COUNTRY-SPECIFIC MARKET IMPACTS OF CLIMATE CHANGE

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Abstract. We develop a new climate-impact model, the Global Impact Model (GIM), which combines future scenarios, detailed spatial simulations by general circulation models (GCMs), sectoral features, climate-response functions, and adaptation to generate country-specific impacts by market sector. Estimates are made for three future scenarios, two GCMs, and two climate-response functions – a reduced-form model and a cross-sectional model. Combining empirically based response functions, sectoral data by country, and careful climate forecasts gives analysts a more powerful tool for estimating market impacts. GIM predicts that country specific results vary, implying that research in this area is likely to be policy-relevant.

1. Introduction

The most recent IPCC reports (Bruce et al., 1996) highlight the state of the art of estimating the net damages from global warming. Although there is a vast amount of information about the direct effects of warming on a host of resources (Watson et al., 1996), only a handful of studies have linked these direct effects to damages. The IPCC report relies heavily on expert opinion (Nordhaus, 1991; Cline, 1992; Titus, 1992; Tol, 1995; Fankhauser, 1995) to make this leap. These authors estimate that a doubling of greenhouse gases would cause total damages in the U.S. ranging from 1.0% to 2.5% of the U.S. Gross Domestic Product (GDP), with 0.3% to 1.3% of the damages coming from market impacts (Bruce et al., 1996). Extrapolation of these results to other countries using physical-impact measures – for example, miles of vulnerable coast line, Holdridge Life Zones, area of wetlands – and judgment suggests total losses in non-OECD countries of 1.6–2.7% of their GDP (Fankhauser, 1995; Tol, 1995).

Integrated assessment (IA) models have taken two approaches to calculating climate impacts: ‘Top-down’ and ‘Bottom-up’. ‘Top-down’ models rely on aggregate damage functions, the simplest of which calculate global damages as a function of only global-mean temperature change (e.g., Nordhaus, 1991; Hope et al., 1993). More recent regional models have constructed damage functions based

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on regional temperatures, but these too remain at an aggregate level (Manne et al., 1993; Nordhaus, 1994). Thus, IA models using the ‘Top-down’ approach lack spatial and structural detail. Further, the ‘Top-down’ models have largely been constructed on expert judgement; there is little empirical foundation for the response functions used in current models. ‘Bottom-up’ IA models have sought to capture the individual direct effects of climate change across the landscape (e.g., Alcamo, 1994). Although these models have done a good job of capturing spatial and sectoral detail, they often contain so much information that they are difficult to interpret. Further, they often lack sound damage estimates because they do not seek to estimate welfare effects and because they fail to account for adaptation. Despite the overwhelming detail included in ‘Bottom-up’ models, they too are far from providing clear and careful damage estimates.

In this study we make use of the strengths of both the ‘Top-down’ and ‘Bottom-up’ approaches. Following the spirit of the ‘Top-down’ approach, we base our model on economic theory and attempt to calculate the economic welfare associated with climate change. However, in the spirit of ‘Bottom-up’ models, we add important spatial detail to the model so that it more accurately captures climate forecasts and differentiates impacts by country. In this effort, we base our climate-response functions on detailed empirical studies, rather than expert opinion. We take special care to include human adaptation as part of the response to warming to avoid the ‘dumb farmer’ syndrome.

We construct a Global Impacts Model (GIM) that combines (1) future world scenarios, (2) geographically detailed climate simulations from a general circulation model (GCM), (3) sectoral data for different countries, and (4) climate-response functions by market sector. GIM estimates climate impacts for 178 countries around the world. Because future world scenarios, climate forecasts, and climate-response functions remain uncertain, we explore alternative models for each of these critical elements. Because impact studies have been completed only for market sectors, the model is currently limited to evaluating market impacts. Important nonmarket impacts, such as health, ecosystem change, and aesthetics have not yet been incorporated into the model. GIM is not a final impact model of the world, but rather an important step towards that goal.

2. Methodology

In this section we describe the future world scenarios used and the three components of GIM: the climate model, the sectoral data, and the climate-response functions. The future world scenarios were taken from Houghton et al. (1994, 1996) and describe the low, middle, and high scenarios used by the IPCC. The scenarios include emission trajectories for carbon dioxide, methane, nitrous oxide and chlorofluorocarbons, and predicted temperature and sea-level changes by 2100. Assuming that the emission scenarios varied largely because of the size of the world economy, we also calculate alternative economic growth rates for each scenario. The low emission scenario (IS92c) is associated with an 0.8% annual economic growth rate, and in 2100, a CO_2 concentration of 500 ppmv, a 1 °C increase in global temperature, and a 14 cm increase in sea level. The middle scenario (IS92a) is associated with a 1.9% annual economic growth rate, and in 2100, a CO_2 concentration of 700 ppmv, a 2 °C increase in global temperature, and a 50 cm increase in sea level. Finally, the high scenario (IS92e) is associated with a 2.6% annual economic growth rate, and in 2100, a CO_2 concentration of 950 ppmv, a 3.5 °C increase in global temperature, and a 95 cm increase in sea level.

These scenarios do not bracket all possible future outcomes over the next century. First, the IPCC scenarios link temperature scenarios and economic development so that high development rates, high emission trajectories, high concentrations, and high temperatures are all correlated. Second, alternative GCMs predict a wide range of distributions of temperature and precipitation across the planet. This is only partially captured by the two GCMs in this paper. Third, there is considerable uncertainty concerning the dynamics of climate change because of questions concerning the carbon cycle, atmospheric feedbacks and ocean responses. The scenarios do not capture the full range of uncertainty but merely illustrate a wide and internally consistent range of forecasts.

For each country, the productivity of each sector is measured given current climate and carbon dioxide levels. This yields a country-specific baseline for each sector. Using the climate forecast and climate response functions, a new estimate is then generated for each sector. By comparing the new forecast with the baseline, one can calculate the impacts of climate change. If productivity increases, the impact is beneficial and if it declines, the impact is harmful. Note that if conditions do not change, there is no impact.

2.1. CLIMATE

GIM obtains predictions of the change in annual surface-air temperature and precipitation using the geographical distributions simulated by two versions of the University of Illinois at Urbana-Champaign (UIUC) atmospheric general circulation/mixed-layer-ocean model. One model has two layers between the earth's surface and 200 mb (UIUC2) (Schlesinger and Verbitsky, 1996), and the other model has 11 layers between the earth's surface and 50 mb (UIUC11) (Schlesinger et al., 1997a). Both models have a horizontal resolution of 4° latitude × 5° longitude. For UIUC2, GIM used results from three simulations: control (326 ppmv, $1 \times CO_2$), doubled ($2 \times CO_2$) and quadrupled ($4 \times CO_2$) CO_2 concentrations. The distributions of surface-air temperature and precipitation changes for CO_2 doubling ($2 \times CO_2 - 1 \times CO_2$) and quadrupling ($4 \times CO_2 - 1 \times CO_2$) were divided by their respective simulated annual global-mean surface-air temperature changes and the resulting normalized distributions averaged to yield normalized values for each GCM grid cell (Schlesinger and Andronova, 1995). For UIUC11, GIM used results from two simulations: control (345 ppmv, $1 \times CO_2$) and doubled ($2 \times CO_2$) CO_2 concentrations. The distributions of surface-air temperature and precipitation changes for the CO_2 doubling ($2 \times CO_2 - 1 \times CO_2$) were divided by the simulated annual global-mean surface-air temperature change to yield normalized values for each GCM grid cell (Schlesinger et al., 1997b). These normalizations of the geographical distributions render them independent of the GCMs' climate sensitivities measured, for example, by their global-mean surface-air temperature change for a CO_2 doubling. For both UIUC2 and UIUC11, country-specific normalized surface-air temperature and precipitation changes were calculated by averaging grid-cell values within national borders. Climate changes above 65° latitude were omitted in estimating national averages because economic activities there are limited.

GIM multiplies the country-specific normalized surface-air temperature and precipitation changes for both UIUC2 and UIUC11 by any given annual global-mean surface-air temperature change to determine the corresponding country-specific changes in annual surface-air temperature and precipitation. Country-specific present-day surface-air temperature and precipitation were obtained by averaging observed surface-air temperature and precipitation across the $4° \times 5°$ latitude-longitude grid cells within national borders (Schlesinger and Andronova, 1995). Country-specific future surface-air temperature and precipitation levels were calculated by summing observed current values with the predicted changes. For small countries, this process of interpolating between grid points provides an accurate depiction of the GCM forecast, since neighboring points are often quite similar. The interpolation, however, is imperfect for large countries because the countries span more than one grid cell. Unfortunately, economic data is most readily available at the country level, forcing GIM to make country-level climate forecasts. Future research could explore the importance of estimating climate changes within countries and connecting these estimates with more micro-economic data.

2.2. SECTORAL DATA

GIM incorporates country-specific information including GDP, average land value, population, cropland, forestland and coastline. The size of each economic sector is measured for each country. We project growth in each sector so that we can measure future sensitivity. For example, given the historic reduction of agriculture as a fraction of GDP, we project that future agriculture sectors will grow more slowly than GDP as a whole. GDP projections suggest that developing countries will grow more rapidly than OECD countries (Houghton et al., 1994). Projecting sectors forward has a large effect on the magnitude of impacts. Although overall impacts appear to remain at the same percent of GDP, the projections predict much larger effects in the future as the world economy grows.

2.3. RESPONSE FUNCTIONS

The response functions to climate change in GIM are based on empirical studies that have been carefully designed to include adaptation by firms and people to climate change. Separate response functions are estimated for agriculture, forestry, coastal resources, commercial and residential energy, and water. We use two alternative response functions for most sectors to demonstrate the sensitivity of our results to the type of response function used. The origins of these response functions are carefully developed in Mendelsohn and Schlesinger (1999).

The first set of response functions is based on a collection of sectoral studies for the United States completed by a team of leading impact experts (Mendelsohn and Neumann, 1998). These studies rely on careful scientific models of each sector as the starting point of the analysis. For example, the farm model relies on a detailed set of agronomic models, the forestry model relies on biogeochemical and biogeographical quantitative ecological models, and the coastal model relies on a detailed sea-level-rise model. These scientific models are combined with economic models to build consistent, comprehensive estimates of damages in each sector. Using the net results from each sector, we have constructed a reduced-form model that links climate scenarios and welfare impacts for each sector to temperature and precipitation (Table I). Note that the reduced-form model is an empirical measurement similar to the detailed modeling approach of the ‘Bottom-up’ models.

We also use a set of cross-sectional comparisons, ‘Ricardian’ studies, to reveal how agriculture, forestry, and energy respond to being in different climates. Note that the sea-level and water results relied entirely on the reduced-form approach because we did not have an alternative cross-sectional method for these sectors. The agricultural Ricardian model (Mendelsohn et al., 1994) measures how long-term farm profitability varies with local climate, controlling for other factors. The forestry model is based on a similar cross-sectional analysis of the effect of climate on the present value of timber grown in the United States (Mendelsohn and Sohngen, 1996). The energy study relies on an analysis of energy expenditures in the commercial and residential sectors (Morrison and Mendelsohn, 1998) across the United States.

We rely on these two approaches because they represent the two leading methods of measuring climate sensitivity and because they each have different strengths and weaknesses. The reduced-form model depends on careful laboratory experiments and process-based models to capture how sensitive crops, trees, and activities will respond. The cross-sectional models compare how each sector behaves in different climates. Because of the carefully controlled nature of laboratory experiments, the reduced-form model can carefully isolate climate from other influences across the landscape. This strength of the reduced-form model is a weakness of the cross-sectional approach that could confuse unmeasured influences with climate. The strength of the cross-sectional approach is that it carefully includes adaptation since it captures how people have adapted to where they live. This is a

TABLE I

Reduced-form climate-response functions (billions of 1990 U.S. $/year)

Agriculture

$$W_a = 2.16L_a * g * \{-302 + 44.07T - 1.89T^2 + 22.63P + 36.5Ln(CO_2/350)\}$$

Forestry

$$W_f = 2.0L_f * g * \{15.7 + 0.82T + 2.52P + 6.8Ln(CO_2/350)\} * \{1 - \exp(-0.0057t)\}$$

Coastal resource

$$W_c = -\exp(1.92 + 2.9M + 0.17t) * \text{Coast/Coast}_{\text{U.S.}} * V/V_{\text{U.S.}}$$

Energy

$$W_e = h * (251,000 + 7380T - 368T^2)$$

Water

$$W_w = g * (134,000 - 4124T + 67.4T^2 + 4941P) * (\text{AGRGDP}/\text{AGRGDP}_{\text{U.S.}})$$

From Mendelsohn and Schlesinger (1999). T is annual temperature (°C), P is annual precipitation (cm/mo), M is sea-level rise by 2100 (meters), CO_2 is carbon dioxide concentrations (ppmv), t is time in years since 1990, h is percentage GDP growth, g is percentage growth of agricultural GDP (AGRGDP), V is average value of land, Coast is kilometers of coastline, and L_a and L_f are land areas (km^2) in agriculture and forestry, respectively.

weakness of the reduced form approach that includes adaptation only to the extent that the modeler explicitly includes it. By using both approaches, one spans our current understanding of climate response.

Both the reduced-form and cross-sectional response functions imply that the net productivity of sensitive economic sectors is a hill-shaped function of temperature (Mendelsohn and Schlesinger, 1999). Warming creates benefits for countries that are currently on the cool side of the hill and damages for countries on the warm side of the hill. The exact optimum temperature varies by sector. For example, according to the Ricardian model, the optimum temperatures for agriculture, forestry, and energy are 14.2, 14.8 and 8.6 °C, respectively. With the reduced form model, the optimum temperatures for agriculture and energy are 11.7 and 10.0. Forestry benefits increase linearly with temperature. Precipitation has a linear and beneficial impact in the reduced-form models in both the agriculture and forestry Ricardian studies. The Ricardian agricultural model measures a quadratic effect with respect to precipitation with an optimum of 10.8 cm/mo.

These hill-shaped response functions are consistent with what we know about global economic productivity. The most profitable sites for most climate-sensitive activities lie in the temperate or subtropical zones, depending on the sector. Both equatorial and polar sites tend to be less productive. Increases in carbon dioxide create benefits because crops and trees are expected to grow faster from carbon

TABLE II

Ricardian climate-response functions (billions of 1990 U.S.$ per year)

Agriculture
$W_a = L_a * r * g * \{-468.1 + 223.2T - 7.87T^2 + 5.63P - 0.26P^2 + 687Ln(\mathrm{CO_2}/350)\}$
Forestry
$W_f = L_f * r * g * \{-177.0 + 29.1T - 0.98T^2 + 6.73P + 57.3Ln(\mathrm{CO_2}/350)\}$
Energy
$W_e = \mathrm{GDP} * \{0.0023 \exp(0.388 - 0.0599T + 0.0023T^2) + 0.0132 \exp(0.0648 - 0.0152T + 0.00097T^2)\}$

From Mendelsohn and Schlesinger (1999). T is annual temperature (°C), P is annual precipitation (cm/mo), CO_2 is carbon dioxide concentrations (ppmv), r is the real interest rate, GDP is gross domestic product, g is the percentage growth in agricultural GDP, and L_a and L_f are land areas (km^2) in agriculture and forestry.

fertilization. These results come largely from laboratory experiments that show a consistent productivity effect.

Some sectors of the economy are well known to adapt quickly. Agriculture, for instance, tends to respond to new crop programs with great speed. For these sectors, it is reasonable to model climate response strictly in terms of current climate. Other sectors, such as forestry and coastal structures, have large capital stocks that cannot adjust readily. The path of climate change is very important to these capital-intense sectors. The more rapid the change, the bigger the impact. Consequently, the climate response functions in GIM for these two sectors depend upon time as well as the level of climate change. Time and level, in this case, capture the speed of climate change.

The response functions are all calibrated to the United States. Unfortunately, there are very few empirical climate response functions calibrated anywhere else in the world. To extrapolate from the U.S. to other countries, we assume that: (1) agricultural and forestry responses are proportional to cropland and forestland, respectively; (2) coastal damages from sea-level rise are proportional to the amount of coastline and the average value of land, the latter approximated using GDP divided by area; (3) energy impacts are proportional to GDP; and (4) water impacts are proportional to agricultural GDP. These are admittedly strong assumptions. While such extrapolations are not unreasonable for developed countries such as those of the OECD, they are crude approximations for developing countries. Accordingly, more systematic country-specific impact studies from around the world are needed to make more careful global estimates. Nevertheless, extrapolating from U.S. studies is the state-of-the-art of global impact studies. All global climate-change estimates to date have been based largely on old U.S. studies. In order to move beyond this state of affairs, the literature needs to make a number of improvements. This paper makes a few of these needed steps by emphasizing the need to use detailed GCM forecasts, building sectoral models by country, including climate response functions, and including adaptation. However, we do not present GIM as a complete global impact model. A complete model is a challenge that will take many years to complete. Accordingly, the results below should be viewed as being preliminary and subject to revision when response functions from countries other than the U.S. become available.

3. Results

GIM can evaluate any time trajectory of global temperature and carbon dioxide levels, it can be adapted to alternative GCM projections, and it can run with alternative climate-response functions. In this paper we illustrate the model by exploring the annual impacts that would occur in 2100 under 12 alternative scenarios. Although GIM is capable of measuring impacts in any year, we focus on 2100 to illustrate how the model behaves. For a careful policy analysis, however, one would need to measure an optimal control path including interim years as well as effects beyond 2100. A complete optimal control model, however, is beyond the scope of this paper.

We examine three forecasts of future world conditions using the low, middle and high scenarios presented by the IPCC (Houghton et al., 1996). For each scenario we apply two GCM projections of world climate, UIUC2 and UIUC11, and two empirically based climate-response functions, a reduced-form model and a Ricardian model (Mendelsohn and Schlesinger, 1999). GIM calculates climate impacts on countries as we project them to appear in the future. This introduces another source of uncertainty because it is difficult to predict economic conditions in a century for each sector and each country. However, climate change will take many decades to unfold and so impacts must be evaluated in terms of future conditions. To keep impacts in perspective, it is important to recognize that, according to the middle scenario, the world economy is predicted to increase from $21 trillion today to $172 trillion by 2100 (all financial estimates are in 1990 U.S.$). The world economy is projected to increase to $51 trillion in 2100 with the low-emission scenario, and to $372 trillion with the high-emission scenario.

Table III presents the aggregate global market results in billions of 1990 U.S.$ for all 12 scenarios. The aggregate impacts are projected to be beneficial in every scenario relative to current climate and carbon dioxide levels. However, benefits do not simply climb with higher temperature scenarios. With the Ricardian model, benefits climb for the first 2 °C of warming and then they decline. That is, warming beyond 2 °C is harmful according to that model. With the reduced-form model, warming benefits climb through 1 °C and then just begin to decline at 2 °C. Warming begins to be harmful between 1 and 2 °C. The overall magnitude of the market impacts is relatively small in all cases, being less than 0.16% of world GDP. Thus, these initial results imply that global warming over the next century is not a serious threat to the world economy, and is likely to be a small benefit. One must be

TABLE III

Global market impacts (billions of 1990 U.S.$) across all scenarios by 2100

Climate model	Response model	Climate change scenarios		
		Low (1 °C)	Mid (2 °C)	High (3.5 °C)
UIUC2	Ricardian	73	266	472
		(0.14)	(0.15)	).13)
UIUC2	Reduced-form	52	166	99
		(0.10)	(0.10)	(0.03)
UIUC11	Ricardian	84	275	458
		(0.16)	(0.16)	(0.12)
UIUC11	Reduced-form	56	149	60
		(0.11)	0.09)	(0.02)

All the aggregate values in these simulations are positive or beneficial. Values in parentheses are impacts as a percent of GDP. Water and coastal effects are the same in the Ricardian and reduced-form aggregate estimates. GDP is 51, 172, and 372 trillion $ in the low, mid, and high scenarios.

careful interpreting across these alternative scenarios because they entail different temperature, precipitation, carbon dioxide, and economic growth assumptions. The reduced-form model is more temperature-sensitive than the Ricardian model so that benefits fall more rapidly with warmer temperatures.

The regional results are not uniform as can be seen in Table IV. According to the Ricardian model, the largest benefits as a fraction of GDP occur in Asia, the Former U.S.S.R. (Eastern bloc), and North America. According to the reduced-form model, the largest benefits occur in the Former U.S.S.R., North America, and Asia. Western Europe enjoys small gains with UIUC11 and small losses with UIUC2. Africa, Latin America, and Oceania enjoy small gains under the Ricardian model but suffer damages under the reduced-form model. The UIUC11 model produces bigger damages for low-latitude countries because it predicts greater warming around the equator.

In Tables V and VI we explore how the sectoral responses differ between the two climate-response functions. In both tables we rely on the middle world scenario of 2 °C warming and the climate forecast of the UIUC11 model. Table V displays the Ricardian results and Table VI presents the reduced-form results. Agriculture has the largest effects and explains most of the variation across countries. The benefits in the agricultural sector are between 110% and 120% of the overall net effects. If there were no agricultural impacts, the net damages in both Tables V and VI would be about $22 billion for the world. Given that the world economy is

TABLE IV

Regional market impacts (billions of 1990 U.S.$) for the 2 °C global-mean warming scenario

Region	Model			
	UIUC2		UIUC11	
	Ricardian	Reduced-form	Ricardian	Reduced-form
Africa	22	–56	0	–143
	(0.28)	(–0.71)	(0.00)	(–1.82)
Asia/Mideast	81	20	90	38
	(1.21)	(0.29)	(1.34)	(0.57)
Latin Am./Car.	31	9	12	–59
	(0.46)	(0.14)	(0.18)	(–0.88)
W. Europe	–7	–15	5	10
	(–0.07)	(–0.14)	(0.05)	(0.10)
F.U.S.S.R./E.E.	86	160	110	228
	(0.84)	(1.56)	(1.07)	(2.22)
North America	49	58	56	87
	(0.47)	(0.55)	(0.53)	(0.83)
Oceania	4	–10	2	–12
	(0.04)	(–0.10)	(0.02)	(–0.11)

Positive values represent benefits and negative values represent damages. Numbers in parentheses are impacts as a percent of GDP.

about $172 trillion in this scenario, all the other market sectors combined amount to a very small impact (0.01%).

With modest warming, the predicted agricultural benefits are concentrated in high-latitude countries. For 2 °C, Russia alone is projected to enjoy agricultural benefits of $124 to $351 billion, the U.S. is expected to benefit between $17 and $35 billion, Canada should enjoy benefits of between $19 and $49 billion, and China should benefit between $39 and $65 billion. The remaining benefits are spread across smaller temperate countries around the world. The warming alone is actually good for the colder countries and not very harmful for temperate ones. Carbon fertilization from the 700 ppmv concentration of CO_2 turns the small damages from warming in the temperate countries into small benefits and enhances the gains in the high-latitude countries. Even with carbon fertilization, low-latitude countries can suffer large damages from global warming. For example, Brazil, India, and Nigeria suffer agricultural losses of $106, $86 and $59 billion, respectively, with the UIUC11 climate model and reduced-form climate response model. These damages are closer to zero using the Ricardian model. The differences between these results illustrate how uncertain impacts are in low latitude countries.

TABLE V

Regional/sectoral market impacts (billions of 1990 U.S.$) from the Ricardian model for a 2 °C warming using UIUC11

Region	Sector					Total
	Agric.	Forest	Energy	Water	Coast	
Africa	11	–1	–3	–6	–0	0
Asia/Mid. East	80	3	–8	18	–4	90
Latin. Am./Car.	17	0	–5	–0	–0	4
W. Europe	17	1	–1	–9	–3	5
F.U.S.S.R./E.E.	117	17	9	–30	–3	110
North America	50	9	1	–3	–0	56
Oceania	4	0	–1	–1	–0	2
Total	297	30	–10	–32	–10	275

Results for the Water and Coast sectors are from the reduced-form model.

TABLE VI

Regional/sectoral market impacts (billions of 1990 U.S.$) from the reduced-form model for a 2 °C warming using UIUC11

Region	Sector					Total
	Agric.	Forest	Energy	Water	Coast	
Africa	–131	2	–7	–6	–0	–143
Asia/Mid. East	37	4	–17	18	–4	38
Latin. Am./Car.	–49	5	–14	–0	–0	–59
W. Europe	17	1	4	–9	–3	10
F.U.S.S.R./E.E.	222	6	32	–30	–3	228
North America	83	4	3	–3	–0	87
Oceania	–8	0	–3	–1	–0	–12
Total	171	22	–2	–32	–10	149

Damages from increased energy costs for heating and cooling also explain some of the differences among the scenarios. In the middle scenario, energy damages are projected to be between $2 and $10 billion globally. Damages are projected to be concentrated in the tropics where most of the world's population is projected to live and where cooling will be expensive. In the high scenario, damages in the energy sector expand to being between $51 and $89 billion. Water is also important. In the middle scenario, damages from reduced runoff in water systems due to higher evapotranspiration are projected to cost between $48 and $70 billion globally.

These damages are expected to be greatest in the Former U.S.S.R., Western Europe and Asia. Coastal damage from a 0.5 meter sea-level rise contributes another $10 billion of damages. Asia and Europe suffer most of the coastal damage because of the extensive and high-valued coastlines on these two continents. Forestry is projected to enjoy a gain of between $25 and $32 billion, with most of these gains occurring in the Former U.S.S.R. and the Western Hemisphere. This increase follows from predicted overall increases in forest productivity and expansions of more productive biomes (Prentice et al., 1992).

Given these regional results, it is no surprise that the impacts of global warming are not felt uniformly across countries. Figure 1 presents the impacts as a percent of GDP for 178 countries around the world according to the reduced-form model, and Figure 2 presents the corresponding picture according to the Ricardian model for the 2 °C scenario with the UIUC11 climate distribution. In Figure 1, countries that are currently cool enjoy the greatest benefits. The countries with the largest losses are either in Africa or they are islands. For a handful of these countries, damages lie between 2 to 5% of GDP. However, the impacts to most countries are less than 1% of GDP. In Figure 2, all countries are projected to benefit from warming. The difference between the two estimates comes largely from different agricultural projections, with the Ricardian estimates being more optimistic. Nonetheless, even in Figure 2, countries that are currently cool have the most to gain from warming, and countries that are currently hot benefit only slightly.

In this analysis, we apply response functions calibrated for the United States to the entire world. Although this has been the basis for all existing world damage estimates, this approach is unsatisfactory. However, to check how well this approach works, we compare the estimates generated by this method for agriculture against some new estimates made for India and Brazil. Recent Ricardian studies on agriculture in Brazil (Sanghi, 1998) and India (Sanghi et al., 1998; Kumar and Parikh, 1998) provide alternative estimates of agricultural impacts in these two countries. Without carbon fertilization, the Brazilian study suggests a 2 °C warming would cause percentage damages equal to 8% in Brazil, whereas the two Indian studies suggest damages of 9% and 12% in India. Without carbon fertilization, the U.S. Ricardian climate-response function predicted percentage losses of 16% for Brazil and 15% for India using this same scenario. In contrast, the American reduced-form model predicted losses of 53% in Brazil and 43% in India, which appear to be serious overestimates.

These results highlight the problem of using U.S. climate response functions for low latitude countries. They will be inaccurate. However, it is important to note that the results from the country studies are more modest than the U.S. projections. The comparison does not undermine the overall result of this analysis suggesting that mild warming will have only a modest impact on the global economy. Further, the comparison seems to support the other important result of this analysis that country specific effects will vary. The challenge facing impact research is to con-

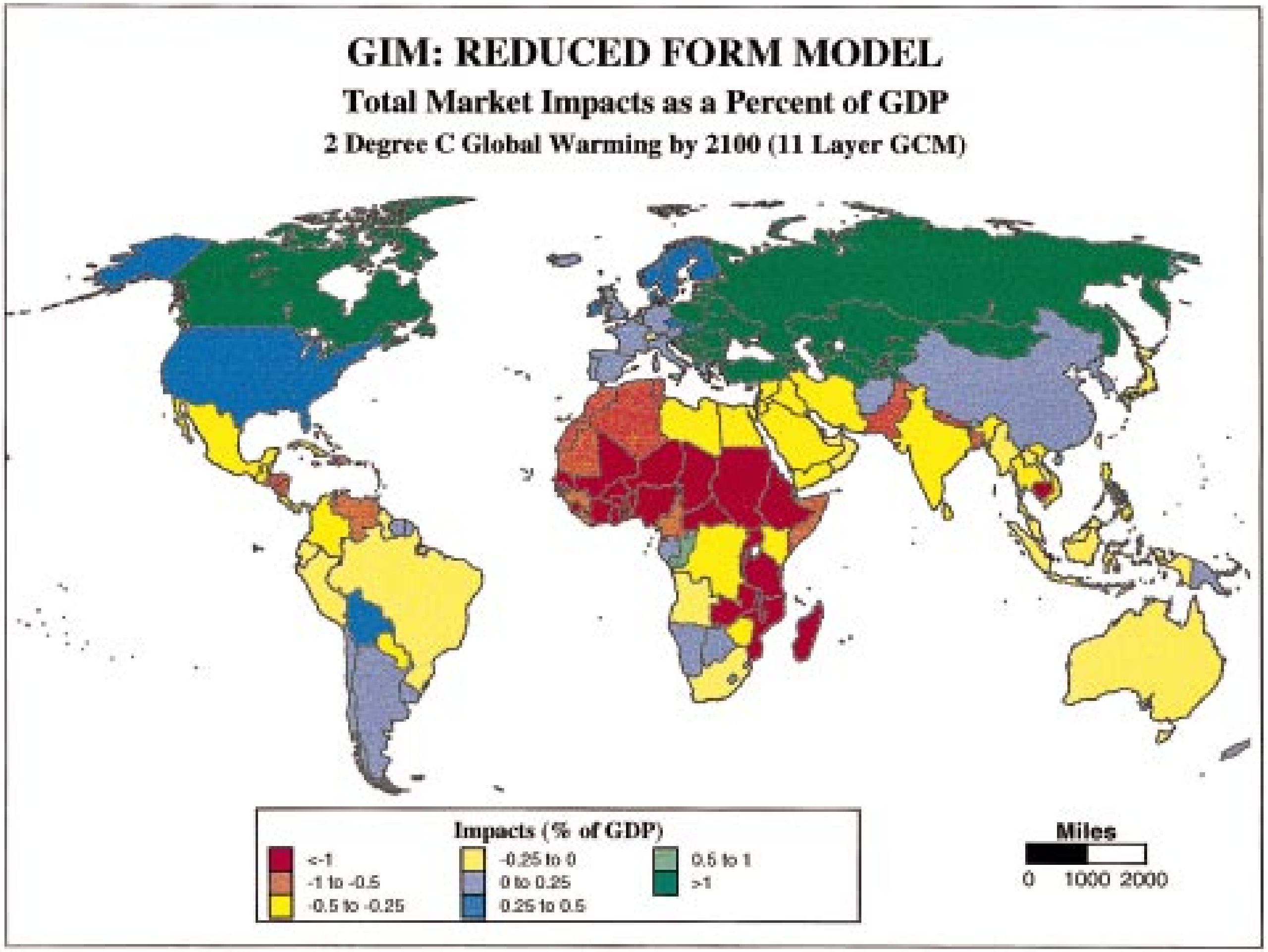

Figure 1. Market impacts as a percent of GDP for a 2 °C warming by 2100 using the reduced-form model.

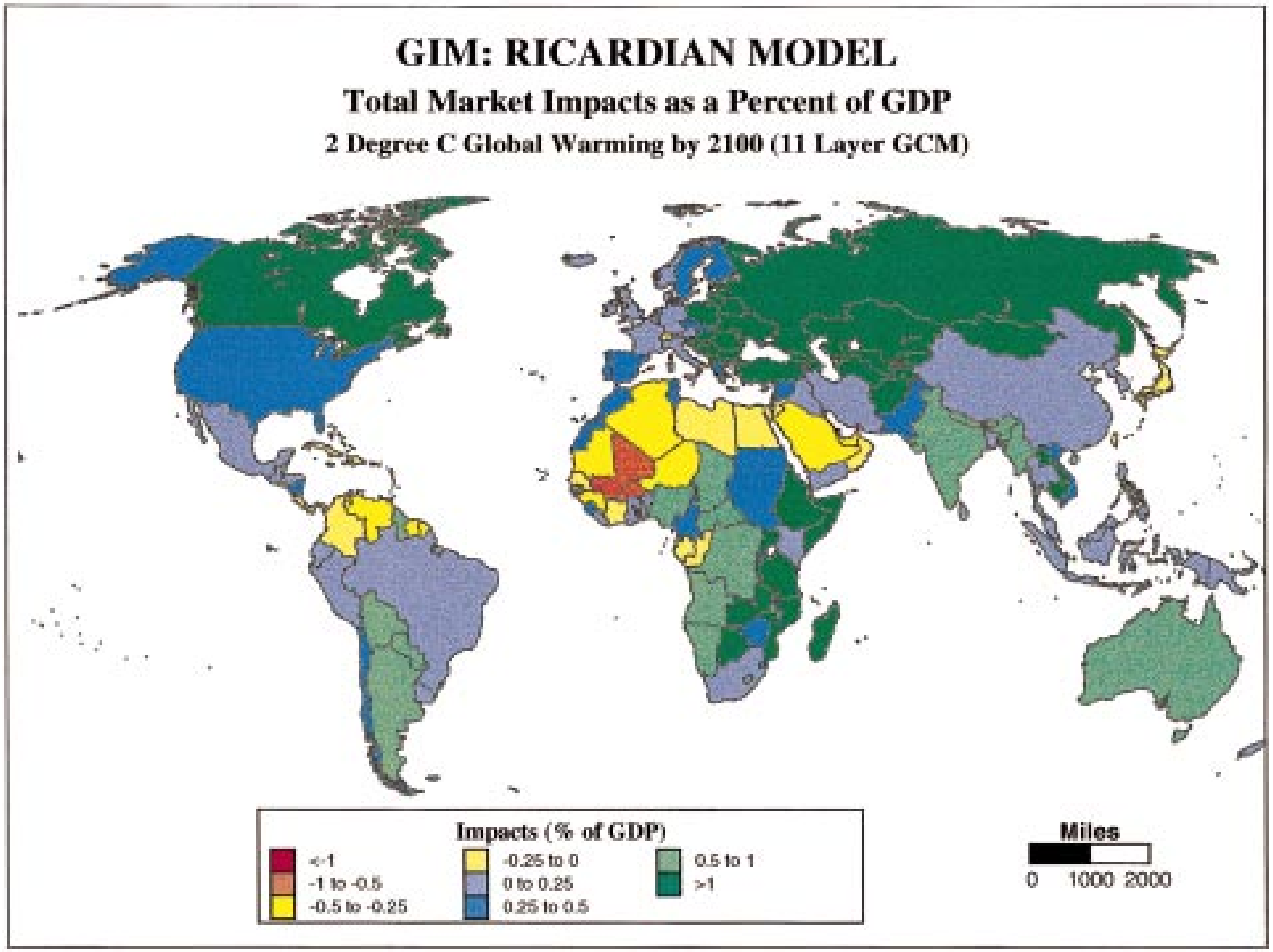

Figure 2. Market impacts as a percent of GDP for a 2 °C global warming by 2100 using the Ricardian model.

duct more climate response studies in low latitude countries so that we can obtain more accurate estimates in the future.

4. Conclusion

This study has several limitations including: (1) the response functions were calibrated only for the United States; (2) the non-climate information about each country is not as extensive as it should be; (3) non-market effects are not included; (4) the resolution of the GCM is coarse relative to the size of small countries and aggregated for large countries; (5) the transient response of the climate system is not considered; and (6) the simulated climate changes are due only to increased CO_2 and not to the partially compensating effects of anthropogenic sulfate aerosols. Nevertheless, the results of this study show that it is possible to integrate detailed climate modeling and empirical climate-response functions to generate country-specific impact estimates. The results suggest that the impacts of climate change on the global economy will likely be modest over the next century. Further, effects are not likely to be uniform from country to country. Country-specific results should be carefully considered by nations. As these results improve, hopefully they will help countries design programs to balance the costs of controlling greenhouse gases against the eventual benefits.

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