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The climate impacts of sulfate aerosols

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Sulfate aerosols (SO_4) from anthropogenic emissions of sulfur dioxide (SO_2) generally have a cooling effect. However, if SO_2 emissions fall over time, accounting for sulfate aerosols will increase the predicted warming from greenhouse gases. This paper integrates the four marker emission scenarios for CO_2 and SO_4 from the Special Report on Emissions Scenarios (SRES), the UIUC general circulation model (GCM), and a country-specific impact model (GIM) to calculate the impacts of sulfate aerosols. By 2100, lower SO_2 emissions slightly increase warming in the temperate and polar regions causing small damages in the former and small benefits in the latter. If SO_2 emissions are also lower in tropical regions, temperatures will rise causing small damages there as well. However, if SO_2 emissions rise in tropical regions, temperatures will fall leading to small benefits.

1. Introduction

Although it has long been known that carbon dioxide (CO_2) is a greenhouse gas (GHG) that tends to warm the atmosphere, it has only more recently been understood that sulfate aerosols (SO_4) generated in the atmosphere from the anthropogenic emissions of sulfur dioxide (SO_2) gas tend to cool the atmosphere [2]. This paper combines country-specific climate and impact models to estimate the impacts of including sulfate aerosols in integrated assessment models. The paper illustrates the value of having more geographically precise integrated assessment models for climate change. The paper is also intended to inform policy makers about the importance to global warming of sulfur-dioxide policies.

The IPCC has constructed four families of alternative future emission scenarios for the Special Report on Emissions Scenarios (SRES) [13]. The scenarios predict both GHG and SO_2 emissions for the 21st century. The CO_2 predictions are intended to represent "business-as-usual" scenarios, that is, what would happen if no greenhouse-gas controls were put in place. The SO_2-emission paths, however, include explicit control policies for sulfur dioxide. Whereas greenhouse gases are predicted to increase over the next century, SO_2 emissions may or may not increase in each region depending upon whether the growth in the fossil-fuel energy consumption outweighs new SO_2 control policies. If control policies reduce (increase) SO_2 emissions, regional temperatures will be higher (lower) than otherwise. Thus, although SO_2 cools the atmosphere, through its control, SO_2 might be responsible for additional warming. This study examines the potential impacts of SO_2 emissions control and explores how alternative scenarios might affect each region.

From earlier research, it is clear that regional SO_2 emissions change the geographic distribution of temperature in 2100 [17]. In this paper, we specifically examine how the alternative SRES scenarios affect impacts. Starting with the SRES scenarios, we use the University of Illinois Urbana Champaign (UIUC) climate model [17] to make country-specific forecasts of climate for each emission scenario. The Global Impact Model (GIM) [8] calculates country-specific estimates of market impacts from the predicted changes in surface temperature and precipitation in each country. By capturing country-specific detail, this integrated assessment approach can capture the geographic detail of changing regional SO_2 emissions.

This research illustrates the value of integrated assessment applied to climate change. It is important to recognize that there are many uncertainties in each component of such an assessment: emissions, concentrations, climate change, and impacts. Although point estimates are presented in this paper, the reader should not interpret these estimates as certain. Further, the models used in this analysis are not the only models of each component. There are a host of predictions of CO_2 emissions, many scenarios of SO_2 emissions, several carbon-cycle models, some 27 general circulation models with many variants, and several impact models. This research does not encompass the full range of estimates for each component. However, the research does give a sense of the magnitude of impacts that are likely to occur in each case. Specifically for the case of sulfates, the research does vary emissions and climate sensitivity, so that the reader can get a sense of some of the range of impacts that is possible.

2. Emissions, models and methods

Three major research efforts are combined here to generate impact predictions. The emission trajectories were developed by the IPCC for the SRES using a series of storylines and numerical models [13]. The climate projections were developed using the UIUC atmospheric general

Table 1
SRES scenarios for year 2100.

SRES emissions scenario	GWP (trillion USD)	Population (billion)	CO_2 concentration (ppmv)[a]	Change in SO_2 emissions from 2000 to 2100 (billion tons sulfur)[b]		
				OECD	Soviet	ROW
B1	338	7.1	562	−20.1	−14.5	−10.4
B2	235	10.4	613	−19.2	−13.4	9.6
A1	528	7.1	693	−18.1	−15.4	−9.7
A2	244	15.0	836	−10.9	−13.8	14.1

[a] The CO_2 concentrations are from Schlesinger et al. [17] for the SRES CO_2 emissions.
[b] The OECD is the developed countries, Soviet includes the former Soviet Union and Eastern Europe, and ROW is the rest of the world.

circulation/mixed-layer-ocean (AGC/MLO) model, a simple climate-ocean model, and a sophisticated interpolation technique [17]. The impacts were calculated by the Global Impact Model (GIM) [8].

2.1. SO_2 emissions scenarios

When it became clear that sulfate aerosols can have a significant effect on climate, it also became clear that sulfate aerosols would have to be included in future climate projections. The IPCC recently completed the difficult exercise of generating a number of alternative emission scenarios for the SRES [13]. It is a difficult task to forecast these emissions far into the future, requiring not only an ability to foresee economic and energy development through the 21st century, but also an ability to predict how future pollution regulation might shape SO_2 emissions.

The authors of the SRES report do not provide a single "best estimate", but instead provide four alternative marker scenarios, each being representative of a scenario family. The authors are very explicit that these are not four equally likely outcomes, but merely four possible alternatives. We examine all four marker scenarios to present a range of possible effects. We, like the authors of the SRES report, do not assess the likely occurrence of each scenario. Some of the SRES marker scenarios may be more likely than others and the set of scenarios does not reflect a broad range of likely outcomes. Consequently the reader must be careful interpreting the results across the scenarios.

The four marker scenarios correspond roughly to four storylines. The A1 scenario is a high economic and low population growth story. Carbon dioxide emissions are moderate and SO_2 emissions are low. The B1 scenario is a moderate economic and low population growth story, with emphasis on reduced materialization of the economy and movement away from fossil fuels. Carbon dioxide and SO_2 emissions are low. The A2 scenario has low economic and high population growth. It results in the highest CO_2 and SO_2 emissions and continued disparity between rich and poor countries. The B2 scenario has low economic and moderate population growth with continued disparity across countries. Carbon dioxide and SO_2 emissions are moderate.

Four different integrated assessment models were used to provide concrete values for each marker scenario. The AIM model generated the A1 scenario [12], the ASF model provided the A2 scenario [21], the IMAGE model created the B1 scenario [1], and the MESSAGE model generated the B2 scenario [11]. The resulting global characteristics of each marker scenario are shown in table 1.

2.2. Climate changes

In principle, climate changes could be calculated for each SRES emission scenario using a coupled atmosphere–ocean general circulation model. However, these models are expensive to run so that, in practice, they cannot be used for the myriad of possible scenarios of interest to policymakers. Consequently, Schlesinger et al. [17] constructed geographical distributions of surface temperature changes using a variant of the scenario-construction method developed by Santer et al. [16]. Here we employ the same method to construct the geographical scenarios of changes in precipitation.

The model begins by predicting the concentration of greenhouse gases and sulfate aerosols for each emission scenario [17]. Carbon dioxide emissions become well mixed in the atmosphere, so that region-specific emissions are not important. All that matters is global emissions. Sulfur dioxide emissions are more short-lived, so they lead to region-specific sulfate levels. Each SRES scenario makes a different forecast of regional SO_2 emissions, leading to different regional sulfate aerosol concentrations. We assume that the spatial distribution of emissions within each region resembles current emissions.

The concentration of greenhouse gases depends on the path of emissions over time. In addition to carbon being released by man-made emissions, some carbon is captured by natural processes through the carbon cycle. Given the concentration of the greenhouse gases and the burden of the sulfate aerosols, the level of radiative forcing is predicted for each scenario.

The Atmospheric General Circulation/Mixed Layer Ocean (AGC/MLO) model calculates the geographical distribution of temperature and precipitation change for eight scenarios. One scenario examines a doubling of CO_2 alone. Six scenarios examine a 10 times increase in sulfates in each of 6 regions individually (Europe, North Africa, Siberia, Asia, North America and the Southern Hemisphere). A final scenario examines a 10 times increase in sulfates jointly from all 6 regions. We rely on this large increase in sulfates in order to obtain a global forcing effect of about the same magnitude as that for doubling of CO_2. We need a large change in radiative forcing in order to observe a statistically significant pattern of geographical effects above the climatic noise inherent in the model. This potentially introduces a flaw in our approach since the policy-relevant changes in SO_2 are likely to be much smaller.

A simple climate/ocean model is used to calculate the time-dependent change in global-mean surface temperature separately for the GHG and SO_2 emissions of each SRES marker scenario. The country-specific changes in temperature and precipitation are then calculated by multiplying the relative change in global temperature from each gas for each scenario by the distribution predicted by the AGC/MLO model [17]. This approach allows us to predict the importance of regional variations in SO_2 emissions.

This method of superimposing the results of the seven $10 \times SO_2$ simulations was evaluated by using it to construct the temperature changes obtained in an eighth AGC/MLO model simulation in which there were SO_2 emissions from all regions but Europe. It was found that the error of the construction is generally less than 10% [17]. The geographical distributions of the climatic changes due to both GHGs and SO_2 were taken as the sum of their individual changes.

Three different values of climate sensitivity were explored to capture the range of effects radiative forcing might have upon average global temperature. Given the radiative forcing from doubling CO_2 concentrations, the three values lead to global temperature increases of 1.5, 2.5, and 4.5°C. These three outcomes reflect the range of uncertainty given by the IPCC [5].

The resultant 12 climate-change scenarios were made country-specific following the method of Schlesinger and Williams [19]. The approach calculates changes in climate in each country from the climate grid boxes within a country's borders. This paper makes an important methodological improvement in this process. In previous research, we used the area-weighted change in climate for each country [8]. However, careful comparisons of area-weighted versus population-weighted climate predictions reveals the population weighted estimates to be more accurate predictors of climate impacts [9,22]. Weighting grids by population is effective because sensitive market sectors are concentrated near population centers. Weighting grid squares by population consequently provides a more accurate estimate of national climate from an impact perspective. This population weighting approach is used throughout this paper.

2.3. Climate impacts

Climate change impact research has been developing rapidly over the last decade. The first estimates of climate change damages were done for the United States [14]. Additional estimates by Cline [3], Fankhauser [4] and Tol [20] quickly followed. The papers by Fankhauser and Tol further expanded the estimates to include all the regions of the world. All of these estimates are captured in the Second Assessment Report by the IPCC [15]. More recently, the estimates for the United States have been redone to capture adaptation, dynamic analysis, and the potential benefits from warming [6].

The primary difference between this paper and earlier efforts to estimate global impacts lies in the geographic detail in this model. By focusing on country specific results, the study can take better advantage of the geographic information of climate models. We view this as one step in the direction of developing more carefully calibrated complete models of impacts.

In this study, the 12 climate predictions were evaluated using the global impact model GIM [8]. Given parameters chosen by the user, GIM forecasts the economy into the future for each sensitive market sector for each country. In this case, we use the GDP growth parameters identified by each SRES scenario to predict the baseline economy in 2100. GIM uses two alternative climate-response functions, experimental and cross-sectional, to predict how each sector will change in each country in response to each climate scenario. The net results by country and region can then be compared across scenarios.

GIM is a spreadsheet model that begins with a country-specific set of climate changes and then predicts market impacts. A separate model is designed for each sensitive market sector: agriculture, forestry, energy, water, and coastal structures. A separate calculation is made for each sector and country that combines the change in climate, sector data, and a climate-response function. This leads to calculations of damages or benefits by sector and country. Quality-of-life effects such as changes in ecosystems, health, and aesthetic losses are not included in this version of the model, as climate-response functions for these effects are not yet available.

The current version of GIM responds to annual temperature and precipitation. Future versions of the model will move to seasonal climate variables to gain more detailed insight into climate impacts. The annual climate changes by country come from the climate-change constructions described above.

For each country, key parameters of each sector are collected. For example, the areas of cropland and forestland, and the length of coastline provide important insights into agriculture, forestry, and coastal structures, respectively. Gross Domestic Product (GDP) by country is also important in several sectors. As GIM becomes more sophisticated, additional parameters will be collected for each country.

The heart of GIM is its climate-response functions. Earlier impact research predicted impacts from a limited set of climate scenarios. Tools that are scenario specific, however, are cumbersome because they cannot evaluate a large number of scenarios or a path of climate change. Consequently, the literature has begun to develop climate-response functions, descriptions of how impacts change within a sector as climate changes [7]. In this paper we rely upon climate-response functions based on empirical research [6].

In Mendelsohn and Neumann, over a dozen leading impact researchers examined each of the climate-sensitive sectors of the US economy. There were four key elements in this new research: inclusion of efficient adaptation, broad sectoral estimates, dynamic analysis when appropriate, and use of future economic conditions. However, the fact that the climate-response functions are calibrated just for the United States is an important limitation of GIM.

The research relied upon the two major alternative methods of measuring the response to climate. Several studies in Mendelsohn and Neumann [6] relied upon the experimental method. This approach is common in the impact literature. The analysis begins with carefully controlled laboratory studies, such as agronomic tests in the field, and uses the results to construct simulation models. The remainder of the studies relied on cross-sectional evidence. By comparing farms and households in cool versus warm locations, one can estimate how people have adapted to their resident climates and how they may react as these climates change in the long run.

The strength of the experimental method is that it can isolate climate effects from other factors in the environment through controlled experiments. Further, it can introduce the effect of factors that are not yet evident in the environment, such as higher levels of carbon dioxide. The weakness of the approach is that experiments are designed to control responses, both environmental and human. Adaptations that ecological systems and people make to climate change are suppressed, thereby exaggerating the damages and reducing the benefits from warming. The strength of the cross-sectional approach is its ability to capture efficient adaptation because the method compares systems already adapted to current but different climates. For example, a farm in a cool place is compared to a farm in a warm place, given all the adaptations that farmers have made to where they live. This advantage of cross-sectional evidence comes at a cost. Cross-sectional studies are vulnerable to unmeasured factors that may be correlated with climate. If these factors are not taken into account, they can be confused with climate effects, thereby leading to misleading results. This is not a problem for the carefully controlled experimental studies. Consequently, the experimental and cross-sectional methods complement each other well, and we rely upon both of them in this study.

3. Results

Table 1 reveals the economic, population, and emission scenarios of each of the 4 SRES marker scenarios. The economic and population scenarios are curiously decoupled from the emission scenarios. The low economic-growth A2 scenario has the highest CO_2 prediction, 836 ppmv, while the highest-growth-scenario, A1, has a more moderate CO_2 prediction, 693 ppmv. Only these two scenarios remain close to the uncontrolled (business-as-usual) CO_2 range of earlier studies of between 700 ppmv and over 1000 ppmv (IPCC 1992). The remaining B1 and B2 scenarios have lower CO_2 concentration predictions that are equivalent to earlier results from relatively stringent policy interventions (IPCC 1992).

Because the SO_2 emissions have regional impacts, we examine the forecasts by region. All four scenarios predict the identical sharp drop in emissions in the former Soviet Union–Eastern European economies of 13–15 billion tons of sulfur. The SRES scenarios consequently do not capture the full range of variation possible from these transition economies. There are effectively only two SO_2 emission scenarios captured for the OECD, a 19 billion-ton reduction (A1, B1, and B2) or a 10 billion-ton reduction (A2). Given that the OECD has already initiated substantial SO_2 reductions, and that the OECD economies could grow substantially over the next century, these scenarios may underestimate the growth possible in SO_2 emissions. The SO_2 predictions for the rest of the world fall into two camps, a reduction of 10 billion tons (A1 and B1) and an increase of 10–14 billion tons (B2 and A2). Both of these scenarios are plausible given the pressure of economic growth to increase emissions and the likelihood that increased per capita income will lead to tighter controls. However, given that the rest of the world could account for $75 trillion (1990 USD) of GDP by 2100, over three times the current world GDP, SO_2 emissions from the rest of the world could increase considerably more than these scenarios predict [8].

Table 2 illustrates the climatic impact in 2100 relative to 2000 of each SRES scenario for three different climate sensitivities (1.5, 2.5, and 4.5°C) due to greenhouse gases alone. All the climate predictions are population weighted. Because they predict similar CO_2 concentrations, B1 and B2 generate similar climate predictions. For example, with a 2.5°C climate sensitivity, B1 generates a 1.9°C average warming and B2 a 2.1°C warming. In contrast, A1 leads to a 2.5°C warming and A2 to a warming of 3.3°C. Table 2 also

Table 2
Global and regional temperature changes in 2100 relative to 2000 due to greenhouse gases alone.

SRES scenario	Temperature changes (°C) Globe	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean
	1.5°C Sensitivity							
B1	1.24	1.14	1.28	1.38	1.23	1.14	1.26	0.78
B2	1.35	1.33	1.50	1.58	1.44	1.33	1.40	0.91
A1	1.62	1.52	1.72	1.84	1.65	1.53	1.60	1.05
A2	2.16	2.23	2.51	2.69	2.41	2.23	2.34	1.53
	2.5°C Sensitivity							
B1	1.93	1.82	2.05	2.20	1.97	1.82	1.91	1.25
B2	2.10	2.10	2.36	2.53	2.27	2.10	2.20	1.44
A1	2.51	2.41	2.71	2.91	2.60	2.41	2.52	1.65
A2	3.26	3.40	3.82	4.10	3.67	3.40	3.56	2.33
	4.5°C Sensitivity							
B1	3.03	2.95	3.32	3.56	3.19	2.95	3.10	2.03
B2	3.28	3.35	3.77	4.04	3.61	3.35	3.51	2.30
A1	3.90	3.84	4.32	4.63	4.14	3.84	4.03	2.64
A2	4.89	5.19	5.84	6.26	5.60	5.19	5.44	3.56

N.A. is North America; W.E. is Western Europe, Sov is the former Soviet Union and Eastern Europe; LA is Latin America, Afr is Africa; and Ocean is Oceania.

Table 3
Global and regional temperature changes in 2100 relative to 2000 due to sulfate aerosol alone.

SRES scenario	Temperature changes (°C) Globe	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean
	1.5°C Sensitivity							
B1	0.25	0.29	0.35	0.38	0.22	0.09	0.08	0.05
B2	0.10	0.21	0.30	0.26	0.09	0.03	0.02	0.00
A1	0.25	0.30	0.34	0.38	0.22	0.09	0.09	0.06
A2	0.05	0.11	0.15	0.14	−0.02	−0.02	−0.04	−0.05
	2.5°C Sensitivity							
B1	0.34	0.40	0.49	0.53	0.28	0.10	0.10	0.05
B2	0.16	0.29	0.35	0.36	0.10	0.02	0.01	−0.02
A1	0.34	0.40	0.48	0.51	0.28	0.11	0.11	0.06
A2	0.03	0.12	0.19	0.16	−0.05	−0.07	−0.09	−0.10
	4.5°C Sensitivity							
B1	0.40	0.49	0.62	0.67	0.32	0.08	0.07	0.01
B2	0.15	0.33	0.42	0.42	0.07	−0.03	−0.05	−0.08
A1	0.38	0.49	0.61	0.64	0.30	0.19	0.06	0.01
A2	−0.10	0.07	0.16	0.10	−0.19	−0.48	−0.23	−0.21

N.A. is North America; W.E. is Western Europe, Sov is the former Soviet Union and Eastern Europe; LA is Latin America, Afr is Africa; and Ocean is Oceania.

Table 4
Market impacts in 2100 due to greenhouse gases alone experimental model.

	A2 SRES scenario							
Climate sensitivity (°C)	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean	Total
1.5	39.7	12.9	153.9	−210.8	−66.1	−147.4	−0.1	−217.9
2.5	27.6	4.4	187.4	−432.8	−136.8	−246.2	−7.0	−603.3
4.5	−4.1	−18.1	214.4	−809.7	−258.2	−333.6	−20.1	−1229.5
	Climate sensitivity 2.5°C							
SRES scenario	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean	Total
B1	26.7	8.7	134.6	−239.8	−76.1	−158.4	−2.9	−307.2
B2	24.1	7.1	127.0	−235.9	−75.1	−152.2	−2.9	−307.9
A1	45.4	14.1	219.6	−394.0	−123.8	−254.9	−4.6	−497.9
A2	27.6	4.4	187.4	−432.8	−136.8	−246.2	−7.0	−603.3

Welfare impacts are in billions of 1990 USD per year. Positive numbers imply benefits and negative numbers imply damages.

illustrates the importance of climate sensitivity. The higher the sensitivity, the warmer are the predictions in every region for each SRES scenario. Note that only the A1 and A2 scenarios with 4.5°C climate sensitivity lie outside the most likely range of 1–3.5°C from the 1996 IPCC report [5].

Table 3 describes the effect of the change in SO_2 emissions alone on population-weighted temperatures. Sulfates have a small effect on global temperatures. The A1 and B1 scenarios increase temperatures between 0.25 and 0.40°C whereas the B2 scenario increases temperature only between 0.10 and 0.16°C. These three scenarios predict sulfates warm the world because they assume that SO_2 emissions fall in every region. Even with the A2 scenario, SO_2 is assumed to fall in every region except the developing countries. The decreasing sulfates in northern latitudes offset the increasing sulfates in the rest of the world leading to a negligible net effect on global temperature.

Although small, the sulfate scenarios do affect regional temperature changes. In the A1 and B1 scenarios, temperatures rise more sharply in northern latitude regions, but only slightly in more tropical regions. The B2 scenario follows this same pattern, except that the effect in Asia is smaller. Only the A2 scenario provides truly contrasting regional results. The assumed rise in SO_2 emissions in developing countries in this scenario leads to a decrease in temperature in more tropical regions. Thus, although there is little change in global temperature under the A2 scenario, regional temperatures do respond to the regional change in SO_2 emissions.

The impacts of the temperature changes are captured in the remaining tables. The impacts in 2100 predicted by the experimental model with greenhouse gases alone are shown in table 4. These scenarios entail global net damages because the damages in tropical regions outweigh the benefits in temperate and polar regions. The greater the temperature increase, the greater the global net damage. The country-specific impacts of the A1 and A2 scenarios are shown in figure 1 for a 2.5°C climate sensitivity. The high-latitude former-Soviet region benefits from warming across both scenarios (note the increasing benefits in the A2 scenarios with higher temperatures). The high-latitude countries in North America and Europe also benefit in both scenarios. The temperate countries in North America and Europe benefit only from modest warming. As regional temperature rises above 2°C, further warming is harmful in the temperate zone and eventually results in overall regional damages. Any warming is harmful to the low-latitude countries. The effects vary in size across the four tropical regions because of varying populations, economies, and land in agriculture. Although not shown, the sector dominating all of these results is agriculture. The more dependent a country is upon agriculture, the larger are the damages as a fraction of GDP. Severe impacts are especially evident in sub-Saharan Africa.

The results from the cross-sectional model (see table 5) are quite different from the experimental model (table 4) for the greenhouse gas-alone scenario. Modest global warming, up to 2°C, is predicted to generate net global benefits. Warming above 2°C reduces these benefits and eventually, with enough warming, turns the net impacts to damages. According to the cross-sectional model, the B1, B2, and A2 scenarios are quite similar, with a small increased benefit associated with the A1 scenario. The country-specific effects can be seen in figure 2 for the A1 and A2 scenarios and a 2.5°C climate sensitivity. The former-Soviet region benefits from increased warming. The temperate region benefits with modest warming, but these benefits shrink as warming exceeds 2°C. The cross-sectional model treats Asia, Oceania, and Latin America as though they were temperate, not tropical, with benefits from moderate warming that fall as warming increases. Only Africa suffers consistent damages for all warming scenarios.

The focus of this paper, however, is on the effect of sulfates. The results from the experimental model (table 6)

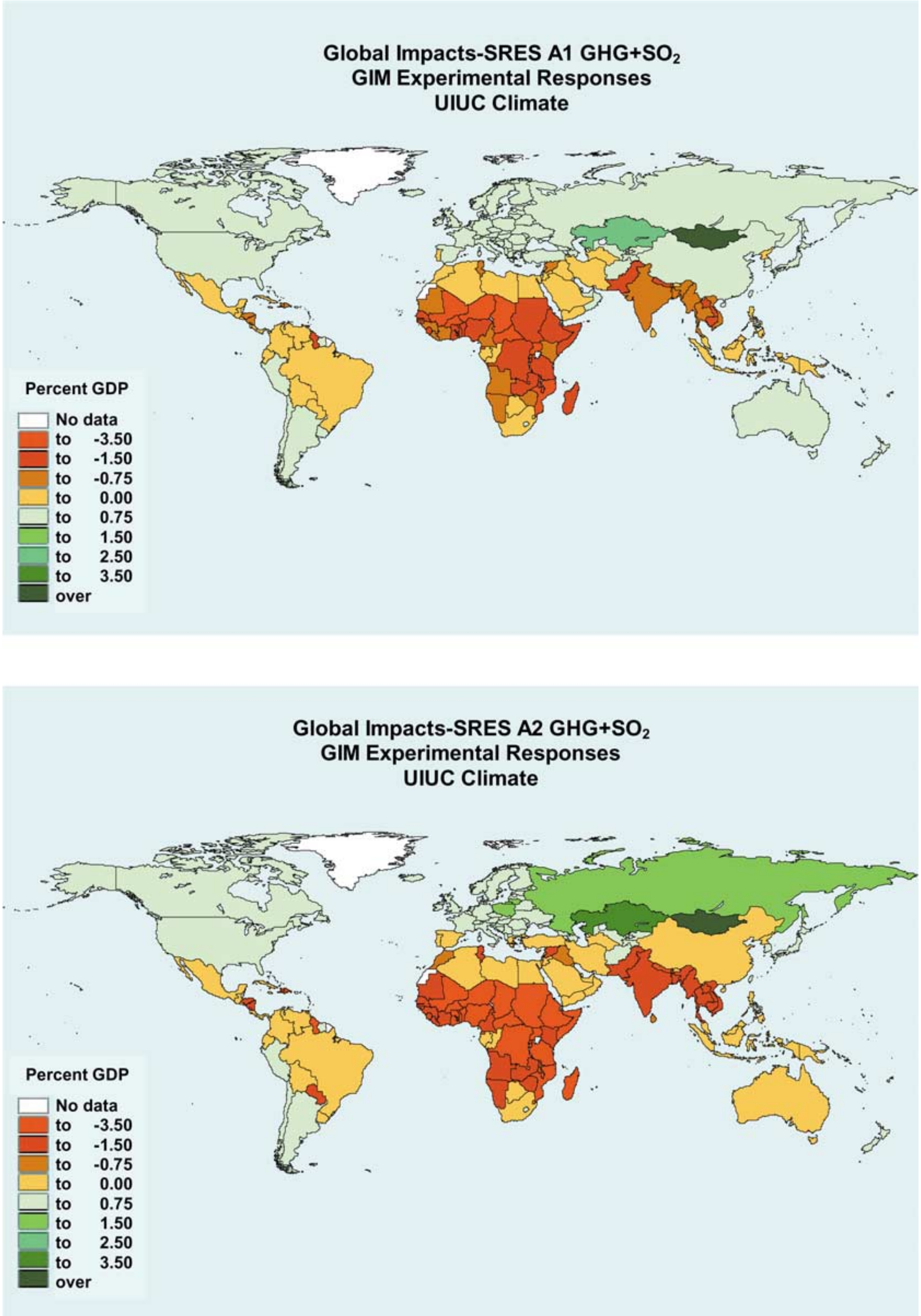


Figure 1. Global impacts calculated using experimental climate response functions. The climate in the upper map is consistent with SRES scenario A1 GHG and SO_2 emissions using methods described in the text. The lower map shows impacts resulting from SRES scenario A2.

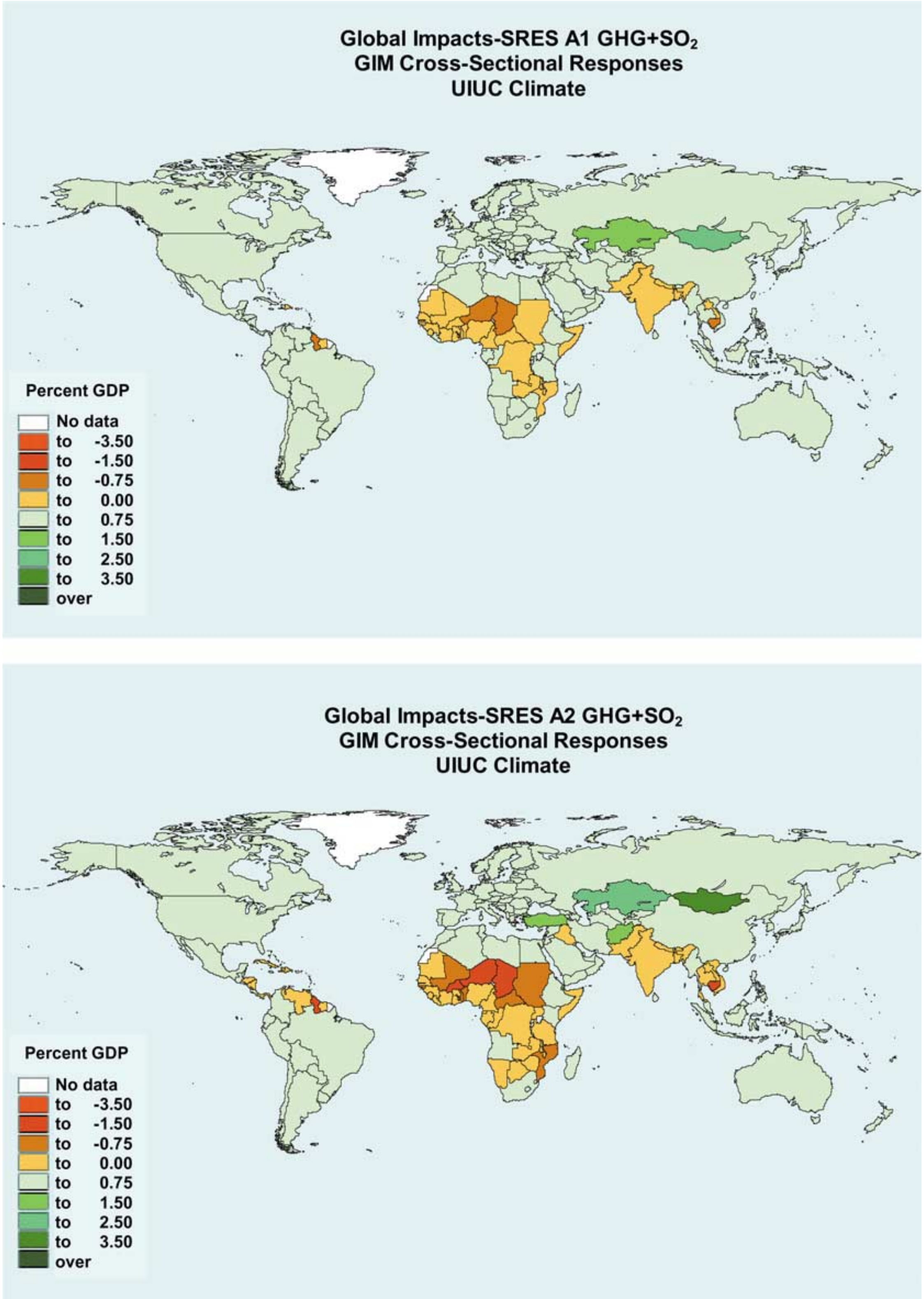


Figure 2. Global impacts calculated using cross-sectional climate response functions. The climate in the upper map is consistent with SRES scenario A1 GHG and SO_2 emissions using methods described in the text. The lower map shows impacts resulting from SRES scenario A2.

Table 5
Market impacts in 2100 due to greenhouse gases alone cross-sectional model.

A2 SRES scenario								
Climate sensitivity (°C)	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean	Total
1.5	40.8	17.9	94.2	44.8	17.1	5.8	6.5	227.0
2.5	37.1	15.5	111.5	−9.8	−0.5	−23.3	4.7	136.2
4.5	25.2	5.6	129.6	−110.1	−32.5	−73.9	1.1	−54.9
Climate sensitivity 2.5°C								
SRES scenario	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean	Total
B1	27.2	13.4	76.1	3.6	3.1	−10.1	3.5	116.9
B2	26.2	12.1	72.8	3.8	2.8	−10.1	3.4	110.9
A1	46.5	22.8	128.1	14.4	8.7	−12.1	6.4	214.9
A2	37.1	15.5	111.5	−9.8	−0.5	−23.2	4.7	136.2

The welfare effects are in billions of 1990 USD per year. Positive numbers imply benefits and negative numbers imply damages.

Table 6
Market impacts in 2100 due to sulfate aerosols alone experimental model.

A2 SRES scenario								
Climate sensitivity (°C)	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean	Total
1.5	−2.0	−0.1	4.9	0.5	5.1	2.5	0.1	10.9
2.5	−3.4	−0.7	3.9	10.9	10.1	4.4	0.5	25.7
4.5	−3.7	−1.2	0.1	44.7	20.2	5.6	1.7	67.4
Climate sensitivity 2.5°C								
SRES scenario	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean	Total
B1	−6.7	−0.2	21.7	−52.6	−2.1	−7.7	−0.3	−47.4
B2	−5.2	−0.1	11.3	−12.1	4.8	0.0	−0.1	−1.5
A1	−9.1	−0.8	23.0	−69.9	−2.9	−11.6	−0.4	−71.7
A2	−3.4	−0.7	3.9	10.9	10.1	4.4	0.5	25.7

The welfare effects are in billions of 1990 USD per year. Positive numbers imply benefits and negative numbers imply damages.

show that the sulfates in the four SRES marker scenarios have relatively small climate impacts compared to the greenhouse gases. The sulfate effects range from a loss of $72 billion to a gain of $67 billion per year, depending on whether emissions fall or rise in developing countries. In comparison, the effect of the greenhouse gases, using the experimental model, leads to damages of $200–1200 billion. The sulfate impact is roughly an order of magnitude smaller than the greenhouse-gas effects. The relative size of impacts is roughly proportional to the relative change in radiative forcing.

The impact of sulfates using the experimental results for the A1 and A2 scenarios with a 2.5°C climate sensitivity is shown in figure 3. The sulfate effect results in warming in temperate and polar locations. This leads to benefits in the former-Soviet region, northern Europe, and Canada. The mid latitude countries suffer small losses as SO_2 emissions are reduced in the temperate region. Effects in more tropical

Table 7
Impacts in 2100 due to sulfate aerosols alone cross-sectional model.

A2 SRES scenario								
Climate sensitivity (°C)	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean	Total
1.5	−0.5	−0.3	2.4	1.1	0.8	0.8	0.0	4.9
2.5	−1.1	−0.2	2.3	3.9	1.9	2.1	0.1	9.2
4.5	−1.2	−0.6	1.0	13.7	4.8	6.0	0.5	24.1
Climate sensitivity 2.5°C								
SRES scenario	N.A.	W.E.	Sov	Asia	LA	Afr	Ocean	Total
B1	−1.6	0.2	10.0	−10.3	−1.0	−1.9	−0.1	3.9
B2	−1.3	−0.4	5.4	−1.7	0.6	0.1	0.0	3.5
A1	−2.4	−0.4	11.2	−14.1	−1.5	−3.0	−0.1	−9.6
A2	−1.1	−0.2	2.3	3.9	1.9	2.1	0.1	9.2

The welfare effects are in billions of 1990 USD per year. Positive numbers imply benefits and negative numbers imply damages.

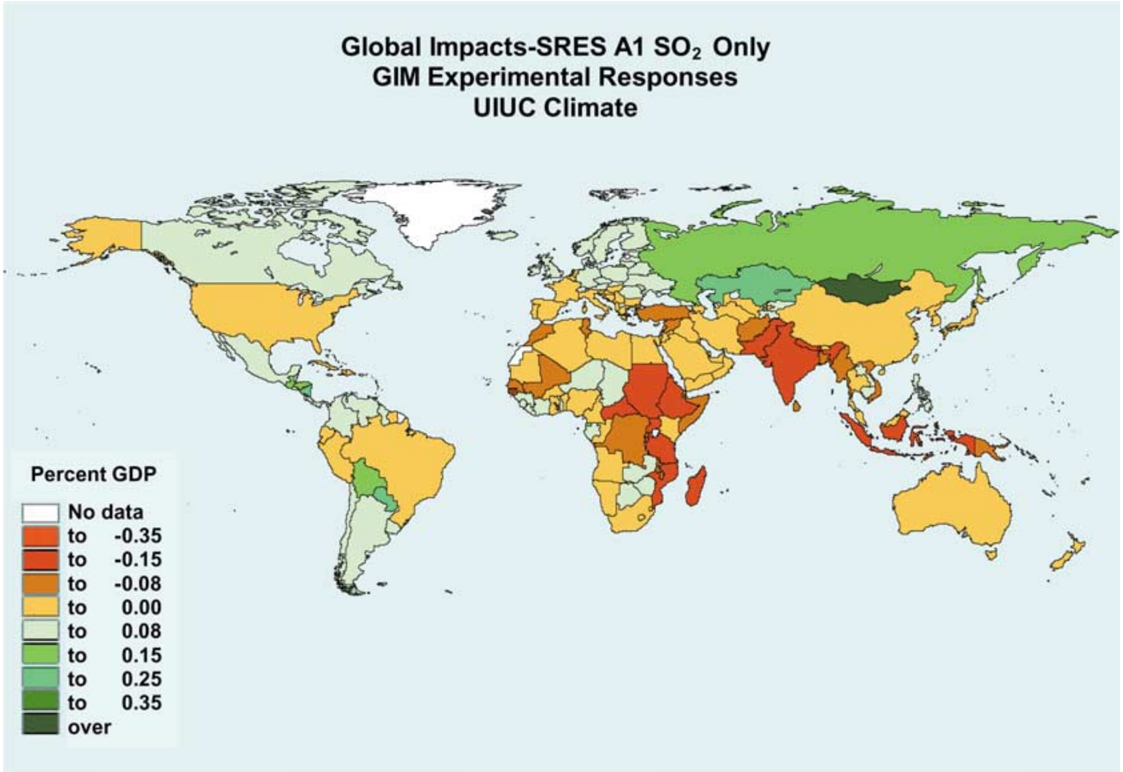
regions depend upon whether the scenario predicts SO_2 to increase (benefit) or fall (damage). The A1 scenario leads to large damages in low-latitude countries because SO_2 falls in these countries as well as everywhere else. This leads to warming in the low latitudes and increased damages. The A2 scenario leads to large gains in the low latitude countries because of predicted increases in SO_2 emissions leading to regional cooling. There are large cooling benefits predicted in Asia, Latin America, and Africa from these increased SO_2 emissions.

The results for the cross-sectional model (table 7) are milder, with no effect exceeding $24 billion per year. The country-specific outcomes for the A1 and A2 scenarios with a 2.5°C climate sensitivity are shown in figure 4. Only the A1 scenario is harmful, as the damages in the rest of the world exceed the benefits in the former-Soviet region. The A2 scenario is slightly beneficial, with small damages in North America and Europe being offset by gains in all the other regions. The B1 and B2 scenarios have little net effect, as the benefits in the former-Soviet region largely offset the damages elsewhere.

4. Conclusion

This study begins with a set of 4 emission scenarios generated by SRES. The UIUC simple climate/ocean model uses each of these scenarios together with geographical distributions from the UIUC atmospheric-general-circulation/mixed-layer-ocean model to generate a set of country-specific climate scenarios. Three different climate sensitivities are examined for each SRES scenario, leading to 12 climate scenarios. An impact model is then used to evaluate the 12 climate scenarios. The impact model involves two distinct climate-response functions, leading to 24 total impact outcomes.

The different SRES scenarios predict varying levels of carbon dioxide, from low levels into the range previously considered by the IPCC. All the SRES scenarios predict



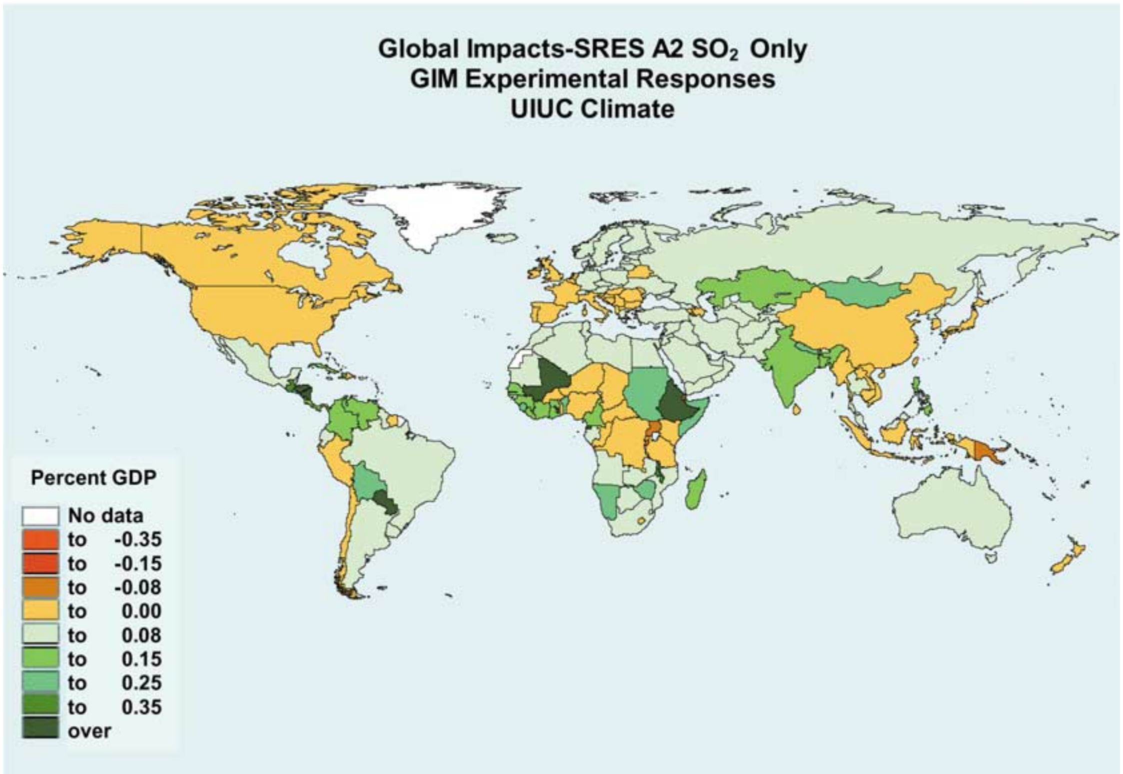


Figure 3. Global impacts calculated using experimental climate response functions. The climate in the upper map is consistent with SRES scenario A1 *SO_2 emissions only*, using methods described in the text. The lower map shows impacts resulting from *SO_2 emissions only* in SRES scenario A2.

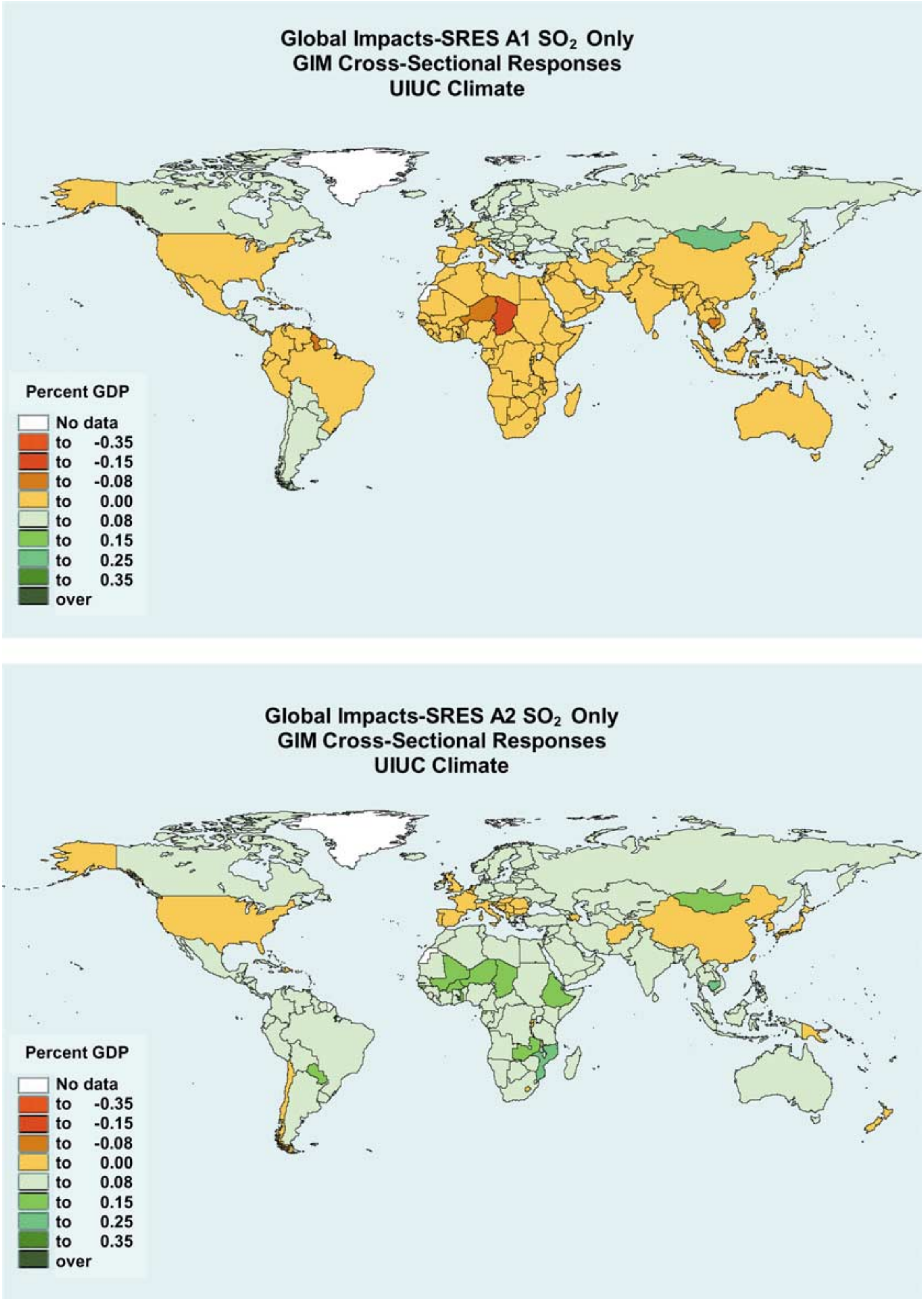


Figure 4. Global impacts calculated using cross-sectional climate response functions. The climate in the upper map is consistent with SRES scenario A1 *SO_2 emissions only*, using methods described in the text. The lower map shows impacts resulting from *SO_2 emissions only* in SRES scenario A2.

a sharp reduction in SO_2 emissions from current levels in every region except the developing countries of the world. Even for the developing countries, only the A2 and B2 scenarios predict that SO_2 emissions might increase over current levels. The SRES scenarios consequently provide a range of emission paths but they are not representative of the full range of alternative scenarios that are plausible.

Although not representative, the SRES scenarios do generate slightly different climate predictions, from mild to large warming. The higher climate sensitivities accentuate this range of effects so that, for example, the climate warming from greenhouse gases alone is 4.9°C for the A2 scenario with a 4.5°C climate sensitivity. The effect of sulfate aerosols on climate also varies. The A1, B1, and B2 scenarios predict general warming from reductions in SO_2 emissions. The A2 scenario predicts more warming in the developed and former-Soviet regions from regional SO_2 emission reductions, but cooling in the tropical regions from regional SO_2 emission increases. None of the SRES scenarios considers a large increase in SO_2 emissions as a result of economic growth and the potential future shift to coal as natural gas and oil run out. Thus, the SRES scenarios do not capture the possibility of an overall increase in SO_2 emissions. The climate forecasts due to just greenhouse-gas emissions lead to net damages according to the experimental model, with especially severe impacts in the tropical regions. Only the former-Soviet region benefits in all scenarios. More temperate areas benefit from modest warming, but these benefits fall as warming increases. The cross-sectional model predicts that modest warming is generally beneficial; although these benefits fall as global temperatures increase above 2°C. According to the cross-sectional model, only Africa is damaged at modest temperature increases.

The impact of sulfates varies across the scenarios. According to the experimental model, sulfates have a net harmful effect in the A1, B1, and B2 scenarios. The additional warming caused by SO_2 emission reductions increases damages everywhere except in the former Soviet Union region. Only the A2 scenario is beneficial, as the warming gains from emission reductions in the former-Soviet region and the cooling gains from emission increases in the tropical region dominate the damages from SO_2 emission reductions by the OECD. The cross-sectional model leads to weaker results, as the different regions in the B1 and B2 scenarios offset each other's effects. Only the A1 scenario leads to increasing damages and the A2 scenario to an increase in benefits.

Although we present 12 scenarios in this paper, the scenarios do not represent the full range of plausible alternatives. The four SRES scenarios may not be representative. The analysis relies on a single model of the carbon cycle and thus does not reflect the range of greenhouse-gas concentrations that each emission path might plausibly cause. The present analysis relies on a single general circulation model and thus does not capture the wide range of climate predictions that a broad set of climate models would likely predict. Finally, the climate-response functions are all calibrated to the United States and use only two possible calibrations. It is likely that relying on the US climate-response functions has underestimated impacts in low-latitude countries. Preliminary evidence suggests that climate-impact sensitivity is higher for less developed countries [10]. It is important that future studies incorporate climate-response functions calibrated to each region, especially the developing countries.

Nonetheless, the paper does illustrate the importance of alternative SO_2 emission predictions. If SO_2 emissions are reduced throughout the world, the Earth will likely warm slightly, exacerbating the harmful effects of global warming in all regions except the high latitudes. If SO_2 emissions increase, especially in tropical developing countries, the resulting sulfate aerosols will likely lead to small benefits through cooling. In contrast, in the high latitudes, such as the former-Soviet region, the cooling from increasing SO_2 emissions is likely to be harmful.

In addition to clarifying how sulfates are likely to affect each region, the study also measures the size of these likely effects. The study indicates that sulfate effects are likely to be small relative to the effects of greenhouse gases. The sulfate effects are generally about one order of magnitude smaller than the effects of greenhouse gases alone. The relative impacts of sulfates to greenhouse gases thus seem approximately proportional to the relative change in the predicted radiative forcing.

Finally, readers should recognize that the estimates in the paper are highly uncertain and not representative of the range of plausible outcomes. Thus we recommend that people focus more on the qualitative results than the precise quantitative outcomes.

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