

## Chapter 9

### Dynamic Forecasts of the Sectoral Impacts of Climate Change

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#### **9.1 Introduction**

It is well documented that the increasing levels of carbon dioxide and other greenhouse gases are likely to change future climates across the planet (Houghton et al. 2001). The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) has synthesized many studies describing the qualitative market and non-market impacts of climate change (McCarthy et al. 2001). However, quantitative estimates of impacts are rare. Most economic impact analyses of climate have focused on comparative equilibrium analyses. They have explored the difference between current conditions and what would occur if greenhouse gases doubled (see Pearce et al. 1996). Economists have rarely tackled the more difficult task of forecasting how impacts might unfold over the century. In this paper, we combine the power of the most sophisticated climate models with recent economic research to predict the path of climate impacts over time.

The modeling begins with forecasts of greenhouse gas emissions in the absence of mitigation. These emissions, in turn, lead to projections of increasing greenhouse gas concentrations in the atmosphere (Houghton et al. 2001). We then use the climate predictions of six dynamic atmosphere-ocean general circulation models (AOGCMs) based on these concentrations. We combine these forecasts with two climate response functions: a relatively pessimistic experimental and a relatively optimistic cross-sectional model (Mendelsohn and Schlesinger 1999; Mendelsohn and Neumann 1999; Mendelsohn 2001). These response functions reflect the range of quantitative impact results found in other studies as well (Pearce et al. 1996; Tol 2002a; 2002b). Combined with background information about each country in the world, these response functions generate 12 forecasts of climate impacts each decade for each sector for each country.

Understanding the path of global warming impacts is very important. First, the appropriate level of mitigation over time depends upon the path of damages. Abatement costs need to be balanced against the stream of aggregate damages that emissions would otherwise cause (Nordhaus 1991). How much should be spent on mitigation and how that should change over time, therefore depends on the size and timing of the damages. Second, countries may be quite interested in learning which sectors are vulnerable to climate damage and when in order to determine what adaptations are worthwhile. Third, countries might want to know what the overall impacts of climate change are in order to seek compensation from the international community. Fourth, countries might want to know when impacts will be large enough to detect and where one should look for them. The predictions would help design effective monitoring programs.

There are a number of caveats that should be kept in mind. Empirical studies of climate impacts are not readily available in all places and for all effects. 1) Most of the empirical studies have been done in the temperate zone; few studies have been done in either the tropics or the high latitudes (McCarthy et al. 2001). 2) Impacts to many nonmarket sectors have not been quantified, although they are likely to occur. For example, although scientists know that climate will affect biodiversity, health, water quality, and air pollution, the value of these impacts has not been measured. 3) The results are uncertain. We have tried to represent uncertainty by showing a range of effects, which is why there are 12 scenarios. 4) Extreme events are not modeled. The analysis does not include such phenomena as the shutdown of the thermohaline circulation or the collapse of the West Antarctic Ice Sheet.

## **9.2. Climate Models**

The origin of global warming lies in the emissions of greenhouse gases (Houghton et al. 2001). The burning of fossil fuels for energy and a host of other manmade activities results in sizeable and growing emissions of carbon dioxide, nitrogen oxide, methane, and other miscellaneous greenhouse gases. Greenhouse gases are accumulating in the atmosphere (Houghton et al. 2001). In this study, we assume that they will continue to accumulate for the next century at a steady rate. One set of model runs assumes that atmospheric levels will increase at one percent a year and the other set assumes that they will follow the IPCC IS92a predicted levels. Both sets of predictions assume that there will be no mitigation.

The greenhouse gases will cause increased amounts of heat to be trapped in the earth's lower atmosphere. We rely on six AOGCMs that have dynamic atmosphere-ocean capabilities to predict dynamic climate paths. The six models, ranked in ascending order on the basis of their 2100 population-weighted temperature change predictions, are the Parallel Climate Model (PCM) (Washington et al. 2000), CSIRO (Gordon and O'Farrell. 1997), Hadley Meteorological Centre (HAD2) (Johns 1996), CCSR (Emori et al. 1999), Hadley Meteorological Centre (HAD3) (Gordon et al. 2000), and the Canadian Climate Centre Model (CGCM1) (Boer et al. 2000). HAD2 and CGCM1 assume that CO<sub>2</sub> concentrations will reach 808 ppm by 2100 while the other four models assume that CO<sub>2</sub> concentrations will only reach 685 ppm by 2100. All six scenarios also account for other greenhouse gases and for sulfates, which tend to cool the atmosphere.

Table 9.1 presents the population-weighted temperature and precipitation changes for each continent and the globe according to each model for 2100. Climate scientists routinely present warming climatologies as area-weighted temperatures and precipitations (Houghton et al. 2001). We rely on population-weighted measures for each country because market impacts occur where people live (Williams et al. 1998). Starting with cubic spline interpolations, to ½ degree grids, the predictions of each model are weighted by population and then added up to obtain country averages.

The AOGCM models predict a range of climate change over time and space. The global population-weighted change in temperature varies from 2.5C to 5.2C across these six models with PCM the lowest and CGCM1 the highest. Warming is expected to increase with latitude (Houghton et al. 2001) and PCM, CSIRO, CCSR, and HAD3 follow this accepted pattern. In contrast, HAD2 predicts that warming in the tropics (except for

Oceania) will exceed warming in the rest of the planet and CGCM1 predicts that Africa will get especially hot. The predicted precipitation also varies across the models. For example, PCM predicts higher precipitation in every continent with Asia at the top of the list. In contrast, HAD2 predicts large losses in Latin America and North America and CCSR predicts losses in Asia.

Although all the models predict global temperature increasing, the decadal changes by region follow random steps. For example, HAD2 starts with the highest prediction of warming by 2010 of 1.2 C° even though its century long prediction lies in the middle of the models. In contrast, the two models with the highest century long predictions, HAD3 and CGCM1, predict only a mild warming by 2010 of 0.8 C°. The decade of greatest warming varies from model to model. CSIRO predicts a large temperature change in 2020-2030 of 0.51C, CCSR predicts a 0.82 C° warming in 2060-2070, and CGCM1 predicts a 0.73 C° warming in 2080-2090. Precipitation changes for countries are also random. For example, HAD2 predicts a sharp drop in precipitation by 2010 concentrated in Asia that disappears by 2020. These sharp climate changes, in turn, affect the path of predicted impacts over time.

We do not use the AOGCM's to predict level rise. Instead we assigned sea level rise scenarios to climate scenario to mirror the range of possibilities highlighted by the IPCC report (Houghton et al. 2001). The low end of the range, a 0.3 m sea level rise by 2100, was assigned to the PCM scenario. The high end of the range, a 0.9 m increase by 2100, was assigned to the CGCM1 scenario. The remaining climate scenarios were assigned the expected sea level rise scenario of 0.5 m by 2100. In all the scenarios, sea level rise is expected to increase monotonically over the century.

### 9.3. Impact Model

There are two sources of evidence to measure the sensitivity of market impacts to climate change: cross-sectional studies and experimental studies (Mendelsohn and Neumann 1999; McCarthy et al. 2001; Mendelsohn 2001). The experimental approach quantifies the links between climate and final impacts in each sector using controlled experiments. For example, with agriculture, the experimental approach would measure how each crop grows in different climate conditions (in laboratories or experimental fields), what affect this would have on farmer's yields, how this would change farmer's decisions to plant the crop, how all these choices would affect supply, and then how prices would change (see Adams et al. 1999). In contrast, the cross sectional approach compares how outcomes in a sector change depending upon which climate zone the firm or household is in. For example, a cross sectional study of agriculture would compare the profits or farm values of farmers in different climate settings to quantify the role of climate (Mendelsohn, Nordhaus, and Shaw, 1994).

Both the experimental and cross sectional approaches have complementary strengths and weaknesses. An important strength of the cross-sectional approach is that it automatically includes adaptation as part of impacts. This is a weakness of the experimental approach. Experimental-simulation models only include adaptation to the extent that the analyst models it. The cross-sectional approach also tends to be representative as large areas are studied by design. The high cost of experiments limits the number of sites that can be tested with the experimental approach. The experimental approach, however, very carefully controls settings and isolates the climate and carbon fertilization effects. These are

weaknesses of the cross-section approach, which cannot measure carbon fertilization impacts and struggles to control confounding influences. The weakness of each method is the strength of the other.

Another reason to include both experimental and cross sectional results in this study is that the two types of studies tend to capture the range of results found throughout the literature. The experimental studies predict large impacts in the market sectors (high climate sensitivity) whereas the cross-sectional studies predict small impacts (low climate sensitivity) for a given climate change. By using both approaches, we reflect the range of climate sensitivity results found in the impact literature.

There are three major features of climate change that cause impacts: temperature, precipitation, and carbon dioxide. The effect of temperature change depends on the initial level of temperature. Many recent studies find a hill shaped relationship between the welfare in each economic sector and temperature (Mendelsohn and Schlesinger 1999; Mendelsohn and Neumann 1999; Mendelsohn 2001). A hypothetical example of the hill shape is shown in Figure 9.1. The exact shape of the hill is different for each sector. For example, the temperature that leads to the lowest energy costs is relatively cool whereas the temperature in which trees grow fastest is relatively warm. Because the response function of most sectors is hill shaped, the impact of temperature change depends upon initial temperatures. High latitude countries tend to benefit from warming, temperate countries have mixed effects, and tropical countries are more quickly damaged. Additional precipitation is generally beneficial unless there are already large amounts of rain in a season. Carbon dioxide is beneficial because it helps forestry and especially agriculture in all regions. The coastal sector is the

only sector immune from the major forces discussed above. The impacts to the coastal sector depend strictly on sea level rise.

Most impact studies are partial equilibrium analyses that assume that prices will remain fixed (two notable exceptions are Adams et al. 1999 and Sohngen et al. 2002). If climate change decreases goods and services and so raises prices, the partial equilibrium studies will underestimate the damages. If climate change increases goods and services, the partial equilibrium studies will overestimate the benefits. In most cases, we expect that the changes to global production will be small so that the partial equilibrium analyses will be adequate. However, if the climate change is large, that will no longer be true. Further, if there is a regional good, such as water, regional changes in price can be large even if net global changes are not. This is one reason why many watershed studies are general equilibrium analyses (Hurd et al. 1999 and Jenkins et al. 2001); they can capture changes in the marginal value of water in the watershed as either the urban or agricultural demand or the water supply changes.

The next generation of impact studies will need to rely on general equilibrium models for each sector (see, for example, Sohngen et al. 2002). This is a demanding task, because if goods are traded, price is determined by global markets. National general equilibrium models of traded goods are not adequate because their price effects are largely based on assumptions about what will happen in the rest of the world (outside the model).

This analysis is one of the few studies that measure all impacts over time (see also Tol 2002a; 2002b). However, there are several dynamic studies of the coastal (Yohe et al. 1999) and timber (Sohngen et al. 2002) sectors. These sectors contain large capital stocks of forests or structures that are slow and difficult to adjust. The more rapidly climate changes,

the larger the damages in these sectors. For example, rapid change may cause some of the trees to die before they can be harvested and coastal properties may be inundated while they still have many decades of useful life. Dynamic adaptation is also important to model. For example, building sea walls too early will increase the cost of protecting coasts tremendously. Cutting trees down before they mature gives much lower returns. Adaptations must be timed in response to the speed of climate change.

Dynamic studies require an interest rate to make intertemporal decisions. The interest rate is the value of time and it is used to compare costs in the present with costs in the far future. Although some analysts argue that a zero interest rate should be used for climate change, it is not prudent for society to use a different value of time for climate change relative to other public investment decisions (Pearce 2003). All investments into social capital should rely on the same interest rate whether the good be a dam, a national park, or the defense of a coastline. As a result, impact studies tend to use either a market rate of interest (five percent) or a social discount rate (three percent) (Sohngen et al. 1999; Yohe et al. 1999).

Another important issue is the location of the economic impact studies. Most empirical impact studies have been done in the US (Mendelsohn and Neumann 1999; Mendelsohn 2001) and so reflect conditions in a highly developed country in the temperate zone. A few studies have measured impacts in developing countries (McCarthy et al. 2001; Mendelsohn et al. 2001). Very few economic studies have actually measured global impacts (Sohngen et al. 2002). Most global estimates are extrapolations from measurements in the temperate zone (Nordhaus 1991; Mendelsohn and Williams 2004). In this study, every attempt was made to reflect our current understanding of the conditions in each region. The

mid latitude impacts are based on our considerable understanding of the US. The high latitude impacts are based on an extrapolation from the US studies. The low latitude impacts are based on a small sample of developing country or global studies. The uncertainty surrounding the impact estimates in the low and high latitudes is high.

The final critical element in the country predictions is capturing other pertinent features of each country. The model includes numerous characteristics from each country such as arable land, length of coasts, population, and GDP. Some of these variables are permanent but, for example, the latter two variables clearly change over time. The model includes a prediction of how these variables are expected to change over time (Houghton et al. 1994). GDP is expected to continue to grow more rapidly in developing countries and more slowly in the developed world. Population is expected to increase but at an ever slower rate until it stabilizes in the second half of the next century. These world forecasts suggest world GDP would reach 200 trillion (year 2000 USD) by 2100 and world population would reach 9.5 billion. These projections are exogenous to this model but are a source of additional uncertainty over both the level of effects and the dynamics.

#### **9.4. Results**

We calculate impacts each decade for each of the six climate scenarios using the cross sectional and experimental climate impact sensitivities for a total of 12 dynamic scenarios. The agricultural impacts dominate the impacts in the other four market sectors. Agriculture accounts for all the global net benefits predicted by PCM and over 50% of the damages in HAD3 and CGCM1 by 2100 in the experimental scenarios.

The dynamic path of agricultural impacts in the 12 scenarios is shown in Figure 9.2. With the sensitive experimental response function, impacts are expected to be quite small at first but then they grow rapidly as climate warms towards the end of the century. There are two exceptions to this general rule. With the PCM scenario, agricultural impacts are beneficial even as early as 2010 as the benefits of CO<sub>2</sub> fertilization and increased precipitation combine with a very mild warming to increase production. The other exception is with HAD2, which predicts very large though temporary agricultural damages in 2010 fueled by very large reductions in precipitation in southern Asia (-20%) coupled with very high temperature increases (1.5C) in the low latitudes. With PCM, these early benefits simply increase linearly with time, however, with HAD2, the damages virtually disappear by 2020 and only resurface near the end of the century. With the cross-sectional response function, the net impacts in agriculture are slightly beneficial for the first 70 years of the century. After that, the climate models vary with some predicting small benefits and some small losses. The only exception to this rule is the PCM climate scenario, which predicts linearly increasing benefits throughout the century.

The results in Figure 9.2, however, hide some important regional differences that are specific to agriculture. As can be seen in Table 9.2, all the scenarios predict that global warming is likely to increase agricultural production in the mid to high latitudes. The temperatures in the mid-high latitudes are currently either slightly too cool or near the optimum for agriculture. Warming will either improve conditions or at least make only a slight difference since the sector is at the flat part of the top of the response hill (see Figure 9.1). Carbon fertilization from higher CO<sub>2</sub> levels will then cause large increases in production. In contrast, the low latitude countries are currently too warm and warming is

likely to result in sharp drops in production. With the experimental response function, the climate models predict large damages for agriculture in the low latitudes in all scenarios except the mild PCM. The cross sectional results are similar but much smaller. According to the cross sectional models, agriculture is not very sensitive to climate change<sup>1</sup>.

The impacts in the energy sector follow a very different pattern than agriculture. Impacts start very small and they simply become more harmful over time. Impacts increase with warming but they are also sensitive to the growth of the economy. Impacts are predicted to be slightly larger with the experimental versus the cross-sectional approach but the range of impacts in energy is smaller than with agriculture.

The timber sector, in contrast, is expected to do well with warming. A warmer, wetter, CO<sub>2</sub> enriched world will result in forests expanding and growing faster. That is, the model suggests that the world is slightly cooler than the optimal growing conditions for timber (subtropics). In all 12 scenarios, warming will cause timber benefits to rise over time. However, in the cross sectional model, the high temperature increases of CGCM1 suggest there is a limit to these benefits and that eventually warming will become harmful to this sector as well. However, in all cases, the benefits in this sector are small because the sector itself is small relative to GDP.

The impacts in water, Figure 9.5, follow the same general pattern seen in energy (Figure 9.3). As warming proceeds, the damages are expected to increase over time. Water becomes very valuable with warming because agricultural and urban demands for water increase while the supply of available water generally declines. Precipitation varies greatly across regions and climate models. However, with greater evapotranspiration and more rapid

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<sup>1</sup> The cross sectional models cannot measure carbon fertilization effects. We attribute small fertilization effects to the cross sectional response function to contrast our assumption in the experimental results.

melting of winter snows, watershed systems are predicted to have less available water even with small precipitation increases. Systems can adapt to these changes by storing more water and allocating the water efficiently across users, but these public adaptations will require effective governmental coordination and funding (Mendelsohn 2000).

The coastal impacts, as shown in Figure 9.6, simply depend on sea level rise. If sea level rise is very modest, the damages will be small as coastline development will adapt without much change. In scenarios where the sea is expected to rise more quickly, damages will increase especially near the end of the century. If the seas rise rapidly, coastal buildings will have to be protected or lost to inundation. The analysis assumes that protection will proceed efficiently with the government timing the size of the protection to the rate of sea level rise. Except in the most dramatic scenario, the damages from sea level rise are expected to be small as the cost of protection is spread out across the century.

The aggregate net global market impacts in each decade are displayed in Figure 9.7. They reflect a change in welfare from the baseline that would have occurred if climate remained the same. With the experimental sensitivity model, the net impacts generally linger near zero through 2060 for all the climate scenarios except the moderate PCM scenario. After 2060, damages start to increase slowly for the CCSR and HAD2 scenarios and more rapidly for the HAD3 and CGCM1 scenarios. Net damages are not apparent in the CSIRO scenario until 2100. The net impacts in the PCM scenario are beneficial and increase linearly with time. These results can largely be explained by the global temperature predictions of each climate model. The mild climate forecasts at the beginning of the century and with PCM, lead to net benefits or no effects, whereas the more severe climate scenarios near the end of the century with many climate scenarios lead to large damages. With the cross section

model, the net impacts for the globe are near zero for the century for the CSIRO, CCSR, CGCM1, and HAD3 climate scenarios. With the HAD2 scenario and especially the PCM scenario, the impacts are beneficial. The cross sectional impacts are smaller than the experimental impacts as expected because it is less climate sensitive.

As a fraction of GDP, these net damages are relatively small. They are small at first, because they hardly differ from zero. Later in the century, they remain small because GDP has grown so much faster than the damages have grown. For example, world GDP is forecasted to be \$200 trillion by 2100 whereas even in the worst scenario, the net climate damages are only \$300 billion.

Although net global impacts may be relatively small, they hide much larger changes that are evident in each region as can be seen in Figure 9.8. The map illustrates the impacts in every country in 2100 for the PCM and HAD3 climate scenarios. Only the results of the experimental response function are shown. The impacts for the cross-section response function are similar but far more muted. Although most of the world benefits in the mild PCM climate scenario, there are damages in Africa, India, Central America, and the South Pacific. In contrast to what is happening to the low latitudes, the high latitudes are predicted to enjoy large benefits. The damages in the HAD3 climate scenario are both more pronounced and more widespread. There are extensive damages to especially Africa but also Latin America and Southern Asia. Virtually all countries in the low latitudes are at risk. These damages even begin to extend to the mid-latitudes by 2100. Nonetheless, high latitude countries are predicted to benefit in this scenario. These regional effects are driven primarily by what is happening to the agriculture sector.

## 9.5. Conclusion

This study combines natural science and economics to predict the future impact of climate change. The twelve forecasts provide a detailed description of how impacts may unfold decade to decade for each country of the world. Net market impacts for the entire globe are small at first and only after 2060 do the more severe scenarios predict large enough temperature increases to generate sizeable net negative global impacts. Net global effects are predicted to be modest primarily because large damages in the low latitudes are offset by benefits in the temperate and high latitudes.

Although net global impacts may remain small into the end of the century, impacts in the tropical and subtropical regions can be harmful by 2020. Warming in the low latitudes is especially damaging to agriculture and these damages increase as warming becomes more severe over time. Asia is particularly vulnerable in large part due to the size of the Asian agriculture sector. As a fraction of GNP, however, Africa is the most vulnerable region since a large fraction of the economy in Sub-Saharan Africa is dependent on agriculture. The model also predicts that agriculture in the former USSR, Eastern Europe, and Western Europe will benefit from warming in most scenarios. North America will also benefit except for climate scenarios that predict a reduction in precipitation in the region.

The study suggests that the first market impacts to become identifiable will be in the agricultural sector in the high and low latitudes. The study predicts benefits in the high latitudes and damages in the low latitudes. Ironically, very few empirical impact studies have been done in these regions, so these forecasts of future impacts remain uncertain. In the mid latitudes, the first evidence of climate impacts may not occur until the end of the century.

The study, however, does not measure all effects. For example, the study omits impacts to health and ecosystems because of the absence of reliable welfare measures and the inclusion of adaptation. The study also does not examine extreme events or climate variance. In this case, it is the absence of a link to near term emissions of greenhouse gases that keep these phenomena from being included. With additional research, many of these effects can be included in the analysis and they may well change the results.

#### ACKNOWLEDGEMENTS

Funding was provided by the Electric Power Research Institute. The views are the authors alone.

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Table 9.1

## Temperature and Precipitation Change Predictions for Climate Models in 2100

Region	PCM		CSIRO		CCSR	
	T(C°)	P(%)	T(C°)	P(%)	T(C°)	P(%)
L. Am.	2.0	6.5%	3.2	1.6%	4.2	-0.7%
Africa	2.3	11.9%	3.8	1.9%	4.7	13.1%
Asia	2.5	19.1%	3.5	1.4%	3.8	-11.6%
Oceania	2.0	6.8%	3.1	1.0%	3.3	-15.1%
N. Am.	2.5	7.2%	4.6	2.8%	3.1	29.9%
W Eur.	2.1	7.1%	3.7	14.9%	3.4	1.4%
USSR&EE	3.1	12.9%	4.8	12.5%	3.3	10.6%
Globe	2.5	16.5%	3.7	2.6%	3.8	-4.5%
Region	HAD2		HAD3		CGCM 1	
	T(C°)	P(%)	T(C°)	P(%)	T(C°)	P(%)
L. Am.	3.6	-16.9%	4.7	-22.0%	4.9	-4.1%
Africa	3.9	11.6%	4.4	3.2%	6.2	-10.3%
Asia	3.7	13.6%	4.4	9.1%	5.2	-6.4%
Oceania	2.1	-2.8%	3.6	4.5%	4.4	-18.5%
N. Am.	5.8	-12.3%	5.6	14.6%	5.7	3.3%
W Europe	5.0	-3.6%	4.5	-7.1%	3.7	-4.0%
USSR&EE	5.8	1.0%	5.6	-4.8%	5.6	7.8%
Globe	4.0	7.7%	4.6	4.1%	5.2	-5.6%

All climate measures are weighted by population not area.

Table 9.2

Agricultural Impacts By Region In 2100<sup>a</sup>

Climate Model	Climate Response Function			
	Experimental		Cross-Sectional	
	Low Latitude	High Latitude	Low Latitude	High Latitude
CGCM1	-321	188	-9	54
HAD3	-297	218	-9	31
HAD2	-273	285	0	78
CSIRO	-211	239	-3	35
CCSR	-175	167	-1	36
PCM	-7	258	12	81

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<sup>a</sup> Impacts are in billions of dollars. Positive values are benefits and negative values are damages. The low latitudes include Latin America, Africa, South Asia, and the Pacific and the high latitudes are the rest of the world.