy trade-off between health and climate damage. Figure 1 shows the paths of the two types of damage under the four policy scenarios. The most notable difference is between policies that take health damages into account and those that do not. The large difference is due to sulfur emission control. Since some sulfur control is already assumed in the SRES B2 scenario, the health damage in the IPCC and DICE scenarios (Figure 1) rises only modestly to about \$80 per capita per year in 2105. Under the sulfur control in the Health Only and Climate and Health scenarios the per capita health damage is held below \$55.

[21] The result of sulfur control is warming, relative to no sulfur control. Figures 1b and 1d plot the per capita climate damage in the different scenarios. The graphs show that a modest increase in temperature is economically beneficial, a controversial implication of the climate damage function used in DICE-99. All the trajectories of climate damage in Figure 1b follow a similar upward trend, not reaching \$20 per capita per year until the middle of the 21st century at the earliest. A comparison with the per capita health damage in Figure 1a reveals why health damage has such a significant, in some cases dominant, impact in cost-benefit-based pol-

icy. Under the assumptions of the model, substantial reductions in health damage can be achieved by application of separate sulfur controls and are justified in relation to the cost.

[22] Figure 2 shows two important “bottom line” measures of the performance of the economy, the rate of consumption per capita, and the global average surface temperature. Figure 2a suggests that the differences among the trajectories are never more than \$50 per capita, well below 2% of the absolute per capita consumption. By definition, the “Climate and Health” scenario would be the “best” in terms of the total discounted per capita utility. Thus “best” would not necessarily imply “uniformly highest” consumption over the next 100 years, though utility is a monotonically increasing function of consumption at a specific time. The worst result for most of the future is associated with the IPCC, business-as-usual path, but this does not prevent the initial consumption from being greater than DICE since part of the net output that would have been diverted to controlling carbon emissions is now consumed.

[23] Figure 2b shows the climate change, measured by the average surface temperature, under the various scenarios; the projected increase in temperature by 2105 ranges from 2.25°C to 2.65°C. Again, the differences among the scenarios are most easily seen in Figure 2d, which mimics qualitatively the climate damage shown in Figure 1d. The DICE scenario, which relies on fossil fuel control to limit warming, taking as given the limited SRES B2 sulfur control, lowers temperature increase by about 0.1°C compared to the IPCC BAU scenario. The inclusion of the health damage in the Health Only and Climate and Health scenarios gives rise to higher average surface temperatures throughout the 21st century in comparison with the IPCC

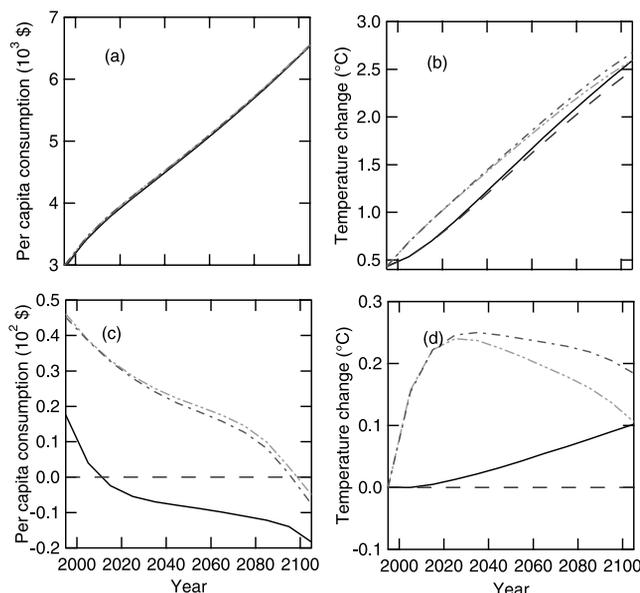


Figure 2. Trajectories of (a) per capita consumption and (b) temperature change in four scenarios and (c) per capita consumption and (d) temperature change differences from the DICE scenario. Curves are as described for Figure 1. See color version of this figure in the HTML.

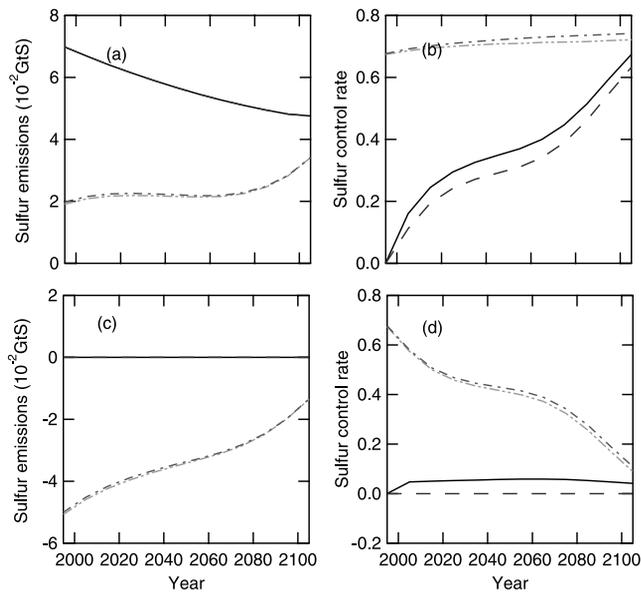


Figure 3. Trajectories of (a) sulfur emissions and (b) control rate in four scenarios and (c) sulfur emissions and (d) control rate differences from the DICE scenario. Curves are as described for Figure 1. See color version of this figure in the HTML.

BAU scenario and with the climate-oriented DICE scenario. The most warming of all the scenarios occurs when both fossil fuel and sulfur controls are put completely at the service of abating the health damage in the Health Only scenario. Aiming at serving both climate and health objectives, the Climate and Health scenario calls for a bit more stringent fossil fuel control and slightly less sulfur control. At the end of the century the predicted temperature in the Climate and Health scenario reaches the same level as in the IPCC BAU scenario (it is 0.04°C lower in 2105) but is rising much less rapidly. At that point the boost to fossil fuel emission control from its positive health impact has a beneficial climate effect by slowing down the pace of warming. Figure 3 displays data on the sulfur emissions and sulfur control rates, which are new to this paper's version of DICE. By construction the sulfur emissions in the IPCC and DICE scenarios follow the SRES B2 emissions, declining gradually from 0.070 Gt S in 1995 to 0.048 Gt S in 2105. In our simulations the sulfur emission levels justified by health benefits would be dramatically lower. The emissions in the Health Only and Climate and Health scenarios remain at around 0.020 Gt S from 1995 to 2075 before increasing modestly, under pressure of economic growth, to 0.033 Gt S at 2105. Relative to the IPCC case the small decrease in fossil fuel in DICE makes it possible to slightly reduce sulfate control, while still meeting the SRES B2 sulfur emission level prescribed in both cases.

[24] The predicted carbon emissions and fossil fuel control rates are plotted in Figure 4. Under all scenarios the carbon emission rate rises substantially throughout the century and is still rising at the end. Figures 4c and 4d reveal the differences among the scenarios. The DICE

scenario calls for the reduction in emissions from the IPCC BAU levels, starting at about 0.30 Gt C in 1995 and reaching 1.50 Gt C in 2105. The carbon emissions are lowest when both health and climate objectives reinforce each other. Interestingly, the carbon control rate when only health damage is taken into account (Health Only scenario) exceeds that when only climate damage is taken into account and sulfur emissions are prescribed (DICE) until the middle of the century.

5. MODEL SENSITIVITY

[25] This work represents an effort to frame a cost-benefit analysis by explicitly taking into account the health damage and sulfur control costs, introducing as new parameters the dose-response function constant and VOSL. The sensitivity to the uncertainties in model parameters has implications for the robustness of the conclusions reached in the paper. Since the literature does not contain reliable estimates, we bound the aggregated uncertainties of the health damage and sulfur control costs terms in the expression for net output by increasing and decreasing the values of the new parameters by a factor of 10.

[26] Because sulfur emissions are fixed and no additional fossil fuel control is available in the IPCC scenario, the variations in both terms cause negligible change in the predicted temperature. For the Climate and Health scenario the predicted temperature changes under the hypothetical lower and upper bounds of the sulfur control costs are compared with the IPCC scenario in Figure 5a. The lowering of the sulfur control costs makes it possible to cut sulfur emissions further below the base case to reap the extra health benefit. The resulting path of temperature change will

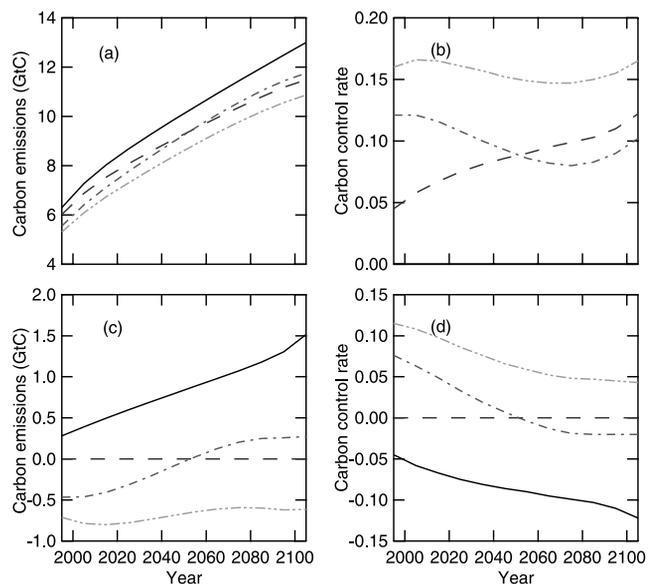


Figure 4. Trajectories of (a) carbon emissions and (b) control rate in four scenarios and (c) carbon emissions and (d) control rate differences from the DICE scenario. Curves are as described for Figure 1. See color version of this figure in the HTML.

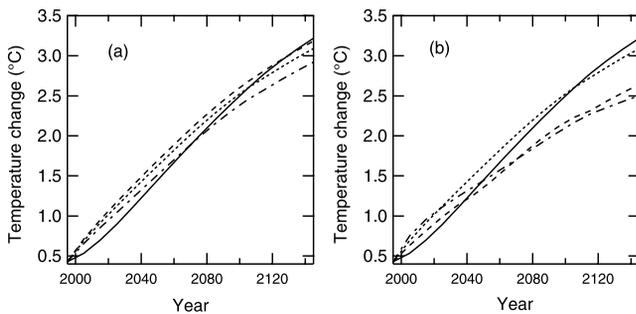


Figure 5. Sensitivity of temperature change to (a) sulfur control costs and (b) health damage (IPCC, solid curve; “Climate and Health,” dotted curve; upper bound, dashed curve; and lower bound, dotted-dashed curve).

not drop below the IPCC scenario until 2135, later than 2115 in the base case. On the other hand, a tenfold increase in control costs drives up sulfur emissions with an effect of suppressing warming, keeping temperatures lower and advancing the crossover with IPCC to 2075.

[27] An increase in health damage calls for a faster deployment of sulfur control measures than in the base case, thus giving rise to slightly higher temperature before 2015, as seen in Figure 5b. When sulfur control becomes prohibitively expensive thereafter, the reduction in fossil fuel usage is the only means left for keeping sulfur emissions in check. The crossover with IPCC occurs at 2025, significantly earlier than 2115 in the base case. Interestingly, the model response to the decrease in health damage is nonlinear when the damage is sufficiently low. For example, once reduced to one tenth of the base case value, the health damage becomes less important than the climate damage, a transition that leads to excessive sulfur emissions and reduced warming while inflicting a tremendous loss of human lives. The temperature in this low-health-cost case is lower than in the base case with a crossover at 2035.

6. CONCLUSIONS

[28] This study explores the opposition between policies to reduce the concentration of sulfate aerosol and its cooling impact and policies to mitigate global warming. As we had expected, the health damage dominates the determination of the sulfur control rate. When sulfur emission controls are available to continue fossil fuel usage while reducing PM, taking into account the health damage results in stringent sulfur controls. The effect of addressing the health effect of sulfur emissions on warming in the short run is lowering of the concentration of sulfate aerosol, giving rise to a powerful warming effect.

[29] The new finding in these calculations lies in the long-term implications of the interaction between climate and health objectives. Wigley [1991] treated sulfur emissions as determined solely by fossil fuel use and hence proportional to CO_2 emissions, making it impossible to quantify the economic responses to pollution controls. That work fixed annual fossil fuel reduction at a rate of 2% and

thus may have partially incorporated the health benefit. Nonetheless, the absence of separate sulfur control effectively renders it impossible to reduce health damage to the extent justified by cost-benefit considerations. By adding the sulfur emission control and its cost as variables in our model, we made explicit the connection between carbon and sulfur controls in order to evaluate the trade-off between health and climate damage. By doing so, we are able to explore the various policy options that are implemented to achieve different policy objectives and to show the ranges of emissions that result for each scenario.

[30] The simulations with a highly simplified global model suggest that the policy that serves both climate and health objectives, using both fossil fuel and sulfur controls, is likely to generate more warming throughout the 21st century. This increase in warming is relative to the reasonable BAU scenario and to a policy directed only at abating global warming by limiting fossil fuel emissions. The warming is attributable both to the short lifetime of sulfate aerosol and to separate sulfur controls that can reduce health damage without reducing CO_2 emissions.

[31] In addition to stringent sulfur controls the health-oriented policies also call for the reduction in fossil fuel use in the long term. Carbon emissions under the policy serving health and climate objectives simultaneously are lower than under the climate-oriented policy, causing the global average temperature to be lower after 2105. If the long-term temperature levels constitute the main policy concern, the health objective helps rather than hinders climate objectives. The sensitivity analysis shows that as long as the health damage dominates in dictating sulfur control, this conclusion is robust under a wide range of model uncertainties. However, the timing of the salutary effect of health-based policy on climate may vary.

[32] The conclusions we have reached are based on a highly simplified model of worldwide aggregation. Accounting for the regional character of sulfate aerosol pollution and its control is an important step in formulating a more complex model and is likely to change the conclusions, perhaps substantially. The first cut taken here suggests such a closer look may be important for understanding the unintended interactions of health and climate policies.

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