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The distributional impact of climate change on rich and poor countries

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ABSTRACT. This paper examines the impact of climate change on rich and poor countries across the world. We measure two indices of the relative impact of climate across countries, impact per capita, and impact per GDP. These measures sum market impacts across the climate-sensitive economic sectors of each country. Both indices reveal that climate change will have serious distributional impact across countries, grouped by income per capita. We predict that poor countries will suffer the bulk of the damages from climate change. Although adaptation, wealth, and technology may influence distributional consequences across countries, we argue that the primary reason that poor countries are so vulnerable is their location. Countries in the low latitudes start with very high temperatures. Further warming pushes these countries ever further away from optimal temperatures for climate-sensitive economic sectors.

1. Introduction

There is a broad consensus among climate scientists that further emissions of greenhouse gases will cause temperatures to increase 1.5°C to 5.8°C and precipitation patterns to shift by 2100 (Houghton *et al.*, 2001). These changes in temperature will in turn cause ecosystems to move poleward and seas to rise. All of these changes will have effects on the global economy and the quality of life around the globe. In this paper, we focus on the distributional impact of climate change on the economies of rich and poor countries. We provide empirical support for a hypothesis, first suggested by Schelling (1992), that the poor may bear the brunt of the economic damages from climate change.

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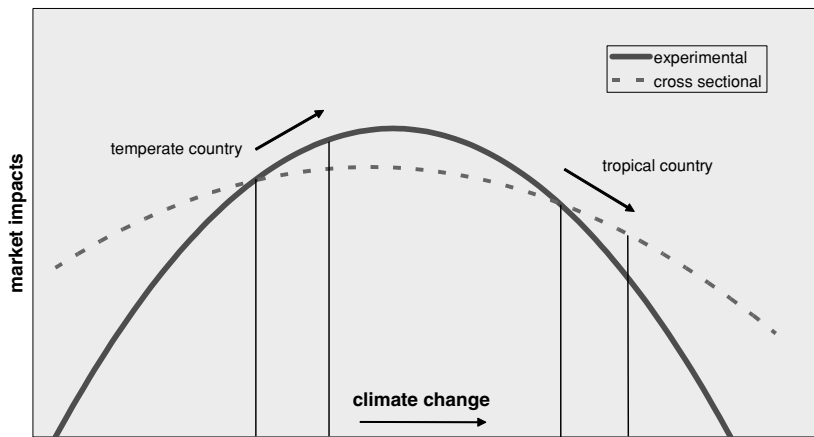


Figure 1. *Generic hill-shaped impact response function*

We want to make clear that this paper does not explain why some countries are poor and others are rich. The standard neoclassical economic growth framework asserts that growth depends primarily on basic economic inputs such as trained labor, capital, and technological development (Solow, 1956). These basic economic factors have been extended to incorporate government policies, the accumulation of human capital, fertility decisions, and the diffusion of technology (Barro, 1997; Bloom and Sachs, 1999; Easterly and Devine, 1998; Barro and Sala-i-Martin, 2004). Our paper has nothing to add to this important debate on growth.

The purpose of this paper is to examine whether there are important distributional consequences of climate change impacts. The early literature on greenhouse gases did not raise serious concerns about the distributional impact of climate change (Nordhaus, 1991; Tol, 1995; Fankhauser, 1995; Pearce *et al.*, 1996). This early literature largely assumed that damages were a linear or quadratic function of the change in temperature. As a result, the early models predicted that every country would suffer damages from warming and that they would be roughly proportional to income. Developing countries were predicted to be slightly more vulnerable because so much of their economies were in climate-sensitive sectors such as agriculture and because low technology operations are expected to have less substitution (Fankhauser, 1995; Tol, 1995). The literature at this time, however, assumed that almost every region would be damaged by warming (Pearce *et al.*, 1996). Further, this sentiment extended to other chapters in the Second Assessment Report of the IPCC where cross-country equity and compensation to low-income countries was overlooked (Arrow *et al.*, 1996; Jepma *et al.*, 1996).

Subsequent empirical research on climate impact sensitivity has revealed new insights into how temperature affects climate-sensitive economic sectors (Mendelsohn and Neumann, 1999; McCarthy *et al.*, 2001; Mendelsohn, 2001; Tol, 2002). The new research indicates that several climate-sensitive sectors have a hill-shaped relationship with absolute temperature. Figure 1 illustrates this relationship in general. For each sector,

there is an optimum temperature that maximizes welfare in that sector. For farmers in regions that are cooler than the optimum temperature, warming would cause net revenues to go up. For farmers in regions that are warmer than the optimum temperature, warming would cause net revenues to fall. These results imply that countries that happen to be in relatively cool regions of the world will likely benefit from warming and that countries that happen to be in relatively warm regions of the world will likely be harmed by warming.

We quantify the market impacts of climate change on every country in the world by combining a range of future climate scenarios with a range of climate response functions and background information from each country. The next section describes the country-specific climate forecasts from the three Atmospheric Ocean General Circulation Models (AOGCM's) used in the paper (Houghton *et al.*, 2001). Section 3 discusses the two sets of climate response functions used to evaluate the climate forecasts (Mendelsohn and Schlesinger, 1999). One set of response functions has a high and the other set a low climate sensitivity. Within each set, there is a separate response function for each of the five major economic sectors that are expected to be affected by climate: agriculture, water, energy, timber, and coasts¹ (Smith and Tirpak, 1990; Pearce *et al.*, 1996; Mendelsohn and Neumann, 1999; McCarthy *et al.*, 2001). Using country-specific background information on such variables as cropland, coastland, population, and GDP, we use previously calibrated response functions (Mendelsohn and Schlesinger, 1999) to develop quantitative forecasts of the impacts in each sector for each country for each climate scenario (Mendelsohn *et al.*, 2000a). We then sum these sectoral impacts to get an aggregate impact for each country. These country-level market impacts are then summed to get multi-country/regional aggregate outcomes.

Non-market impacts to health, the environment, and aesthetics are not included in the calculations. Although non-market effects will certainly add to expected damages, reliable estimates of the magnitude of the resulting welfare impacts do not yet exist. The reported market impacts thus underestimate the total impacts of warming. However, it is likely that the non-market impacts will not change the distributional consequences of warming. Health effects and aesthetic effects are likely to strike low latitude countries the hardest as well. Only ecological changes have an ambiguous distributional outcome.

In section 4, we use these tools to evaluate the distributional impacts of climate change. First, the world's population is divided into quartiles on the basis of per capita income in 2100. The predicted impacts of the three climate models and two response functions are displayed for each quartile. The results indicate that the poorest half of the world's nations suffer the bulk of the damages from climate change, whereas the wealthiest quarter has almost no net impacts.

¹ Technically, the early literature also assumed that there would be commercial fishery losses. They have not been included here because the ecological link between warming and fishery losses is still speculative and so it is not known how fisheries would change. Further, fishery impacts are likely to be small since this is a small sector, but that may not be true for some countries.

There are many reasons why rich and poor countries are different and they are all included in the results across quartiles. We consequently engage in two tests to isolate whether climate change and initial climate play an important role. In order to test the role of climate change, we assume all countries face identical climate change, although everything else about the countries may differ. We do a similar test with respect to initial climate by assuming that every country has the identical initial climate. The tests reveal that forcing climate change to be the same has no effect on the distributional outcome of impacts. The poor still bear the brunt of the world's damages. However, forcing the initial climate to be the same for all countries changes the distributional results. If all countries had the same initial climate, the absolute magnitude of climate damages would rise with income, because richer nations have larger climate-sensitive sectors. As a fraction of GDP, poorer nations would still suffer higher climate damages than richer nations, but the difference is small. These tests reveal that the poor nations of the world bear the brunt of climate change damages primarily because they are located in the low latitudes and are already too hot. The rich nations may well benefit from climate change because they are located in the mid to high latitudes and are currently cool. The proportion of GDP in agriculture, technology, wealth, and adaptation contribute to the distributional outcome, but play a smaller role. These strong distributional results across countries suggest that compensation needs to be a part of the greenhouse gas policy agenda along with mitigation and adaptation. The final section of the paper discusses some policy alternatives.

2. Climate scenarios

We explore the results of three AOGCM's to predict the impact of greenhouse gases. The Parallel Climate Model (PCM) comes from the National Center Atmospheric Research (Washington *et al.*, 2000). The Center for Climate Research Studies (CCSR) model was developed at NIES (Emori *et al.*, 1999). The Canadian General Circulation Model (CGCM1) was developed at the Canadian Climate Centre (Boer *et al.*, 2000). All three models are dynamic coupled ocean-atmosphere models that include greenhouse gases and sulfates. The PCM and CCSR models assume the IS92a path of greenhouse gases and the CGCM1 model assumes a 1 per cent exponential path of greenhouse gases. These two paths result in CO₂ levels of 685ppmv for PCM and CCSR and 808ppmv in CGCM1 by 2100.

These three models were selected to demonstrate the consequences of a full range of climate scenarios. Each model predicts changes in individual grid points across the earth. We use the grid points in each country to create a climate change scenario by country for 2100. The grid points are weighted by population and not by area. We prefer the population weighting method of evaluating climate change forecasts because most impacts occur near where people are living (Williams *et al.*, 1998; Mendelsohn *et al.*, 2000b). The population-weighted changes for each country are the inputs to the impact model. We also use population weights to generate regional average changes in temperature and precipitation.

The three models make very different forecasts of global temperature change: PCM predicts 2.5C, CCSR predicts 4.0C, and CGCM1 predicts 5.2C

Table 1. *Changes in temperature and precipitation predicted by each climate model in 2100*

Region	PCM		CCSR		CGCM1	
	T(C°)	P(%)	T(C°)	P(%)	T(C°)	P(%)
L. Amer.	2.0	5.9	3.3	-10.8	4.9	-4.3
Africa	2.3	11.9	3.9	11.6	6.2	-10.3
S. Asia	2.4	21.5	3.6	16.1	4.5	-1.6
Pacific	1.8	7.3	2.6	14.4	4.2	-8.6
N. Amer.	2.4	7.9	5.5	-23.1	5.4	1.7
Europe	2.4	8.2	5.3	-6.0	3.9	-1.8
N. Asia	2.9	22.5	4.0	10.0	6.4	-12.6
FSU	3.5	10.2	5.7	9.6	7.1	9.9
Globe	2.5	15.5	4.0	7.7	5.2	-5.6

Note: Temperature changes measured in centigrade and precipitation in percentage changes. The climate measurements are weighted by population not area.

by 2100. Global precipitation changes also vary by model. PCM predicts a 16 per cent increase, CCSR predicts an 8 per cent increase, and CGCM1 predicts a 6 per cent decrease in global precipitation by 2100.

The distribution of population weighted temperature changes across continents varies as seen in table 1. Warming is expected to increase with latitude (Houghton *et al.*, 2001). PCM and CCSR follow this accepted pattern and show more warming in the polar and temperate regions versus the tropical regions. CCSR predicts that this difference across latitudes will be extreme, whereas PCM shows more modest differences. CGCM1 shows a more random flux of temperatures, with Africa getting especially hot but Western Europe warming less than the rest of the planet.

The AOGCM models also predict a wide range of changes in population-weighted precipitation. PCM predicts higher precipitation in every continent, but especially in Africa, North Asia, and South Asia. CCSR predicts large losses of precipitation in Latin America and North America and small losses in Europe but large gains elsewhere. CGCM1 predicts losses of precipitation in every continent except North America and North Asia. There is clearly no consensus across the models about what will happen to local precipitation. However, the models do suggest that local precipitation might change significantly in very different ways across the planet.

The climate scenarios provide four driving forces that can have an effect on economic sectors: changes in mean or seasonal temperature, changes in mean or seasonal precipitation, increases in carbon dioxide, and increases in sea level. In addition to these climate changes, global warming can also cause an increase in the variance of temperature and precipitation, a slowing of the thermohaline circulation (resulting in northern cooling), and the sudden loss of ice sheets (rapid sea level rise). These latter forces were not evaluated in this paper, partially because they are more speculative and partially because there is less known about their timing and magnitude.

3. Impact methodology

We look at two different empirical approaches to determine the climate sensitivity of each economic sector: experimental and cross-sectional studies. The experimental studies have been done in controlled settings such as laboratories or greenhouses (see Reilly *et al.*, 1996 for a good summary of experimental results in agriculture). These studies carefully control for unwanted variables but they struggle to include adaptation fully. In contrast, cross-sectional studies examine actual outcomes from place to place in order to measure climate impacts. The Ricardian method is a good example of this approach in agriculture where the values of farms in different climates are compared (Mendelsohn *et al.*, 1994). The cross-sectional studies include efficient adaptation by design, but they struggle to control for unwanted influences. Comparing the experimental and cross-sectional method, the strength of each empirical methodology is the weakness of the other. The experimental method has the added advantage that it can measure the direct effect of carbon dioxide, which the cross-sectional method cannot.² Both models predict that temperature has a hill-shaped relationship with agriculture, forestry, water, and energy; that increased precipitation is generally beneficial; and that coastal damages increase as sea level rises. Details about the shapes of these functions can be found in Mendelsohn and Schlesinger (1999).

The results from experimental studies lead to steeper hill-shaped climate response functions compared with the cross-sectional results. The experimental model predicts that countries that are cooler than optimum will gain more from warming and countries that are warmer than optimum will lose more than the cross-sectional model predicts. As in the cross-sectional model, precipitation is predicted to have a beneficial impact on agriculture, forestry, and water but no effect on energy. The experimental model depends only on average annual climate, whereas the cross-sectional model captures a full array of seasonal temperatures and precipitation levels. Carbon dioxide, through fertilization, is strictly beneficial and helps forestry and especially agriculture in all regions (see Reilly *et al.*, 1996 and Sohngen *et al.*, 2002). It is assumed that carbon fertilization benefits increase with the log of CO₂ and are the same in both models.

In a complete general equilibrium model, global warming could change the supply and demand of all goods and services, leading to new global prices for everything. In practice, the climate changes expected over the next hundred years will not change overall economic conditions enough to affect most prices. For example, across a host of climate scenarios, market damages as a fraction of GDP were estimated to be less than 1 per cent (Mendelsohn *et al.*, 2000b). Even the higher estimates found in the early literature suggested that damages would be just 2 per cent of GDP (Pearce *et al.*, 1996). Such small changes in output do not warrant using a general equilibrium model.

Most price changes that will occur because of warming will be limited to the sectors directly affected by climate change. In these sectors, warming would affect consumers and suppliers across the world through direct

² Carbon dioxide effects from the experimental studies are used to predict carbon dioxide impacts in the cross-sectional results.

effects and prices could change. Models that take these price effects into account have been constructed to study climate impacts on timber (Sohngen *et al.*, 2002). Reliable global models for agriculture and energy have not yet been developed.³ This paper relies on studies that assume climate has no effect on output prices in agriculture, timber, and energy. Global impact studies of these sectors have not been done but it is likely that climate-induced global price changes would be small. However, if this is not the case, assuming constant prices biases the welfare estimates. If climate change causes global scarcity and therefore increases prices, the presented results will underestimate total damages and miss consumer damages completely. If climate change increases abundance and reduces prices, the presented results will overestimate total benefits and miss consumer benefits completely. What will happen to supplier welfare is ambiguous.

In contrast to the sectors with global markets, water is likely to have only a regional market because it is hard to transfer across basins. Water supply and demand in specific regions can change dramatically across climate scenarios and so there could be profound local price effects. These are captured by the model, which measures basin water prices using water supply and demand changes (Hurd *et al.*, 1999).

Two response functions to sea level rise are used in the model (Neumann and Livesay, 2001). In the cross-section model, we assume that landowners have foresight and so they depreciate buildings, anticipating they will be abandoned to sea level rise. In the experimental model, we assume that landowners have no foresight and that leads to slightly higher costs. The coastal study examines a series of decisions made each decade to either protect or abandon coastline in response to the rising seas. By stretching out responses across the century, costs are held to a relatively low level in each decade. At least in the US and Singapore, the model predicts that valuable coastlines will be protected (Neumann and Livesay, 2001; Ng and Mendelsohn, 2005). However, coastal protection is an adaptive response that generally requires government planning and coordination. It is not clear whether governments will make efficient decisions to protect coastlines.

We find that the hill-shaped response functions are slightly different between developed and developing countries (Mendelsohn *et al.*, 2001). The developing countries have lower crop net revenues per hectare and they are more temperature sensitive. The agriculture crop response functions to temperature in both developed and developing countries are hill shaped. But the developed country response function is both higher and flatter than the developing country response function, presumably because the high technology farmers have more capital and they can substitute capital for climate. The model predicts that agriculture in developing countries is more vulnerable to higher than optimal temperatures. We assume that this more vulnerable climate response function applies to countries whose 2100 per capita income is less than \$7,000. Empirical research suggests that

³ There are some well-calibrated general equilibrium models in agriculture that examine country-specific impacts (see for example Adams *et al.*, 1999), but these simply assume global price changes.

Table 2. Aggregate market impacts in 2100 (USD Billions/yr)

	Climate predictions					
	PCM		CCSR		CGCM1	
	CS	Exp	CS	Exp	CS	Exp
Total	63.8	217.1	-22.8	-93.5	-19.1	-273.3
% GDP	0.03%	0.10%	-0.01%	-0.04%	-0.01%	-0.13%
Per capita	6.69	22.77	-2.39	-9.81	-2.00	-28.7

Note: We assume that sea level rise by 2100 is equal to 0.3 m by 2100 in PCM, 0.5 m in CCSR, and 0.9 m in CGCM1.

agriculture in developing countries is more climate sensitive (Mendelsohn, *et al.*, 2001), but this particular income cutoff value is arbitrary. The cutoff roughly separates out the poorer from the richer half of all nations. Both the cross-sectional models and the experimental-simulation models assume efficient adaptation. Users are assumed to maximize their net benefits: gross private benefits minus the costs of adaptation. The results reported in this paper include the most recent efforts to incorporate adaptation. The experimental-simulation results are consequently not as severe as some of the earlier analyses in the literature, which made less of an effort to include efficient adaptation (see Pearce *et al.*, 1996).

Each country has numerous characteristics such as land, length of coasts, population, and GDP that also play a role in determining country-specific impacts. Some of these factors are constant over time such as coastline and land. However, several of these factors will change over time and the changes could be profound by 2100. All the future scenarios use the same economic and demographic assumptions. Population growth is assumed to decline over time in every country. The average population growth over the next century for developed countries is 0.7 per cent a year, for China it is 0.5 per cent a year, and for all other developing countries it is 0.9 per cent a year. GDP is expected to grow by 1.9 per cent a year for developed countries, by 0.9 per cent a year for Sub-Saharan Africa, and by 2.9 per cent a year for developing countries. Agriculture is expected to grow at 0.25 per cent a year for Africa and at 0.5 per cent a year for the rest of the world. Agriculture is consequently expected to be a smaller fraction of GDP over time. All of these assumptions are based on the IS92 scenario (Houghton *et al.*, 1994), although they are consistent with predictions of other international agencies (World Bank Group, 2002).

4. The distributional impacts of climate change

For each of the climate predictions from the three AOGCM's and for both climate sensitivity functions, we calculate the global net market impacts by 2100 by aggregating individual country results. Table 2 presents these results for the world as a whole. Global impacts are positive or beneficial under the PCM climate, because it is a very mild climate change scenario. The experimental response function leads to larger benefits than the cross-sectional function. In contrast, the more severe climate change scenario

Table 3. Market impacts in 2100 by income (Billions USD/yr)

Income Group		Impacts by climate predictions					
		PCM		CCSR		CGCM1	
		Cross section	Experimental	Cross section	Experimental	Cross section	Experimental
Poorest	Impact	-1.2	-8.0	-4.8	-69.4	-6.9	-140.7
Quartile	%GDP	-0.2	-1.4	-0.8	-11.8	-1.2	-23.8
Second	Impact	4.5	19.7	-5.6	-30.2	-9.5	-92.0
Quartile	%GDP	-0.4	1.6	-0.5	-2.4	-0.8	-7.4
Third	Impact	21.8	56.6	-0.7	-7.1	-4.5	-64.1
Quartile	%GDP	0.8	2.1	-0.0	-0.3	-0.2	-2.4
Richest	Impact	38.8	148.7	-11.7	13.2	1.8	23.5
Quartile	%GDP	0.2	0.9	-0.1	0.1	0.0	0.1

in CCSR is predicted to lead to small global net damages in both cases with experimental results again being larger. Finally, under the severe climate change scenario in CGCM1, damages will be slightly smaller for the cross-sectional response function but much larger for the experimental response function. This range of global net impacts is consistent with the Third Assessment Report of the IPCC, although the Report focuses more on the potentially harmful end of this range (McCarthy *et al.*, 2001). Annual market impacts as a fraction of GDP in 2100 range from slightly beneficial (+0.1 per cent of GDP) to slightly harmful (-0.12 per cent of GDP). These market impacts amount to an annual benefit of about \$23 per person to a loss of about \$27 per person.

It is clear that the different climate change scenarios have a large impact on the overall results one sees for the world. Specifically future climate scenarios that predict larger temperature increases and precipitation losses, lead to larger overall net global damages. However, the focus of this paper is upon the distributional impacts of these global changes, not their overall magnitude.

In order to understand how these climate impacts affect countries of different income levels, we order countries by per capita income in 2100. We then divide the country list into quartiles on the basis of their projected population in 2100. Each quartile represents one-fourth of the world's population by 2100. A list of all countries and which quartile they fall in are shown in the Appendix. Table 3 shows the market impact results by quartile. The poorest quartile earns less than \$4,380 per capita and includes 53 countries, mostly from Africa. The second quartile group earns from \$4,380 to \$5,785 per capita and includes only six countries, notably India and China. The third quartile earns between \$5,785 and \$25,000 and includes 65 countries from all over the world. Although the bulk of these countries are from warm latitudes, there are a few cooler countries in this group. The richest quartile of the world's population includes 52 countries from North America, Europe, and the Middle East and a handful of countries from other continents. The richest quartile includes most of the countries in the mid-high latitudes and a scattering of countries

Table 4. *Market impacts assuming identical climate change in all countries (Billions USD/yr)*

<i>Income Quartile</i>		<i>+2C 0%P</i>	<i>+3.5C 0%P</i>	<i>+5C 0%P</i>	<i>+3.5C +10%P</i>	<i>+3.5C -10%P</i>
Poorest	Exp	-41.4	-102.0	-153.8	-78.7	-124.2
	Crs	-2.3	-4.6	-6.9	-4.5	-4.6
Second	Exp	-12.3	-50.3	-94.1	-39.3	-71.9
	Crs	-3.3	-5.4	-7.5	-5.4	-5.2
Third	Exp	31.9	-1.9	-44.1	30.4	-35.7
	Crs	19.2	10.3	-0.7	11.4	8.7
Richest	Exp	96.7	65.9	12.4	126.6	2.8
	Crs	43.6	22.5	-6.0	24.9	19.3

Note: Climate change is assumed to be uniform across the world.

in the low latitudes. Most of the largest economies in the world are in this group. The richest quartile controls 78 per cent of the world's GDP in 2100, the poorest quartile only 2.5 per cent.

Table 3 shows what happens to aggregate market impacts in each quartile for each climate scenario and for each response function. Examining impacts across quartiles, the poorest quartile suffers damages across all six scenarios. The second poorest quartile suffers damages in all but the PCM scenario with the cross-sectional response function. The third richest quartile also suffers damages in all but the PCM scenario with the cross-sectional response, but these damages are smaller than what the two poorer quartiles suffer. In contrast, the richest quartile suffers damages in only the CCSR scenario with the cross-sectional response. In all other cases, the richest quartile actually benefits from warming. The results provide strong evidence that the bulk of the damages from climate change will fall on the poor countries of the world.

Table 3 also shows the impacts as a percentage of GDP. These calculations reveal that climate impacts are likely to be burdensome to the poorest countries. The lowest quartile would suffer damages from 12 per cent to 23 per cent of their GDP with the more severe climate scenarios and the experimental response function. In contrast, the range of impacts for the richest quartile is between a damage of 0.1 per cent to a benefit of 0.9 per cent of GDP. The results suggest there is a very large cross-country distributional issue associated with climate change impacts.

Why are poor countries so vulnerable? One hypothesis is that poor countries have more severe climate change scenarios than rich countries. We test this hypothesis by forcing climate change to be the same for all countries in the world. Table 4 presents the results of this experiment. The three levels of global temperature chosen roughly correspond to the global average predictions from the three AOGCM's. The results provide a similar pattern as in table 3. Damages are greatest for the poorest quartile and they decline with income, eventually becoming beneficial for the richest group. Eliminating the difference in climate change predictions across countries does not change the distributional results.

Table 5. Current observed temperature and precipitation in each region

Region	Temperature (C)	Precipitation
Africa	29.1	7.2
South Asia	28.5	10.0
Latin America	25.9	11.9
Pacific	29.6	18.3
North Asia	19.7	7.4
North America	19.5	8.0
Europe	13.7	6.1
Former Soviet Union	12.0	4.8

Note: Observed measurements are population weighted averages not area weighted averages as usually shown.

Table 6. Market impacts assuming identical climates and climate change in all countries (Billions USD/yr)

Income Quartile		+2C 0%P	+3.5C 0%P	+5C 0%P	+3.5C +10%P	+3.5C -10%P
Poorest	Exp	1.8	-37.4	-82.0	-8.5	-65.3
	Crs	-2.2	-5.0	-7.7	-5.0	-5.0
Second	Exp	-0.8	-29.7	-64.6	-9.2	-50.2
	Crs	-3.4	-6.1	-8.8	-6.0	-5.9
Third	Exp	-2.1	-60.9	-131.7	-19.6	-102.3
	Crs	17.8	5.7	-8.6	7.0	4.6
Richest	Exp	-30.8	-156.2	-304.4	-80.0	-232.4
	Crs	21.9	-14.9	-59.3	-11.6	-17.0

Note: All countries are assumed to have the identical global average climate. Climate change is assumed to be uniform across the world.

An alternative hypothesis is that poor countries are more vulnerable because they are located in the low latitudes and have higher current observed temperatures. Table 5 shows the current variation in temperature and precipitation by region. These starting climates can be very important because they determine whether a sector is already too hot or too cool compared with the optimum for that sector. Table 5 shows that the low latitude regions are currently hot. These temperatures are actually beyond the optimum for most climate-sensitive economic sectors. In contrast, the mid latitude regions enjoy a range of current temperatures near the optimum. The former Soviet Union and northern Europe have cool current temperatures that make warming good for their economy.

In tables 6 and 7, we assume that all countries have the same climate both now and in the future. This assumption places every country under the same climate experiment, although it allows countries to be different in other ways. As shown in table 6, if both present and future climates are the same in every country, it would no longer be true that the poorest countries would suffer the brunt of the damages from climate change. In fact, damages

Table 7. Market impacts assuming identical climates and climate change in all countries (% GDP)

Income Quartile		+2C 0%P	+3.5C 0%P	+5C 0%P	+3.5C +10%P	+3.5C -10%P
Poorest	Exp	0.3	-6.3	-13.9	-1.4	-11.1
	Crs	-0.4	-0.9	-1.3	-0.8	-0.9
Second	Exp	-0.1	-2.4	-5.2	-0.7	-4.0
	Crs	-0.3	-0.5	-0.7	-0.5	-0.5
Third	Exp	-0.1	-2.3	-4.9	-0.7	-3.8
	Crs	0.7	0.2	-0.3	0.3	0.2
Richest	Exp	-0.2	-1.0	-1.9	-0.5	-1.4
	Crs	0.1	-0.1	-0.4	-0.1	-0.1

Note: All countries are assumed to have the identical global average climate. Climate change is assumed to be uniform across the world.

would rise with income, because the climate-sensitive economic sectors in the richer quartiles are larger. Although agriculture plays a much larger role in developing countries today, it is expected to play a much smaller role by 2100. Further, energy and water are much larger sectors in the richer countries and their role does not shrink over time. Differences in current climates do explain why poor countries are predicted to suffer the net global impacts of climate change. Because most poor countries happen to be in the low latitudes, they begin with temperatures that are already too warm.

Table 7 displays the results for this same experiment using impacts per GDP as the measure. Here, the results are not as dramatic as in table 6. Even if climates were the same across all countries, poor countries would still have higher impacts per GDP. The difference between rich and poor shrinks but does not disappear. Poor countries still have larger proportions of their economy in climate sensitive sectors (namely agriculture) and the absence of capital and technology still gives them fewer adaptation options. Location is not the only reason why poor countries are likely to have higher impacts per GDP than rich countries, but it is a very important reason.

Figure 2 maps annual market impacts in 2100 for each country in the world, using the cross-sectional impact model. The figure illustrates the geographical distribution of impacts across the world. Three very different future climates provide a range of climate changes. The relatively flat response function of the cross-sectional model produces a subdued impact pattern across these future climates. Mid latitude regions do well and even tropical parts of the western hemisphere see small benefits under all three projected climates in 2100. Russia, Mongolia, Kazakhstan, and Eastern Europe do better than the rest of the world. However, across all the scenarios, the poor countries of Africa and southeastern Asia experience noticeable adverse impacts.

Figure 3 maps 2100 impacts using the more steeply hill-shaped experimental response functions. The benefits accruing to Russia, Mongolia, Kazakhstan, and Eastern Europe are larger in figure 3 than with the cross-sectional model. Africa and the poor tropical countries are worse off in this

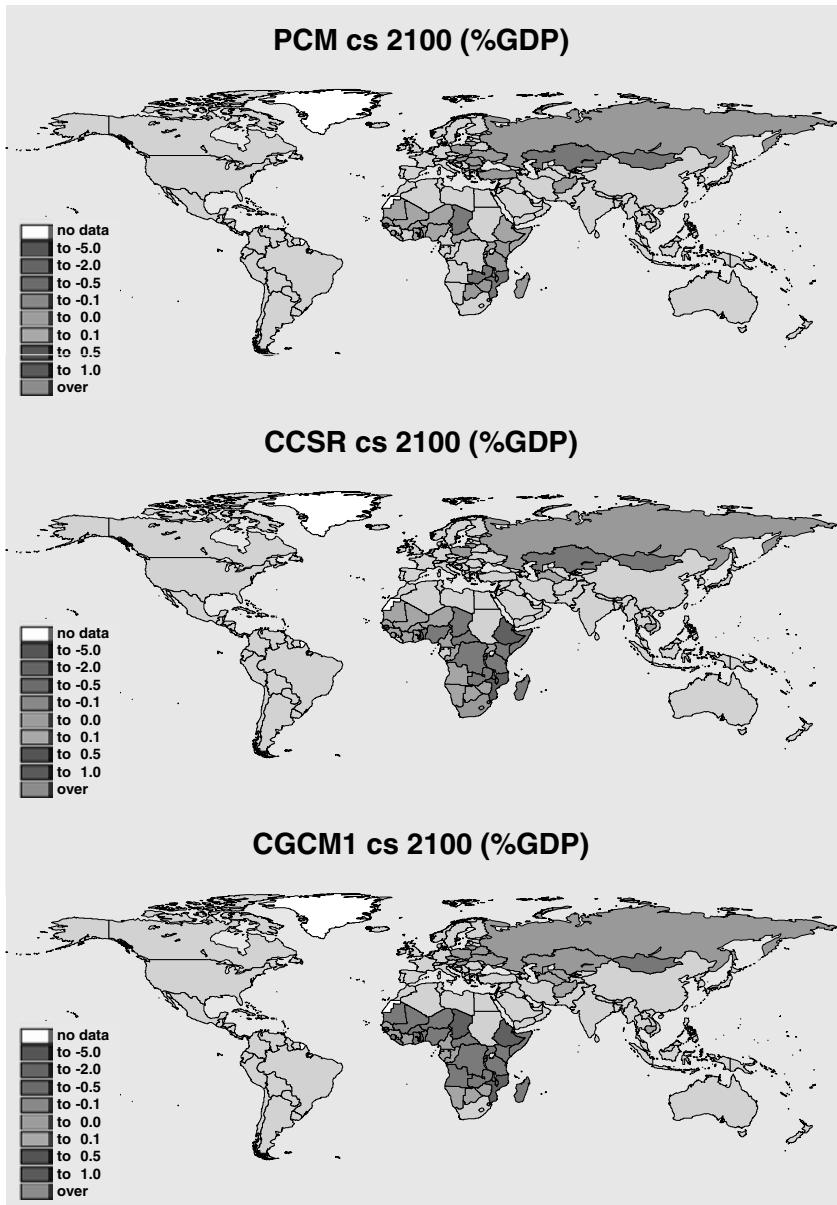


Figure 2. Annual market impacts (percent GDP) estimated for each country in 2100 using the cross-sectional impact model. The climatologies are based on the PCM, CCSR, and CGCM1 AOGCMs

figure. Two of the three climate forecasts show that the experimental model leads to damages in tropical South America as well. Even the United States shows mild losses under the warming predicted by CCSR.

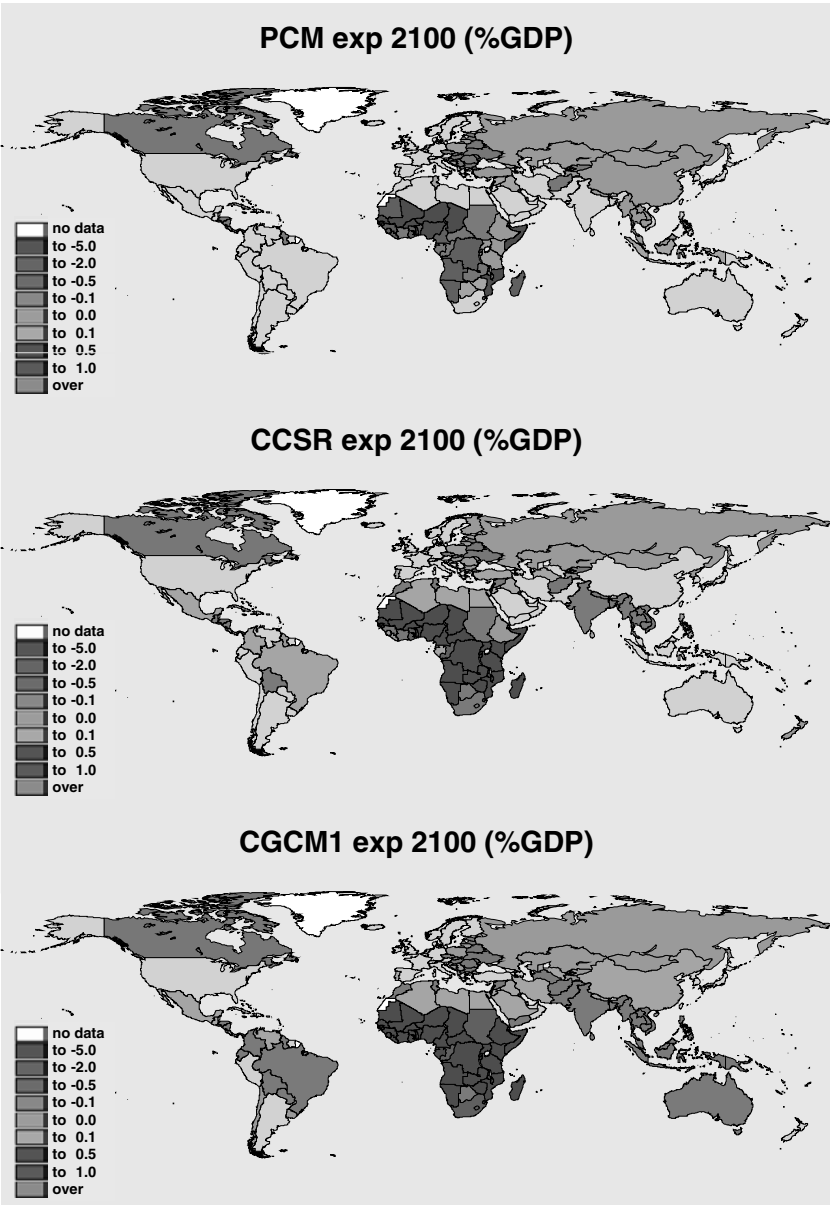


Figure 3. Annual market impacts (percent GDP) estimated for each country in 2100 using the experimental impact model. The climatologies are based on the PCM, CCSR, and CGCM1 AOGCMs

The maps of figures 2 and 3 (color maps are available from the authors upon request) reveal that under all climate forecasts and with both impact models, the poor countries of Africa and Southeast Asia are harmed by projected climate change in 2100. These results demonstrate that the low latitude regions will be hard hit by climate change. Almost all of the poor

countries of the world lie in the low latitudes. The maps consequently support the analysis and suggest that warming will be hard on poor countries.

The simulation model does not assume that damages increase with income (the model actually predicts the opposite). The key assumption in the model is that impacts have a hill-shaped relationship with temperature. Countries that are already hotter than optimal (the top of the hill) will suffer damages with warming. The distributional impacts predicted in this paper are caused because poor countries just happen to be in the low latitudes (which are already hot), whereas most rich countries happen to be in the mid to high latitudes (which are currently cool).

5. Conclusion

The paper investigates whether the impacts from climate change have distributional consequences across countries. This analysis uses predictions about future climate change and calibrated climate response functions to calculate market impacts in 2100 for each country in the world. In order to capture the range of outcomes likely from climate change, we present the results of six scenarios (three climate scenarios times two response functions). For each scenario, we aggregate the impacts across countries by income per capita. Specifically, we divide the world's population into quartiles on the basis of their GDP per capita. We then calculate the market impacts for each quartile.

The results indicate that the poorest quartile will suffer damages in all scenarios. The next poorest quartile will suffer damages in all but the mildest climate change scenario. Although the third richest quartile also suffers damages in all but the mildest climate change scenario, the damages are quite small compared with the poorer half of the world. The richest quartile, in contrast, benefits in all but one case. Overall, the poor will suffer the bulk of the damages from climate change, whereas the richest countries will likely benefit.

The analysis then tests whether poor countries face more devastating climate change scenarios than more wealthy countries. We test how impacts would change if every country faced identical climate changes. The results in this experiment are almost identical to the findings with the AOGCM predictions. Poor countries continue to bear the burden of climate change damages, whereas rich countries likely benefit.

Finally, we test whether poor countries bear a larger burden of climate damages because they are already hot. In this test, we assume every country has the identical current climate as well as climate change. Countries still differ from one another because of economic, demographic, and geographic reasons. In this test, damages rise with income. Damages are concentrated in poor countries specifically because of their current climate. Because they happen to be located in low latitude regions, poor countries are currently much hotter than optimal, whereas more wealthy countries located in the mid to high latitudes are currently cool. Increases in temperature consequently cause more damages to poor countries compared with more wealthy countries.

The fact that damages increase with income, once current climate is controlled, deserves some additional explanation. More wealthy countries bear larger damages because the climate-sensitive economic sectors in these

countries are larger. By 2100, the importance of agriculture in GDP has shrunk, whereas other climate-sensitive sectors, namely water and energy, have maintained their relative share. The lower climate sensitivity implied in more advanced economies apparently has little effect on aggregate impacts. However, as a fraction of GDP, even controlling for climate, poor countries have higher impacts. The size of the climate impacts pales in comparison with the size of the economies of the richer nations. Poor countries consequently bear a larger burden as a fraction of their GDP than rich countries because of the many reasons raised in the literature, including lower capital, technology, and adaptation options.

Although these national results are insightful, they do not necessarily predict what will happen to individual poor people. That is, many countries are large enough so that different regions will have different effects within national borders. Further, what happens to some countries in aggregate does not necessarily indicate what will happen to the poor residents of a country. The approach used in this paper cannot identify within-country effects. However, alternative studies such as rural income analysis (Mendelsohn *et al.*, 2003) can identify how effects are distributed within a nation. There are several reasons to expect that individual poor will be burdened even more than the aggregate national numbers suggest. In most countries, there is a wide disparity of agricultural productivity across regions. In the low latitudes, the rural poor tend to live in the hotter and drier regions of each country. Warming is likely to damage these regions more harshly than the more temperate zones of each country. The poor are also likely to suffer larger damages than country averages because the poor do not have access to capital. Without capital, the poor will find it harder to adapt to warming. The poor may have more difficulty moving away from changes in climate, as their assets may be closely tied to specific pieces of property that may be of low value once climate changes. Finally, the poor cannot purchase their way out of reductions in crop productivity; they may not have the resources to buy food.

An important limitation of this paper is that most of the empirical impact studies that support these results have been done in the US (Smith and Tirpak, 1990; Mendelsohn and Neumann, 1999; Mendelsohn, 2001). Only a few studies have attempted a more global reach (Rosenzweig and Parry, 1994; Sohngen *et al.*, 2002) or have measured welfare impacts in other countries. Very few studies have been done in developing countries (Mendelsohn *et al.*, 2001; Kurukulasuriya and Rosenthal, 2003). Most of what we assume will happen in the low and high latitudes is inferred from a few empirical studies. We consequently have less confidence in our results for the low and high latitudes. This is important to remember because the largest predicted impacts from climate change are in the low and high latitudes.

This paper has shown that climate impacts have large distributional consequences. The bulk of the damages from climate change are likely to fall on the poor countries of the world. These results have bearing on climate change policy. If one applies equity weighting, the damages from climate change will be greater (Fankhauser, Tol, and Pearce, 1997; Azar, 1999; Tol, 2001) and the urgency to apply mitigation and adaptation will increase. However, we believe the most important policy change that

is required is to consider cross-national compensation. The distributional results found in this paper suggest that climate change negotiators must talk about compensating poor countries from the low latitudes. These countries will bear the brunt of the damages from climate change even though they made only a small contribution to cumulative emissions.

If compensation is considered, how will a compensation program be designed? One idea that has been circulated in the UNFCCC (United Nations Framework Convention on Climate Change) negotiations is to provide some compensation to help poor countries mitigate emissions (see Marrakesh accords at www.unfccc.int). The Marrakesh accords also recommend holding a workshop to help developing countries insure themselves against the adverse impacts of climate change. The specifics of this idea are not yet developed. One possibility is that an international fund such as GEF (Global Environmental Facility) could subsidize adaptation. For example, the GEF could provide poor countries with financial and technical support for joint-public adaptations such as water projects, coastal protection, or endangered species protection. Efficient programs that support mitigation or adaptation are definitely possible compensation schemes.

Another alternative is to create a climate impacts insurance fund for low latitude countries. Countries could apply for relief from the fund whenever they suffer a climate impact. In practice, this is likely to be difficult to administer because countries will claim harm with every weather event whether or not it is related to greenhouse gases. Unlike severe events such as hurricanes and floods, the gradual nature of global warming will make it very difficult to measure damages as they occur. Finally, paying victims compensation may create deleterious incentives that encourage people to put themselves in harm's way.

A final alternative is to compensate low latitude countries by investing in their economic development. Rapid development could help low latitude countries adapt to future climate change by reducing vulnerability, although it would increase emissions. As countries develop, they move away from agriculture, making their economies more resilient to climate change. An effective development program would also provide the needed technological progress that would make even climate-sensitive sectors less sensitive to future climate change. But, most importantly, an economic development program could address the imbalance between those who currently benefit from emissions and those who are likely to pay the consequences of climate change. A well-designed economic development program would bring large benefits directly to the people of poor countries.

International development institutions such as the World Bank could administer such development programs. They could be an effective intermediary between the countries that generate greenhouse gas emissions and the countries likely to be harmed. For example, the Bank could collect a modest carbon tax on all countries in order to fund a development program for low latitude countries. They could help design an effective development program and then use the carbon revenues to fund it. Rather than focusing strictly on mitigation, the carbon program would modernize developing countries, making them more capable of taking care of themselves. The development program could address the fundamental

inequity of greenhouse gases and provide the poor nations of the world with immediate benefits.

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Appendix A: List of countries by income quartile

Lowest (poorest) Quartile

Angola, Bangladesh, Benin, Bhutan, Botswana, Burkina Faso, Burundi, Cambodia, Cameroon, Cape Verde, Central Afr. Rep, Chad, Comoros, Congo, Cote d'Ivoire, Djibouti, Equatorial Guinea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Guyana, India,* Kenya, Lao People Dem. Rep., Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Nepal, Niger, Nigeria, Pakistan, Rwanda, Sao Tome/Principe, Senegal, Sierra Leone, Somalia, South Africa, Swaziland, Togo, Uganda, United Rep. Tanzania, Vietnam, Zaire, Zambia, Zimbabwe

Second Highest Quartile

Albania, China,* Haiti, India,* Lebanon, Myanmar, Sri Lanka

Third Highest Quartile

Afghanistan, Armenia, Azerbaijan, Belarus, Belize, Bolivia, Bosnia/Herzegovina, Bulgaria, Chile, China*, Columbia, Costa Rico, Croatia, Czech Republic, Dem. People Rep. Korea, Dominican Republic, Ecuador, Egypt, El Salvador, Fiji, Georgia, Guatemala, Honduras, Hungary, Indonesia, Iraq, Iran, Jamaica, Jordan, Kazakhstan, Kyrgyzstan, Lithuania, Macedonia/FYR of, Maldives, Malta, Mexico,* Moldova, Mongolia, Morocco, Nicaragua, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Portugal, Romania, Saint Lucia, Saint Vincent/Grenadines, Serbia and Montenegro, Seychelles, Slovakia, Solomon Islands, Sudan, Syria, Tajikistan, Thailand, Tunisia, Turkey, Turkmenistan, Ukraine, Uzbekistan, Vanuatu, Western Samoa, Yemen

Highest (Richest) Quartile

Algeria, Antigua/Barbado, Argentina, Australia, Austria, Bahamas, Bahrain, Barbados, Belgium, Brazil, Brunei Darussalam, Canada, Cuba, Cyprus, Denmark, Dominica, Estonia, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Kuwait, Latvia, Libya, Luxembourg, Malaysia, Mexico*, Netherlands, New Zealand, Norway, Oman, Qatar, Republic of Korea, Russia, Saudi Arabia, Singapore, Slovenia, Spain, Suriname, Sweden, Switzerland, Taiwan, Trinidad/Tobago, United Arab Emirates, United Kingdom, United States, Uruguay, Venezuela

* These countries have been split between two quartiles. Impacts have been apportioned in proportion to population in each quartile.