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PEW CENTER ON Global CLIMATE CHANGE

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Prepared for the Pew Center on Global Climate Change

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

Over the next century, global climate change is likely to have substantial consequences for the economy of the United States and the welfare of its citizens. As scientists work to narrow remaining uncertainties about the magnitude and timing of future warming, it is becoming increasingly important that we improve our understanding of the likely implications for human and natural systems.

In this report, a team of authors led by Dale Jorgenson of Harvard University developed an integrated assessment of the potential impacts of climate change on the U.S. market economy through the year 2100. The analysis combines information about likely climate impacts in specific market sectors with a sophisticated computable general equilibrium model of the U.S. economy to estimate effects on national measures of productivity, investment, consumption and leisure. To account for uncertainties—both in the trajectory of future climate change and in the ability of different sectors to adapt—a variety of scenarios were modeled to characterize a range of possible outcomes.

The results indicate that climate change could impose considerable, lasting costs or produce smaller, temporary benefits for the U.S. market economy in coming decades. Importantly, potential costs under pessimistic assumptions are larger and persist longer than potential benefits achieved under optimistic assumptions. Because of “threshold effects” in key sectors like agriculture, initial benefits from a moderate amount of warming begin to diminish and eventually reverse as temperatures continue to rise toward the end of the century and beyond. These findings suggest that near-term action to limit the pace and scale of future climate change would be warranted not only because the potential damages outweigh potential benefits (which are transient in any case), but because early intervention would reduce the long-term damage under either set of assumptions, and reduce the need for more costly measures if pessimistic scenarios materialize.

This study makes an important contribution to our current understanding of the potential impacts of climate change, but it represents at best a partial assessment of the full range of those impacts. Certain market sectors (e.g., tourism) and a variety of indirect effects (e.g., climate change induced healthcare expenditures) could not be included because of a lack of data. Even more significantly, the analysis does not account for critical non-market impacts such as changes in species distributions, reductions in biodiversity or loss of ecosystem goods and services. These types of effects are described in a companion Pew Center report—*A Synthesis of Potential Impacts of Climate Change on the United States*—but remain extremely difficult to value in economic terms. Their inclusion in a more complete evaluation of both market and non-market impacts would almost certainly offset any temporary market benefits and add to the negative impacts, thereby underscoring the case for mitigative action.

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Executive Summary

The continued accumulation of heat-trapping gases in the atmosphere is projected to have far-reaching consequences for earth's climate in coming decades. For example, in 2001, the Intergovernmental Panel on Climate Change (IPCC) predicted that average global temperatures could rise anywhere from 1.4°C to 5.8°C (2.5-10.4°F) over the 21st century, with warming for the United States as much as 30 percent higher. Climatic shifts of this magnitude would affect human and natural systems in many ways. Therefore, quantifying these impacts and their likely costs remains a critical challenge in the formulation of appropriate policy responses.

This study aims to advance understanding of the potential consequences of global climate change by examining the overall effect on the U.S. economy of predicted impacts in key market activities that are likely to be particularly sensitive to future climate trends. These activities include crop agriculture and forestry, energy services related to heating and cooling, commercial water supply, and the protection of property and assets in coastal regions. Also considered are the effects on livestock and commercial fisheries and the costs related to increased storm, flood and hurricane activity. Finally, the analysis accounts for population-based changes in labor supply and consumer demand due to climate-induced mortality and morbidity. Impacts in each of these areas were modeled to estimate their aggregate effect on national measures of economic performance and welfare, including gross domestic product (GDP), consumption, investment, labor supply, capital stock and leisure.

At present, our knowledge of the direct or indirect impacts of climate change on a broad range of economic activities is incomplete. Accordingly, there are important sectors and activities—such as tourism—that are omitted from this effort. Similarly, there is little information concerning possible interactions among the benefits and costs in different sectors. For example, the impacts on crop and livestock agriculture may have consequences for human health. Given the absence of reliable insights into such externalities or spillovers, these effects are also excluded from consideration. These limitations suggest that the results of this analysis are likely to understate the potential market impacts of climate change.

More importantly, this analysis does not consider the non-market impacts of climate change such as changes in species distributions, reductions in biodiversity, or losses of ecosystem goods and services. These considerations are essential to a complete evaluation of the consequences of climate change but are very difficult to value in economic terms. A companion Pew Center report, *A Synthesis of Potential Impacts of Climate Change on the United States,* provides more detail on the relative vulnerability of different U.S. regions to both the market and non-market impacts of climate change.

To capture the range of market consequences potentially associated with climate change in the United States and to address the considerable uncertainties that exist, several distinct scenarios were developed for this analysis. Each incorporates different assumptions about the magnitude of climate change over the next century and about the direction and extent of likely impacts in the market sectors analyzed. Specifically, three different levels of climate change (low, central and high) were considered in combination with two sets of market outcomes (optimistic and pessimistic) for a total of six primary scenarios. In terms of climate, the low, central and high scenarios encompass projected increases in average temperature ranging from 1.7ºC to 5.3ºC (3.1-9.5ºF) by 2100, together with precipitation increases ranging from 2.1 to 6.6 percent and sea-level rise ranging from 17.2 to 98.9 cm (7-40 inches) over the same period. In terms of impacts, the optimistic and pessimistic scenarios reflect a spectrum of outcomes from the available literature concerning the sensitivity of each sector to climatic shifts and its ability to adapt. As one would expect, the optimistic scenarios generally project either smaller damages or greater benefits for a given amount of climate change compared to the pessimistic scenarios.

Because several of the market sectors included here are especially sensitive to changes in precipitation, two additional scenarios were analyzed. The first assumes the high degree of temperature change combined with lower precipitation (“high and drier”) while the second assumes the low level of temperature change combined with higher precipitation (“low and wetter”).

By introducing the sector-specific damages (or benefits) associated with each of these scenarios into a computable general equilibrium model that simulates the complex interactions of the U.S. economy as a whole, the combined effect of climate impacts across multiple sectors could be assessed in an integrated fashion. Detailed results are described in the body of this report, but five principal conclusions emerge:

1) Based on the market sectors and range of impacts considered for this analysis, projected climate change has the potential to impose considerable costs or produce temporary benefits for the U.S. economy over the 21st century, depending on the extent to which pessimistic or optimistic outcomes prevail. Under pessimistic assumptions, real U.S. GDP in the low climate change scenario is 0.6 percent lower in 2100 relative to a baseline that assumes no change in climate; in the high climate change scenario, the predicted reduction in real GDP is 1.9 percent. Under the additional "high and drier" climate scenario, however, real GDP is reduced more dramatically—by as much as 3.0 percent by 2100 relative to baseline conditions. Furthermore, under pessimistic assumptions negative impacts on GDP grow progressively larger over time, regardless of the climate scenario. In contrast, under optimistic assumptions real U.S. GDP by 2100 is 0.7 to 1.0 percent higher than baseline conditions across the low, central and high climate scenarios, but these benefits eventually diminish over time. Nevertheless, to the extent that responses in certain key sectors conform to the optimistic scenarios, there is a distinct possibility that some degree of climate change can provide modest overall benefits to the U.S. economy during the 21st century.

2) Due to threshold effects in certain key sectors, the economic benefits simulated for the 21st century under optimistic assumptions are not sustainable and economic damages are inevitable. In contrast to the pessimistic scenarios which show increasingly negative impacts on the economy as temperatures rise, the economic benefits associated with optimistic scenarios ultimately peak or reach a maximum. Specifically, the agriculture and energy sectors initially experience significant cost reductions, but only so long as climate change remains below critical levels. Once temperature and other key climate parameters reach certain thresholds, however, benefits peak and begin to decline—eventually becoming damages. Different thresholds apply in different sectors and the time required to reach them depends on the rate at which warming occurs. In the high climate change scenario, the trend toward economic benefits under optimistic assumptions slows and peaks around mid-century, whereas, in the central climate case, this transition appears toward century's end. In the optimistic, low climate change scenario, benefits continue to accrue throughout the 21st century. Nevertheless, the existence of these thresholds means that continued climate change—even if it proceeds slowly—eventually reverses market outcomes so that predicted economic benefits are only transient and temporary.

3) The effects of climate change on U.S. agriculture dominate the other market impacts considered in this analysis. Currently, the agriculture, forestry and fisheries industries represent about 2.0 percent of total U.S. industrial output and about 3.5 percent of real GDP. However, agriculture accounts for a much larger share of the overall climate-related economic impact estimated in this analysis. For example, across the low, central and high climate change scenarios, field crop and forestry impacts account for over 70 percent of the total predicted effect of climate change on real GDP under optimistic assumptions and almost 80 percent of the total GDP effect under pessimistic assumptions. These figures rise to 75 and 85 percent, respectively, if one includes climate effects on livestock and commercial fisheries. Clearly, significant impacts in relatively small sectors can exert a disproportionate influence on the overall economic consequences of a given climate change.

4) For the economy, wetter is better. All else being equal, more precipitation is better for agriculture —and hence better for the economy—than less precipitation. Not surprisingly, reductions in precipitation are costlier at higher temperatures than at lower temperatures and the negative impacts of drier climate conditions are greater under pessimistic assumptions than they are under optimistic assumptions. These results are driven by model assumptions about the relationship between agricultural output and different levels of precipitation; they do not consider regional or seasonal variability nor do they account for possible changes in the incidence of extreme events such as drought and flooding. To date, variations in precipitation have not been routinely incorporated in assessments of the agricultural impacts of climate change; nevertheless, they are potentially quite important and could significantly affect actual benefits or damages associated with climate change in this sector of the economy. Therefore, in future assessments, more attention should be paid to the specific effects of precipitation under different climate scenarios.

5) Changes in human mortality and morbidity are small but important determinants of the modeled impacts of climate change for the U.S. economy as a whole. An increase in climate-induced mortality or illness reduces the population of workers and consumers available to participate in the market economy, in turn leading to a loss of real GDP. In this analysis, mortality and morbidity effects alone account for 13 to 16 percent of the aggregate predicted effect of climate change on the economic welfare of U.S. households. Failure to include such effects therefore understates the potential market impacts of climate change as well as the likely benefits of climate-mitigating policies. Furthermore, the economic consequences of the mortality and morbidity effects arising from a given change in temperature are at the low end of mortality valuations found in the reported literature. Hence, the contribution of health effects to the aggregate market impacts of climate change could be even higher than these results suggest.

Taken together, these findings have important implications for current policy debates and for ongoing efforts to further refine our understanding of the likely impacts of global climate change. From a policy standpoint their primary relevance lies in the extent to which they support (or diminish) the case for intervention to avoid or mitigate the impacts being evaluated. Specifically, does the analysis suggest that the likely consequences of future climate change will be sufficiently negative as to warrant near-term actions aimed at reducing greenhouse gas emissions? This question is all the more difficult to answer because the benefits of policy intervention tend to accrue slowly, over a long period of time, while the costs of mitigative action must be borne in the near term.

On the one hand, the results of this analysis clearly point to the possibility that climate change could produce measurable negative impacts on the U.S. economy within this century that might justify anticipatory policy responses. On the other hand, the fact that some of the scenarios analyzed produce positive, albeit temporary, benefits for the U.S. economy in the same timeframe might seem to weigh in favor of forgoing, or at least delaying, such actions.

A number of nuances in these results—together with several larger considerations related to limitations inherent in the study's design—argue against the latter conclusion. Within the scope of this analysis, perhaps the most important point is the fact that most, if not all, potentially positive impacts of climate change under optimistic assumptions are likely to be transient and unsustainable over the long run in the face of steadily rising temperatures. If, on the other hand, pessimistic assumptions prove to be more correct, the economic impacts of climate change are not only immediately negative, but worsen steadily over time. Thus, the potential for temporary economic benefits must be balanced against the potential for immediate and lasting economic damages.

A second important point is that the modeling results reveal asymmetries in the magnitude of potential benefits versus potential damages. Specifically, the economic losses estimated under pessimistic assumptions are generally larger than the transient benefits gained under optimistic assumptions in all but the low climate change scenarios. Moreover, the asymmetry becomes more pronounced with rising temperatures as certain types of costs—such as those associated with extreme weather events—increasingly offset possible benefits to other sectors of the economy.

A further caution relates to the partial and incomplete nature of the analysis itself. This effort was limited from the outset to considering only market impacts of global climate change within the United States. As has already been noted, it was not possible to include all potentially climate-sensitive market sectors in the analysis; nor was it possible to account for all externalities or spillover effects. Moreover, the results of this analysis are not likely to be representative of other parts of the world, especially for those countries whose overall economic well-being is more closely tied to sectors like agriculture. For these countries, the potential damages associated with future climate change could be a much larger proportion of GDP than in the United States and the downside risks under pessimistic assumptions—especially in regions where climate change is likely to cause increasingly warmer *and* drier conditions—could be far more substantial.

Even more significant, in terms of drawing policy conclusions from these results, is the fact that the underlying analysis does not address a host of potential non-market impacts associated with climate change. These include shifts in species distribution, reductions in biodiversity, losses of ecosystem goods and services and changes in human and natural habitats. Such impacts—many of which are explored in other Pew Center reports—are probably of great concern to the public and could carry substantial weight in future policy deliberations. They are, however, extremely difficult to value in economic terms. To the extent that they have been assessed—even qualitatively—the results suggest that climate-related impacts on natural systems are far more likely, on the whole, to be negative rather than positive. As such they would tend to add to any negative market impacts associated with future climate change, while offsetting potential market benefits of the kind simulated in this study under optimistic assumptions.

In sum, the disparity in results between optimistic and pessimistic scenarios—and the likelihood that a consideration of non-market impacts would tend to exacerbate this disparity—highlights the continuing uncertainty associated with quantifying climate change impacts. The fact that the economic losses associated with pessimistic scenarios are both larger and more continuous than the transient benefits gained under optimistic scenarios would seem, by itself, to provide some support for cautionary action on climate change. In fact, such action—by slowing the pace and magnitude of temperature increases in the coming decades—actually could forestall any damages or even improve the odds that optimistic rather than pessimistic outcomes prevail. If, on the other hand, worst-case scenarios appear more likely over time and ultimately justify more dramatic intervention, early efforts to achieve moderate near-term emissions reductions may help avoid the need for more costly measures later on. Meanwhile, high priority should be given to improving and integrating future assessments of market and non-market outcomes and to refining our understanding of the probabilities associated with varying degrees of climate change and the positive or negative responses that follow.

I. Introduction

Current projections suggest that global climate change is likely to have far-reaching consequences for the United States over the next century. Calculating the market and non-market impacts of these consequences remains a critical challenge. Market impacts refer to changes in the demand, supply and price of marketed goods and services. Non-market impacts include changes in mortality, health and quality of life, as well as effects on environmental goods and services, habitats and ecosystems, and biodiversity. The impacts of climate change on particular sectors of the U.S. economy can appear favorable under certain conditions and unfavorable under others. To further complicate matters, there is considerable uncertainty about the relative probabilities associated with different projections of future climatic trends and equally significant uncertainty about the magnitude of benefits and costs likely to arise from a particular climate trajectory.

This analysis has a narrow but important mission. Specifically, the goal is to extract from the available literature a plausible range of estimated market outcomes for the U.S. economy as a result of global climate change. The market impacts cover the effects on crop agriculture and forestry, on energy services related to heating and cooling, on commercial water supplies, on the need for coastal property protection and on the lives and health of U.S. residents. In addition, consideration is given to impacts on livestock and commercial fisheries and to storm, flood and hurricane damages. These effects, driven by varying climatic conditions, form the basis of an integrated assessment of market damages. By introducing sector-specific damage estimates into a computable general equilibrium (CGE) model designed to simulate the growth and structure of the U.S. economy, it is possible to quantify the impacts of sectoral changes on overall levels and patterns of economic activity.

An important underlying point throughout the analysis that follows is the notion that market impacts are but one set of climate change phenomena and that aforementioned non-market impacts merit equal attention in the crafting of national and international climate policies. A broad range of climatic impacts on natural systems—including changes in species diversity or losses in ecosystem goods and services—have been reviewed in several previous Pew Center Reports (see http://www.pewclimate.org/global-warming-in-depth/environmental_impacts/reports).

The results generated in this analysis stem from a single methodological view of the nation's economy and indicate a range of possible market outcomes, depending on how climate conditions change over the next century. As such, they contribute to one aspect of the broader analytical process needed to fully inform the development of future climate policies. Ultimately, a comprehensive assessment of the benefits and costs of climate change policies requires that estimates of market impacts, non-market impacts and mitigation costs be combined into a coherent whole. Quantifying market consequences is therefore but one—albeit important—step in the development of a more inclusive and comprehensive cost-benefit assessment of global climate change.

The remainder of this report is organized as follows. Section II provides an overview of the analysis, while Section III provides additional detail about climate change and its potential effects on different sectors of the market economy. Section IV describes the predicted consequences of these sectoral impacts for national measures of overall economic performance and welfare. This section also discusses the causal mechanisms underlying these consequences. Section V summarizes five major findings drawn from the results presented in Section IV. The implications of these findings for future climate change analysis and public policy are discussed in Section VI.

II. Analytical Overview

This analysis builds on an earlier effort (Scheraga et al., 1993) that estimated the aggregate economic effects of climate change. Temperature- and sea level-dependent impact functions were used to approximate the ranges, rates and levels of damages (or benefits) associated with alternative climate change scenarios. Key market impacts associated with these scenarios and damage relationships were simulated using a detailed model of the U.S. economy known as the Inter-temporal General Equilibrium Model, or IGEM. IGEM is a computable general equilibrium (CGE) model developed by Jorgenson, Wilcoxen and Ho (see Appendix B for more detail). It served to integrate the changes predicted for specific sectors and, in turn, generated estimates of market responses within the broader economy.

This analysis extends and updates the earlier work by Scheraga et al. (1993) in the following important ways:

- It uses more recent climate scenarios developed for the Pew Center by Dr. Tom Wigley and reported in Wigley (1999, 2000);
- It uses more recent studies, such as the 2001 U.S. National Climate Change Assessment, to develop sector impact estimates; and
- It adds two effects not previously examined, namely: climate impacts on water supply and human health.

The initial phase of this exercise involved developing updated damage estimates for specific sectors of the U.S. economy under altered climate conditions. Introduction of these damage functions into IGEM allowed for the combined estimation of the direct and indirect market consequences resulting from climate change. The damage estimates rely on available data from a wide variety of impact studies developed over the last decade or so. Using model results to estimate and quantify impacts establishes an empirical basis for what is often merely an application of expert judgment (e.g., Nordhaus, 1991 and

1994; Cline, 1992; Frankhauser, 1995; Tol, 1999; Nordhaus and Boyer, 2000). The goal of the current approach is to describe and quantify how market processes might be affected over the coming century as predicted climate trends materialize and begin to influence different sectors of the economy.

The damages portrayed in this analysis are functions of temperature, precipitation and sea-level rise. Their magnitudes depend on the trajectory of climate changes implied by a specific climate change scenario. Recognizing the uncertainties inherent in predicting these relationships, the analysis depicts both optimistic and pessimistic outcomes for each sector in response to three primary climate change scenarios, as well as two additional scenarios that vary key assumptions concerning precipitation.

Impacts are quantified for the following areas of economic activity:

- Crop agriculture;
- Forestry;
- Energy services related to space heating and cooling;
- Water supply;
- Coastal protection; and
- Population and labor supply, which are influenced by the following:
    - Air quality (mortality and morbidity consequences of the incremental ozone exposures arising from higher temperatures); and
    - Health (cardiovascular and respiratory mortality related to thermal stress).

Climate change impacts on livestock production and commercial fisheries, as well as climate-related changes in storm, flood and hurricane damages were explicit in the work of Scheraga et al. (1993) and are given limited consideration in this analysis. However, it was not possible—based on the available literature—to develop a broad range of optimistic and pessimistic damage functions for these sectors.

As previously noted, the IGEM model is a dynamic general equilibrium model of the U.S. economy that is capable of measuring the impacts of fundamental shifts in market activities within and among its represented industries. The model is described in detail elsewhere (e.g., Jorgenson and Wilcoxen, 1990, 1993; Jorgenson et al., 1992) and in Appendix B of this report. The following lists some of the key features of IGEM. Specifically, it:

- Provides a unified accounting framework consistent with the structure of the U.S Department of Commerce's Bureau of Economic Analysis National Income and Product Accounts, and with the principle that prices adjust to balance supply and demand;
- Considers multiple industries and joint production spanning 35 producing sectors and 35 available commodities;
- Covers all aspects of long-run economic growth, including growth in the supply of primary and intermediate inputs to production, rates and directions of technical change for each producing sector, and elasticities of substitution among inputs and commodities in production (and consumption);
- Recognizes the process of capital accumulation as the result of saving and investment behavior by households and businesses;
- Recognizes the role of capital as an essential input to production and consumption;
- Represents household decisions regarding present and future consumption and saving, and labor and leisure;
- Incorporates both backward-looking and forward-looking dynamics. The model is backward-looking in the sense that it recognizes capital availability as the result of past investment behavior. It is forward-looking in the sense that it assumes, first, that capital goods prices are equal to the discounted present value of future rental prices for capital services and, second, that household decisions occur with perfect foresight concerning future prices, interest rates and permanent income;
- Ensures that markets balance in both value and quantity terms, including the limits on private investment arising from domestic and foreign saving behavior and the net expenditures of governments;
- Bases change on observed market behavior, revealed over time; and

- Includes traditional measures of economic performance (e.g., Gross Domestic Product or GDP, income, consumption, investment, etc.), as well as measures that focus directly on individual and collective welfare (e.g., household expenditures on goods, services, and leisure).

The effects of climate change are captured in the model through damage functions that describe how unit costs (i.e., productivity) or the supply of input factors change in response to altered climate conditions. Damage functions for crop agriculture, forestry, energy and water are expressed as the percentage change in unit production costs caused by changes in temperature and precipitation while keeping production quantities constant. Equivalently, these damage functions represent changes in productivity as defined by the amount of inputs required to produce a unit of output. For coastal protection, the damage function is a measure of the diversion of investment goods to uses unrelated to production or output. In other words, sea-level rise creates costs by necessitating the diversion of investment goods for purposes that do not add to the economy's productive capital stock; in this case, solely to protect existing coastal assets. As a result, the supply of investment goods available as capital inputs to other market activities is diminished. In this analysis, there is no presumption as to the destruction of capital caused by rising sea levels, whether compensated or not by private insurance or government assistance. Finally, the mortality and morbidity effects related to thermal stress and ozone exposures directly affect the total number of consumers demanding goods and services as well as the potential labor supply or, equivalently, the total amount of time available to the working-aged population for allocation to work and leisure.

III. Details of the Analysis: Climate Scenarios and Damage Estimates

As indicated in the last section, five climate change scenarios (three primary scenarios plus two additional scenarios that vary key assumptions about precipitation) form the drivers for estimating direct effects. The scenarios appear in Wigley (1999, 2000) and describe alternative climate patterns from a scenario-generating (SCENGEN) analysis of selected general circulation model (GCM) results (Hulme et al., 1995). Together, they cover a wide range of climatic possibilities based on current estimates of potential changes in mean global temperature and different GCM-based assumptions about resulting temperature and precipitation changes averaged over the United States. Table 1 summarizes important parameters for each of the climate change scenarios.

Table 1

Summary of Modeled **Climate Change Effects**

	Global Mean Temperature Increase (°C)				U.S. Mean Temperature Increase[a] (°C)				Sea Level Rise (cm)				U.S. Mean Precipitation Increase [b] (#1,2,3), [c] (#4), [d] (#5) (% change)			
Year	2020	2050	2080	2100	2020	2050	2080	2100	2020	2050	2080	2100	2020	2050	2080	2100
Scenario 1 Low	0.3	0.7	1.1	1.3	0.4	1.0	1.4	1.7	2.6	7.4	13.1	17.2	0.5%	1.2%	1.8%	2.1%
Scenario 2 Central	0.4	1.3	2.1	2.4	0.6	1.7	2.7	3.1	7.2	21.8	42.1	54.8	0.7%	2.2%	3.4%	3.9%
Scenario 3 High	0.8	1.8	3.1	4.0	1.0	2.4	4.0	5.3	16.2	42.3	74.5	98.9	1.2%	2.9%	5.0%	6.6%
Scenario 4 High & Dry	0.8	1.8	3.1	4.0	1.0	2.4	4.0	5.3	16.2	42.3	74.5	98.9	-2.8%	-6.6%	-11.2%	-14.8%
Scenario 5 Low & Wet	0.3	0.7	1.1	1.3	0.4	1.0	1.4	1.7	2.6	7.4	13.1	17.2	2.5%	6.4%	9.4%	11.0%

a. Estimated ratio from Wigley (1999), Figure 9, estimated as +1.3 degrees per degree C change in global mean temperature.

b. Estimated ratio from Wigley (1999), Figure 10, estimated as +1.6% per degree C change in global mean temperature.

c. Estimated from Wigley (2000) and Hulme et al. (1995) SCENGEN of the BMRC GCM for precipitation sensitivity of –3.7% per degree C in global mean temperature.

d. Estimated from Wigley (2000) and Hulme et al. (1995) SCENGEN of the HADCM2 GCM for precipitation sensitivity of +8.6% per degree C in global mean temperature.

On average, the fifteen GCMs within SCENGEN project that the United States will experience a 1.3°C change in mean temperature and a 1.6 percent change in precipitation for each degree of change in mean global temperature. There is considerably more variation across GCMs with respect to the precipitation changes they predict compared to the temperature effects they predict. These differences underscore the technical difficulty of using GCMs to estimate local and regional impacts, particularly where water resources are concerned (Felzer and Heard, 1999). For this reason, two additional scenarios were developed to extend the range of possible precipitation changes considered in this analysis. Specifically, the wetter and drier scenarios assume average precipitation changes of +8.6 percent and –3.7 percent, respectively, for each degree of change in mean global temperature. These figures correspond to the range of precipitation sensitivities given by two GCMs within SCENGEN; the estimate used in the wetter scenario derives from the Hadley Centre Unified Model 2 Transient model (HADCM2), UK and the estimate used in the drier scenario derives from the Bureau of Meteorology Research Centre (BMRC), Australia.

Much of the growing literature that examines the direct effects of climate change on particular sectors and activities is detailed in the Pew Center's *Environment* Series (see Smith, 2004 for a synthesis of this work). As discussed in this series and elsewhere (e.g., Nordhaus, 1994), the prevailing literature reports quite divergent estimates of the market impacts of climate change on the United States. They suggest that for some activities under some circumstances, climate change has the potential to provide market benefits, while for other sectors or under different circumstances, climate change results in economic costs. The studies drawn upon for this analysis capture this divergence and reflect the optimistic and pessimistic extremes of published estimates. Table 2 describes the sources used to generate climate response functions for different market sectors in this analysis.

Table 2

Sources of Climate Response Funtions for Market Sectors

Impacts on:	Optimistic sources	Pessimistic sources
Crop agriculture	USNCCA, 2001	Adams et al., 1990
Forestry	Sohngen and Mendelsohn, 1999	Callaway et al., 1995
Cooling and heating	Rosenthal et al., 1995	Morrison and Mendelsohn, 1999
Water supply	Hurd et al., 1999[a]	Frederick and Schwartz, 1999[a]
Coastal and storms	Yohe et al., 1999	Titus et al., 1991
Air quality	Chestnut and Mills, 2000	Chestnut and Mills, 2000
Health	Martens, 1997	Kalkstein and Greene, 1997

a. When computing impacts on water supply costs in the "low and wetter" scenario, estimates based on Frederick and Schwartz (1999) appear beneficial in comparison to those based on Hurd et al. (1999). Hence, to preserve numeric consistency, the Frederick and Schwartz results were used to construct the optimistic impacts and the Hurd results were used to construct the pessimistic outcomes for this scenario.

Table 3 provides summary estimates of the direct effects of climate change on specific market sectors. Here, positive effects represent market benefits while negative effects signal economic costs. These impacts are shown as annual averages over the period 2000–2100 and result from applying the range of damage functions developed from the available literature to the climate change scenarios summarized in Table 1. Appendix A contains detailed descriptions of the assumptions and methodologies used to develop the damage functions that lead to the summary estimates shown below.

Table 3

Summary of the Estimated Direct Market Impacts of Climate Change

	Optimistic			Pessimistic		
	Low	Central	High	Low	Central	High
Crop agriculture	+13.6	+20.4	+23.6	-14.0	-25.8	-39.2
Forestry	+4.6	+8.4	+12.7	-3.7	-6.7	-10.1
Water supply	+1.7[a]	-2.9[a]	-4.2[a]	-11.2[b]	-20.6[b]	-31.3[b]
Energy	+4.0	+6.7	+5.8	-0.5	-1.1	-2.2
Coal	+10.5	+17.5	+15.1	-0.3	-0.8	-1.6
Wood	+10.5	+17.5	+15.1	-0.3	-0.8	-1.6
Petroleum	+9.4	+15.7	+13.5	-0.3	-0.8	-1.6
Electricity	-4.9	-8.1	-7.0	-0.7	-1.6	-3.2
Natural gas	+10.1	+17.0	+14.6	-0.3	-0.8	-1.6
Coastal protection	-12	-37	-69	-393	-1,219	-2,265
Mortality						
Population	+1,170	+2,126	+3,170	-1,813	-3,295	-4,906
Working aged	+571	+1,040	+1,555	-884	-1,611	-2,409
Morbidity	0	0	0	-141,278	-256,529	-387,057

All values represent average annual changes for the period 2000–2100.

For crop agriculture, forestry, water supply and energy, the units are percentage improvements (+) or deteriorations (–) in unit cost functions or productivity.

For coastal protection, the units are millions of constant 2000 dollars.

For mortality, the units are persons gained (+) or lost (–).

For morbidity, the units are labor-leisure days lost for the working-aged population.

[a] Hurd et al. (1999)

[b] Frederick and Schwartz (1999)

The estimates shown in Table 3 indicate that under optimistic assumptions, crop agriculture and forestry become less expensive (more productive) with climate change, the higher costs of electricity-based space cooling are more than offset by the lower costs of fossil fuel-based space heating, and avoided deaths from milder winter weather more than compensate for any additional deaths associated with hotter summers. Under pessimistic assumptions, crop agriculture and forestry become more expensive (less productive), space heating and cooling are generally more expensive (less productive), and mortality and morbidity increase, on balance, as a result of higher temperatures.

Furthermore, for forestry and mortality, both benefits and costs increase as climate change becomes more pronounced. With optimistic outcomes in these areas, higher temperatures and precipitation secure greater market benefits for the economy. However, under pessimistic assumptions, higher temperatures and precipitation impose greater costs.

For water supply and coastal protection, climate change generally involves economic costs; water supply in the optimistic, low warming case is the lone exception. Moreover, in these sectors, increasing the severity of climate change makes matters unambiguously worse. Commercial water supplies become ever more costly as more inputs are required per unit of output and the growing need for coastal protection as sea level rises diverts ever more investment goods to non-productive uses.

The damage functions for crop agriculture and energy in this analysis feature a dynamic characteristic that is of particular interest and relevance to subsequent results. Under the pessimistic view, the unit costs for crop agriculture and space heating and cooling rise continuously with increasing temperatures, both within and across each of the climate scenarios. The higher the temperature, the greater is the adverse impact.

However, under the optimistic view, there are inflections in the climate response functions that occur when climate conditions reach key thresholds. For agriculture, the inflection occurs when the rise in U.S. mean temperatures reaches a threshold of just under 3.3ºC; the precipitation threshold occurs when the relative change in precipitation is slightly in excess of 130 percent. For energy, the inflection occurs when U.S. mean temperatures rise by more than 2.6ºC. Below these thresholds, climate change produces overall benefits that rise with increasing temperatures (and greater precipitation). These benefits occur because, on balance, temperature and rainfall conditions are favorable to agriculture and because reduced space heating costs offset increased space cooling costs. Above these thresholds, however, the benefits of climate change begin to erode. Continued warming, even with increased precipitation, is no longer as beneficial to agriculture and the increased costs of space cooling begin to dominate the savings associated with reduced space heating. Indeed beyond a U.S. mean temperature increase of 5.2ºC, climate change imposes an economic cost as the net benefits related to cooling and heating are fully dissipated. Once these inflection points or thresholds are passed, the benefit trends inherent in the optimistic outcomes are dampened and eventually reversed, as are any resulting benefits to the larger economy.

In terms of the relevant inflection point for agriculture, the predicted increase in mean U.S. temperature reaches the threshold level of 3.3°C by the year 2067 in the high climate change scenario, by 2110 in the central climate change scenario and by 2230 in the low climate change scenario. Together with precipitation effects, optimistic benefits for agriculture peak around 2075 in the high climate change scenario, are nearing their peak by 2100 in the central scenario, and are substantially below their peak by 2100 in the low climate change scenario.

In terms of the relevant inflection point for energy costs, the predicted increase in U.S. mean temperature reaches the threshold level of 2.6°C by 2055 in the high warming scenario and by 2077 in the central scenario; it remains well below this threshold by 2100 in the low climate change scenario. Hence, like agriculture, threshold effects are apparent for energy in both the central and high warming cases. In fact, the increase in U.S. mean temperature exceeds 5.2°C by 2100 in the high climate change scenario, resulting in overall energy costs to the economy by the end of the century.

Such inflections or thresholds are common in the literature on agriculture and climate change and arise from the quadratic relationships between crop production and temperature and precipitation. Though not employed in this analysis because they are neither as pessimistic nor as optimistic as those actually used, two studies demonstrate the nature of these climate change thresholds in agriculture. Reflecting a pessimistic view, the results from Adams et al. (1999) suggest that U.S. agriculture is near, or already has crossed, the temperature threshold and that additional warming—with precipitation and carbon dioxide (CO_2) levels held constant—unambiguously entails economic losses.

Providing an optimistic example, Mendelsohn et al. (1999) use a different modeling approach to generate a range of alternative possibilities. Divergent estimates of climate-related cost-benefit outcomes for crop agriculture depend on whether historical climate variability is included in the method used to aggregate regional effects into an overall measure of national impact and on whether the fertilization effects of exposing plants to higher CO_2 concentrations are included. In the absence of historically observed climate variation and depending on the choice of geographic weighting schemes, the “optimal” temperature for U.S. agriculture is estimated to be 1 to 4°C less than the current average. This result, consistent with the findings of Adams et al. (1999), suggests that the temperature threshold has already been crossed and that further increases in temperatures will have an adverse impact on agriculture. However, if observed climate variation is included and, again, depending on the choice of geographic weighting schemes, the "optimal" temperature for U.S. agriculture is estimated to be 1 to 6°C warmer than the current average. This suggests potential benefits to agriculture from future climate change. For Mendelsohn et al. (1999), the inclusion of observed climate variability shifts the predicted effects of modest warming from harmful to beneficial within the agriculture sector. However, even under the various weighting schemes used by Mendelsohn et al. (1999), there is the possibility that these benefits will give way to costs as climate conditions become more severe.

Leaving aside any interactions related to storm, hurricane and flood damages, variations in precipitation have large impacts on crop agriculture and water supply, small impacts on forestry costs and no measurable effects on the remaining market sectors considered in this analysis. Table 4 summarizes the impacts of precipitation and includes comparable effects from Table 3. Clearly, the large impacts estimated for crop agriculture and water supply mean that changes in precipitation will have an enormous effect on overall measures of the direct market consequences of climate change. More precipitation is beneficial and less precipitation is costly under both optimistic and pessimistic views. This result, like the existence of threshold effects discussed above, significantly influences the overall findings of this analysis and represents another important concern for future research.

Table 4

Variations in Precipitation Summary of the Estimated Impacts of Climate Change

	Optimistic		Pessimistic	
From Table 3	Low	High	Low	High
Crop agriculture	+13.6	+23.6	-14.0	-39.2
Forestry	+4.6	+12.7	-3.7	-10.1
Water supply	+1.7	-4.2	-11.2	-31.3
	Low and Wetter	High and Drier	Low and Wetter	High and Drier
Crop agriculture	+20.4	-1.1	+14.9	-88.1
Forestry	+4.3	+13.5	-3.7	-10.1
Water supply	+11.9[a]	-9.3[a]	+0.8[b]	-70.3[b]

Values represent average annual percent changes in unit cost functions, 2000–2100.

Positive numbers indicate benefits and negative numbers indicate costs.

a. Hurd et al. (1999)

b. Frederick and Schwartz (1999)

Before discussing further results of this analysis, it is useful to consider some limitations of the underlying study design. Policy evaluation necessarily involves a comprehensive examination of all relevant benefits and costs. In the arena of climate change, these benefits and costs clearly include both market and non-market considerations. Yet, this analysis focuses only on the former. It includes no measures of climate effects on habitats, ecosystems and biodiversity and their associated values to society. Similarly, no attempt is made to quantify society's willingness to pay for, or accept, changes in mortality and morbidity beyond their valuations at observed market prices (see Box 2 on page 38).

Second, there are limitations even within the market focus of this analysis. First, the possibility that initial benefits from warming will eventually reverse and create net costs in sectors like agriculture and energy clearly demonstrates the importance of accounting for non-linearities or thresholds in any damage functions. Accurate estimates of the potential benefits and costs of climate change depend on accurate characterizations of the underlying damage response functions. That the pace and scale of future climate shifts would likely influence the direction and magnitude of these response functions is both intuitive and realistic. Therefore the modeling community should consider and search for inflection points, thresholds and other non-linearities that would alter expected market responses to varying climate conditions (see Schneider and Thompson [2000] for additional information on the incorporation of these phenomena into economic modeling).

Third, the current analysis offers no spatial or geographical details for either the climate drivers or their market outcomes beyond what is inherent in the methodologies and assumptions from which they are drawn. While estimated national impacts represent an aggregate of regional consequences, there is presumed to be no differential regional variation as climate conditions change. Increasing the severity of climate change alters only the scale or magnitude of the estimated benefits or costs; the specific impacts predicted for any particular region stay proportionally similar.

Fourth, there is no consideration of the specific pathways whereby climate change could create benefits or damages within different sectors, nor are associated externalities or possible spillover effects included. For example, climate-related changes in food prices may indirectly affect health and healthcare expenditures. Similarly, effects on morbidity and mortality may prompt a restructuring of household expenditure patterns. Because these types of interactions generally have not yet been quantified in the available literature, they could not be included in the current analysis. Consequently, the results of the analysis are likely to understate the potential effects of future climate change.

Finally, there are undoubtedly numerous errors of omission among the identifiable market effects that were included in the analysis. That some potentially climate-sensitive sectors or economic activities (such as tourism) were not included does not imply that they are unimportant in assessing the true magnitude of potential climate impacts; rather, it reflects a lack of available data. For some sectors, impacts have not yet been quantified; for others, a sufficient diversity of studies does not yet exist to develop a range of possible outcomes.

IV. Market Effects and the Overall Economy

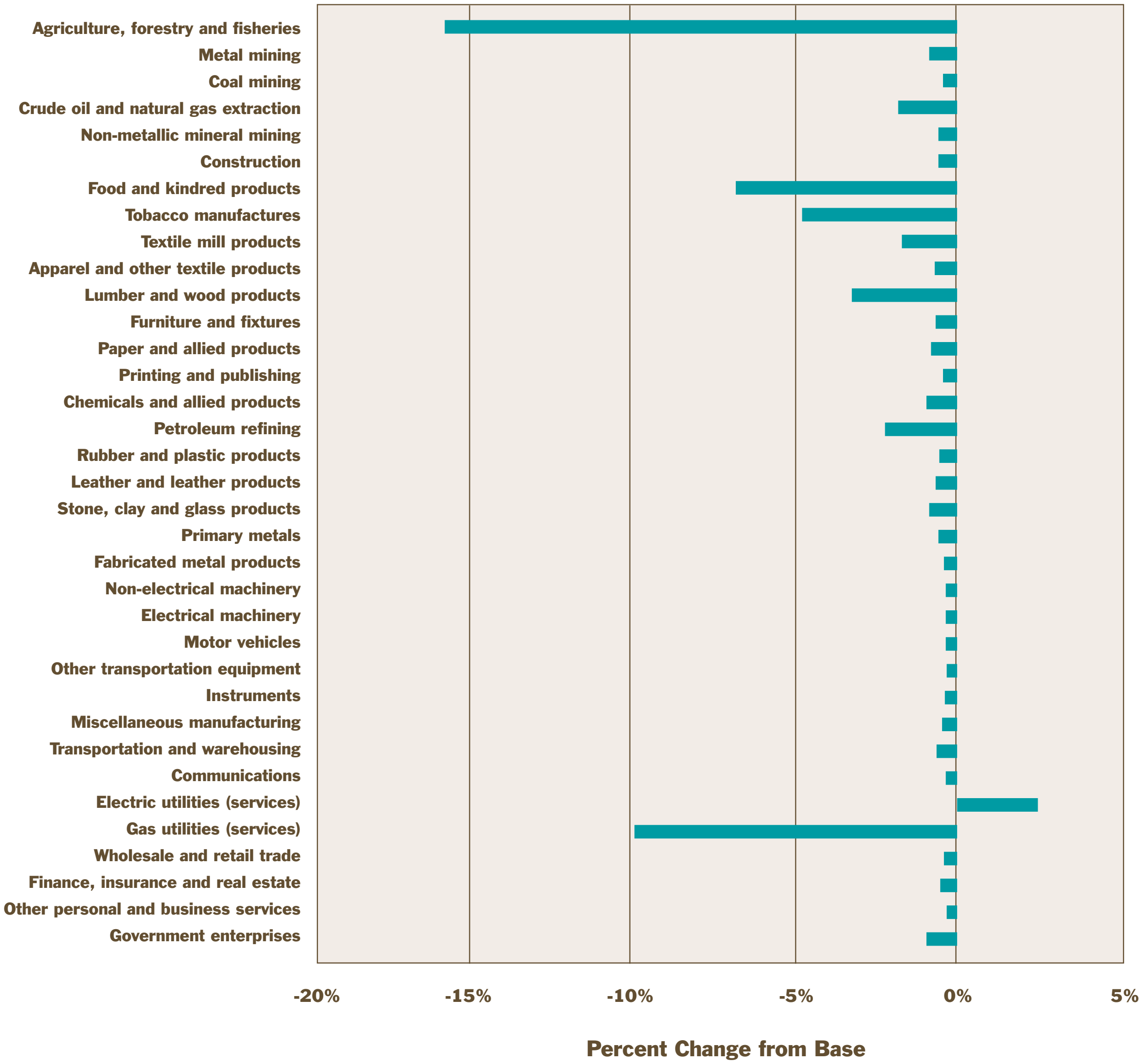
Climate change, operating through a variety of market drivers, can directly affect the costs and availabilities of economic outputs and inputs alike. In turn, these changes both directly and indirectly influence the level and structure of overall economic activity. For real GDP, which measures current, inflation-adjusted production, income and spending, there is ultimately a three to four percent spread between the most optimistic and most pessimistic results generated in this analysis. To the extent that climate change leads generally to reductions in unit costs (or, equivalently, improvements in productivity) and to a decline in mortality, the economy benefits and improves. Under optimistic assumptions, real GDP in 2100 could be almost one percent higher in the "central" and "low and wetter" climate change scenarios, compared to a baseline that assumes no market effects from climate change. By contrast, if pessimistic outcomes prevail, real GDP in 2100 could be two to three percent lower under extreme conditions (i.e., the "high" and "high and drier" climate change scenarios). (See Figures 3, 8, 13 and 14 for more detail.)

A. Outcomes Under Optimistic Cases

What accounts for these divergent assessments of the potential impacts of climate change? In the optimistic cases, commodity prices decline, as there are benefits from warming in all areas, with the exception of electricity-based space cooling, under each of the climate change scenarios. Prices fall because of the unit cost reductions that occur as a result of higher temperatures and increased precipitation. As shown in Figure 1, the price reductions are largest for agriculture and related industries. The price changes are next largest for energy where cost savings from reduced space heating more than compensate for increased expenditures on electricity-based space cooling. These unit cost reductions appear as productivity increases and, thus, represent additional productive resources that are available to other activities within the economy. To the extent that climate change does involve some costs even under optimistic assumptions (for example, water supply and coastal protection), these costs are small and do not offset the productivity gains achieved elsewhere in the economy. Finally, in these optimistic cases, there are more persons as consumers and as suppliers of labor services because climate change promotes longevity.

Figure 1

Impacts on **Domestic Supply Prices** in 2050: Central, Optimistic Scenario



The effects of these price changes are most directly observable in the altered structure of domestic production. As illustrated by Figure 2, agriculture, food, tobacco, lumber and textiles benefit measurably under the optimistic views of climate change. In addition, changing requirements for space conditioning produce an economy-wide substitution of natural gas for electricity.

Figure 3 portrays the time paths of real GDP for the optimistic low, central and high climate scenarios. The importance of climate change thresholds is clearly in evidence. In the low case, real GDP increases steadily but at a slowing rate, ending almost 0.75 percent higher by 2100. That agriculture and energy are nowhere near their benefit maxima in this low case suggests that climate change benefits are sustainable through the 2100's in this scenario. In the central case, the positive benefit to real GDP reaches a peak of just over 1.00 percent around 2075, where it stabilizes. Were the simulation to extend beyond 2100, there would be a downturn in the benefit path as agriculture benefits soon peak and begin to erode, thereby reducing the aggregate benefit to real GDP. In the high climate change scenario, a peak real GDP benefit in excess of 1.00 percent occurs in 2055, after which benefits decline to match those of the low case by century's end. Were the high case extended beyond 2100, there would be an overall cost to the economy from climate change as continued warming no longer produces any direct benefits in domestic agriculture or space conditioning. In sum, if sectoral responses conform to optimistic predictions, there is a distinct possibility that some degree of climate change can lead to market improvements

Figure 2

Impacts on **Domestic Output** in 2050: Central, Optimistic Scenario

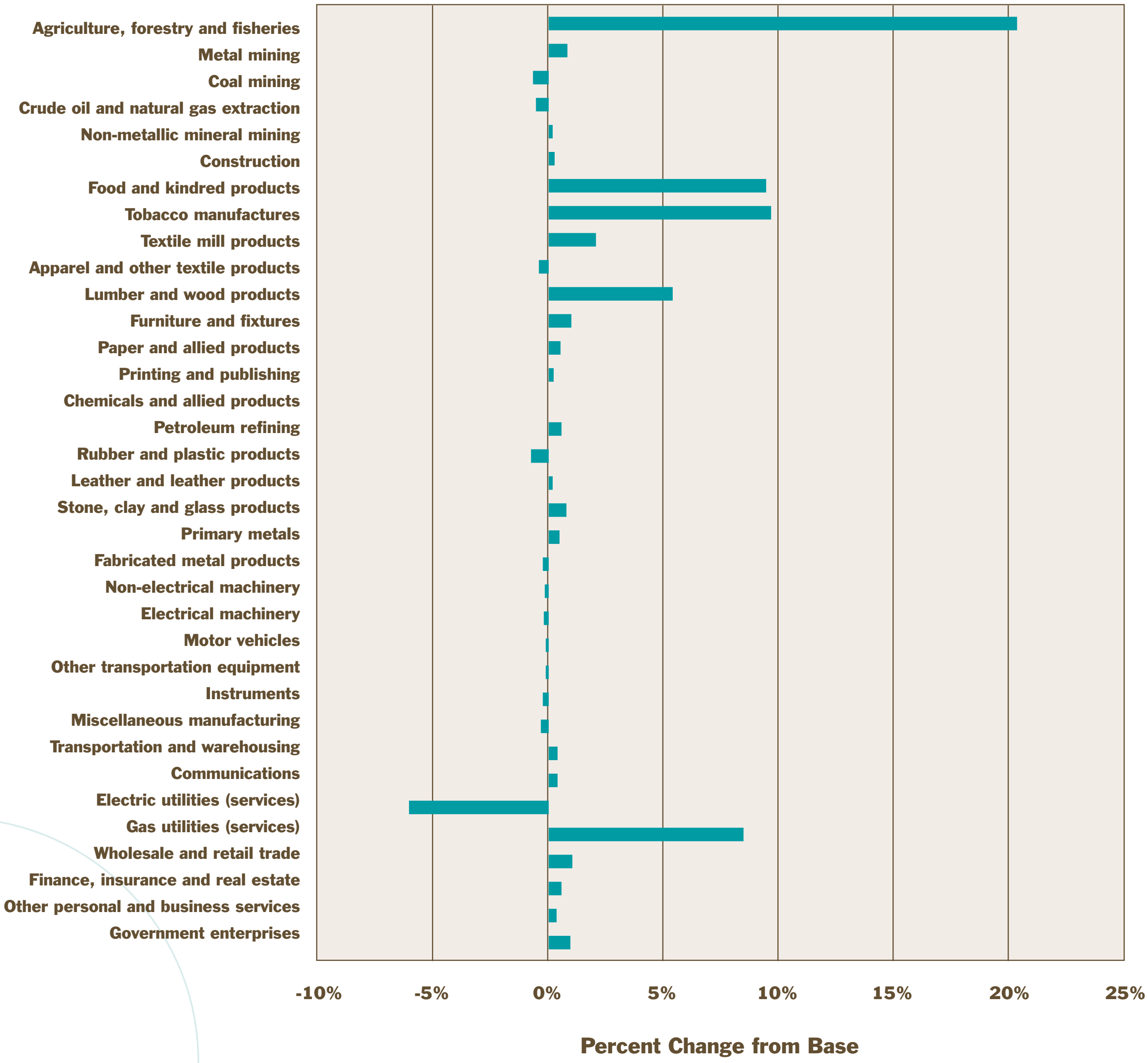
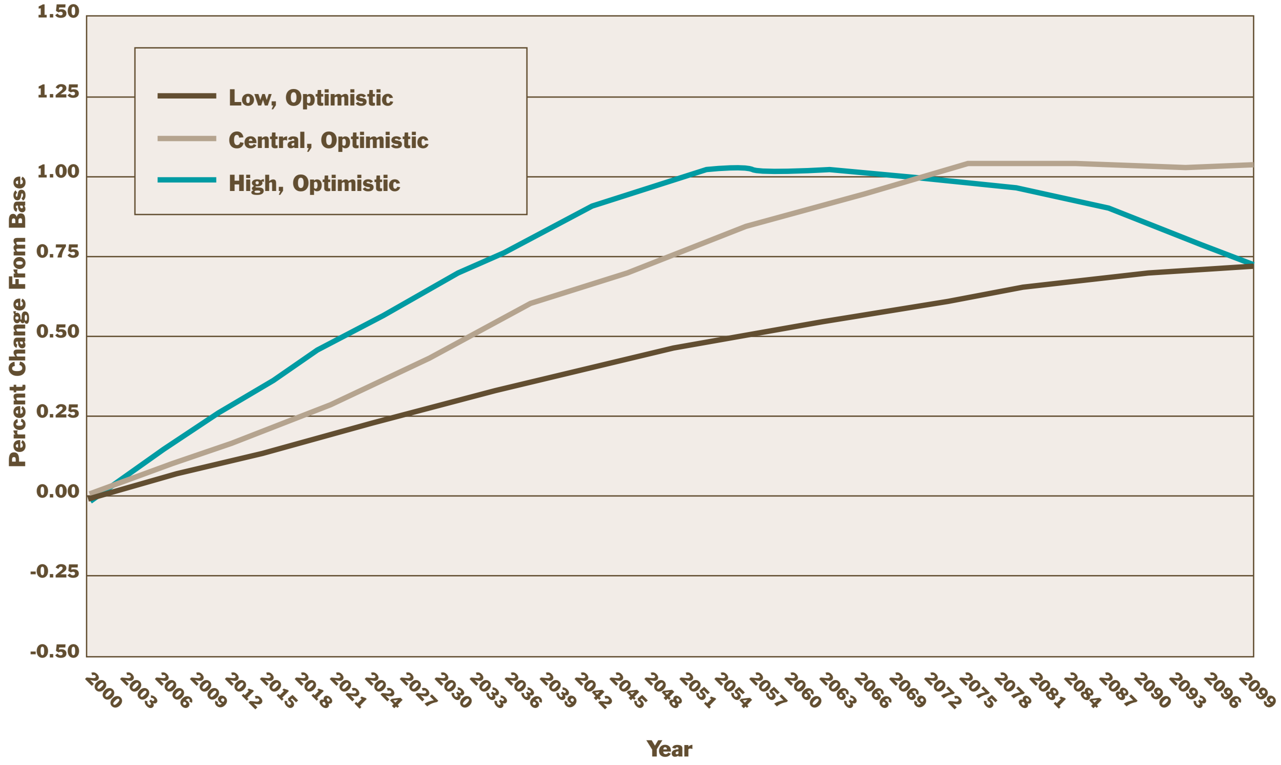


Figure 3

Optimistic Impacts on **Real GDP** in Low, Central and High Scenarios

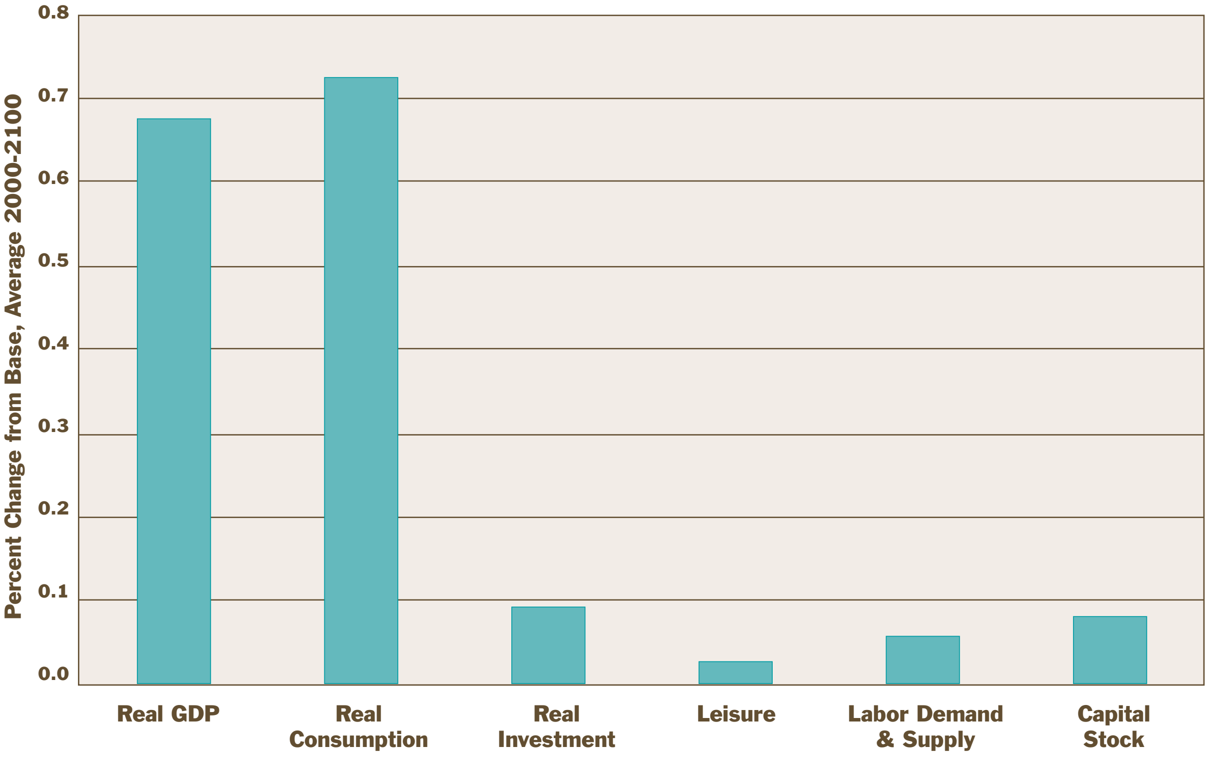


in the U.S. economy over the next century. However, as climate conditions worsen these benefits ultimately give way to costs; the question is not whether this will happen, but when.

The price reductions and increased labor supply projected under optimistic assumptions lead to higher real incomes, which, in turn, promote increased consumer and investment spending, although the latter trend slows over the long run. Consumer spending increases more than investment spending because consumer prices are more directly affected by climate change. Agricultural products, energy and water are consumer goods, not investment goods. Accordingly, the prices of consumer goods fall relatively more than the prices of investment goods. Indeed, the optimistic central and high climate change scenarios ultimately predict higher consumer spending and labor availability, but lower investment spending and capital availability relative to baseline conditions. The gradual squeeze on capital accumulation occurs as consumption increases relatively more than income over time, thereby reducing saving and investment; lower future prices reduce the need for, and return on, current saving. Future price reductions in

Figure 4

Macroeconomic Change in Central, Optimistic Scenario



investment goods are not enough to compensate for the loss in funding arising from lower saving. Figure 4 summarizes these effects and also serves to highlight the dominance of productivity effects over those of primary factor supplies (i.e., capital and labor) as the principal drivers of overall economic change. This dominance is evident in the relative size of GDP changes in comparison to changes in capital and labor.

Government spending increases because the larger economy produces higher tax revenues and, with no change in projected deficits and surpluses, lower prices allow greater real purchases.

Real exports increase because domestic goods and services are more competitive abroad and real imports decrease as import substitution occurs. These trade patterns serve to strengthen the U.S. dollar, which partially dampens the improving trade balance. The degree to which import prices are assumed to be affected by climate change has virtually no impact on overall economic performance and only a modest influence on the details of trade and industry structure. For example, if import prices proportionally follow domestic prices, smaller export gains and smaller import declines are observed but changes in the real trade balance and GDP are virtually unaffected.

In sum, real GDP is higher because of higher consumer and government spending and higher net exports. Real investment augments these increases early in the simulation horizon but plays a smaller role later as the incentives to consume rather than save become greater.

B. Outcomes Under Pessimistic Cases

For the pessimistic cases, the above mechanisms reverse and climate change leads to higher unit costs and prices. As before, agriculture and energy are the most affected sectors (see Figures 5 and 6). Electricity-based space conditioning experiences relatively

Figure 5

Impacts on **Domestic Supply Prices** in 2050: Central, Pessimistic Scenario

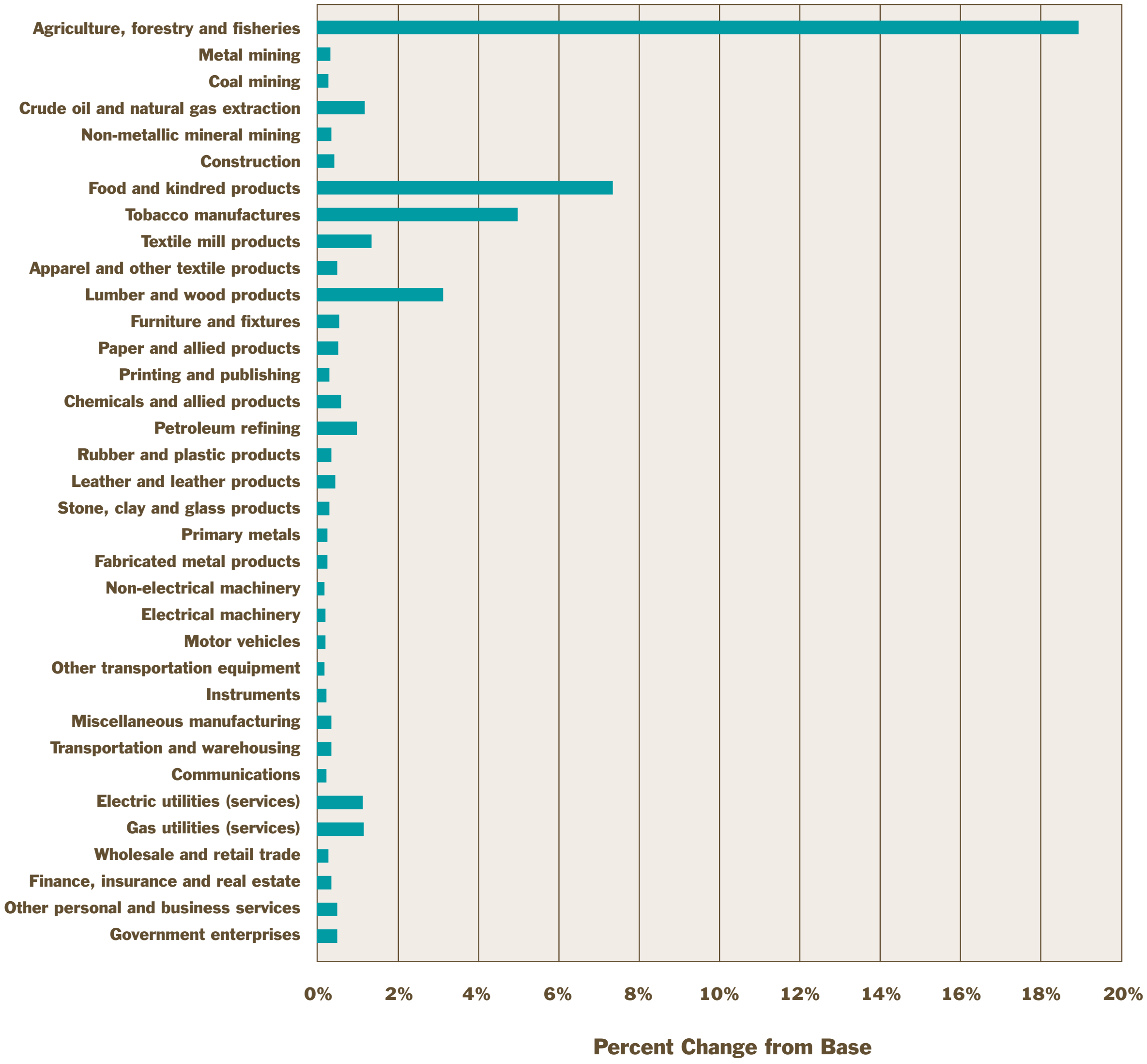


Figure 6

Impacts on **Domestic Output** in 2050: Central, Pessimistic Scenario

larger productivity losses than does space conditioning from coal, wood, petroleum or natural gas; accordingly, its (direct) unit cost rises faster. There are no thresholds or inflections in the damage response functions applied under pessimistic assumptions. For agriculture, energy and the remaining categories, damages increase as climate conditions worsen over time and across scenarios. Productive resources are diverted from more efficient uses to the affected sectors, leading to overall productivity losses. In contrast to the optimistic cases, climate change produces no benefits and its costs are larger.

Negative effects on mortality and morbidity result in a diminished pool of consumers and suppliers of labor services. Combined with higher prices, a reduced population has both demand- and supply-side consequences. On the demand side, real incomes and real household purchases decline. With lower tax receipts and higher prices, real government purchases also decrease. Higher domestic prices discourage exports and promote imports leading to a worsening real trade balance that only partially improves from a weakening dollar. As before, varying assumptions about the degree to which climate change influences import prices have a small impact on trade patterns and industry structure, but virtually no impact on predicted changes in aggregate economic performance. These combined effects

Figure 7

Macroeconomic Change in Central, Pessimistic Scenario

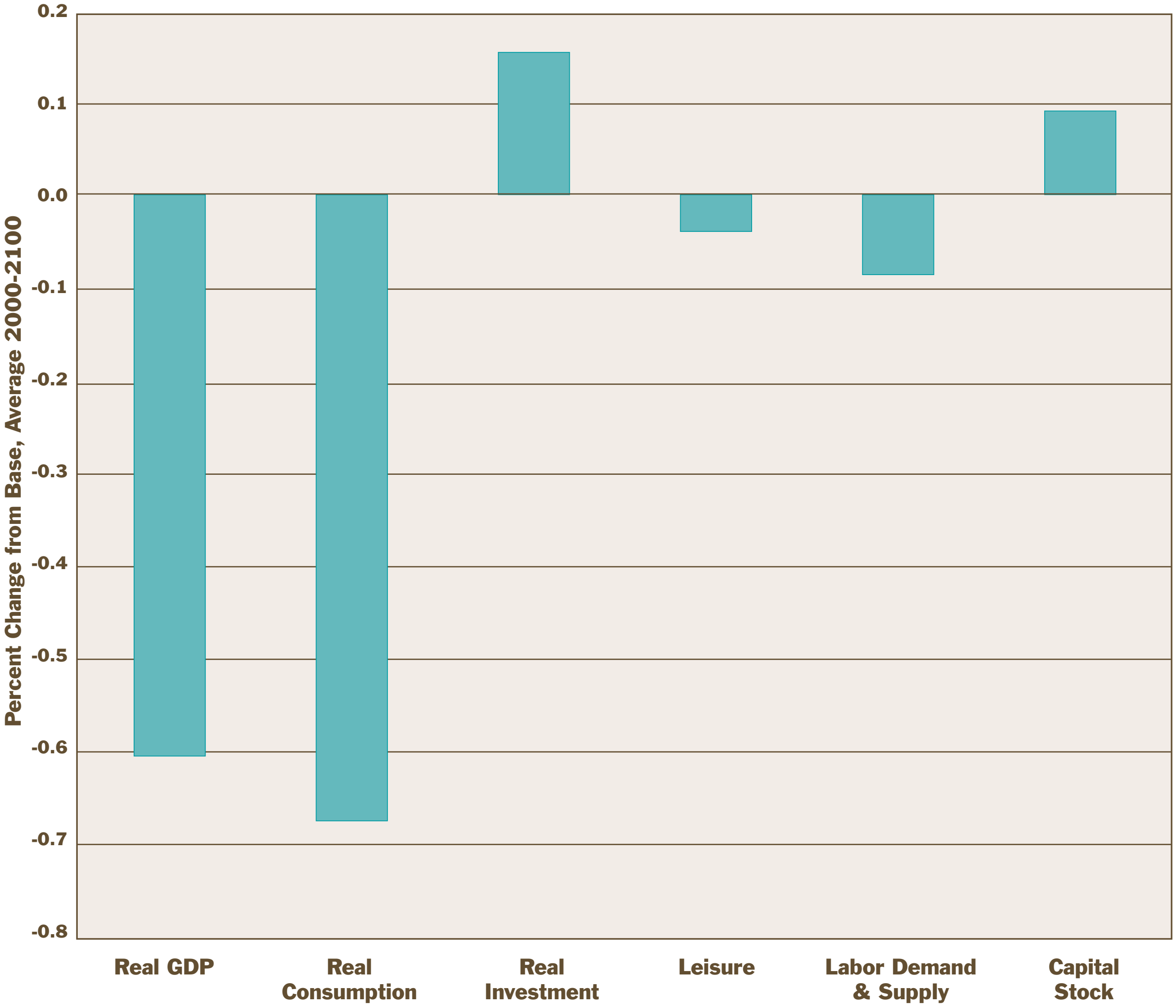
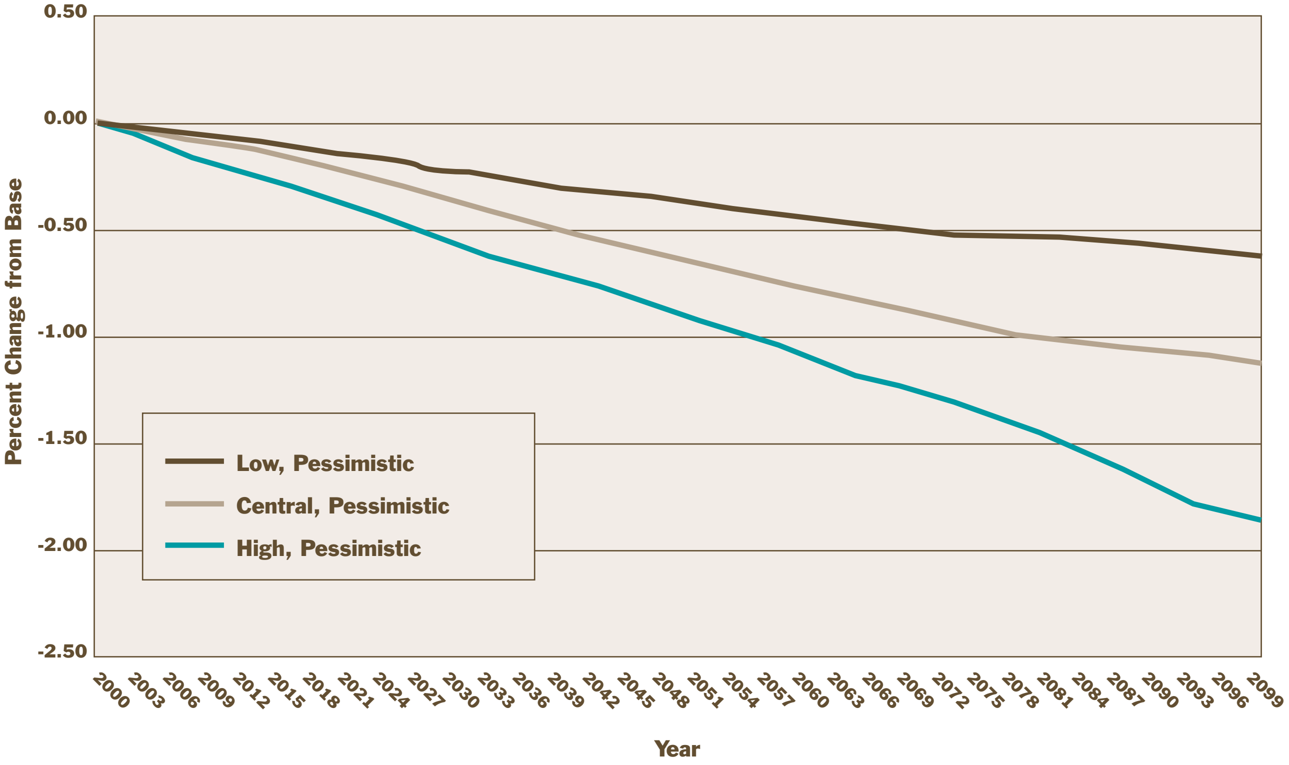


Figure 8

Pessimistic Impacts on **Real GDP** in Low, Central and High Scenarios



are sufficient to cause a reduction in overall spending or real GDP.

The only positive change observed in the pessimistic cases involves increased investment and capital input on the supply side. Reduced labor availability alters the relative prices of capital and labor, favoring the former. In addition, higher future prices stimulate the need for, and return on, current saving. Business and household saving increase. This occurs because the reduction in real incomes is smaller than the reduction in household consumption and because the rate of return on saving and investment increases. Greater saving leads to greater real investment and a greater capital stock, even though prices of investment goods are slightly higher. On the supply side, real incomes decline because of small losses in labor income and larger losses in productivity. The effects of these losses would be much greater were it not for improvements in capital availability and capital income. Figure 7 summarizes these macroeconomic adjustments.

Figure 8 portrays the time path of real GDP for the pessimistic low, central and high climate change scenarios. Unlike their optimistic counterparts, there are no threshold effects in either the driving assumptions or the results. By 2100, real GDP is 0.6 percent lower in the low climate change scenario, 1.1 percent lower in the central scenario and 1.9 percent lower in the high scenario. Over the period 2000-2100, GDP losses average 0.3, 0.6 and 0.9 percent in the low, central and high scenarios, respectively. Notably, none of the pessimistic cases assume that damages will become progressively more severe as temperatures continue rising over time, as could be the case if thresholds or inflection points caused an acceleration of impacts once a certain level of climate change had been reached. While no such thresholds are assumed for the pessimistic cases in this analysis, it seems entirely plausible, in view of the optimistic results, that damages could accelerate under conditions of prolonged drought and higher temperatures (see Figures 13 and 14). Nevertheless, even without such inflections, the cost gap grows and widens both over time and across scenarios as temperature increases become more pronounced.

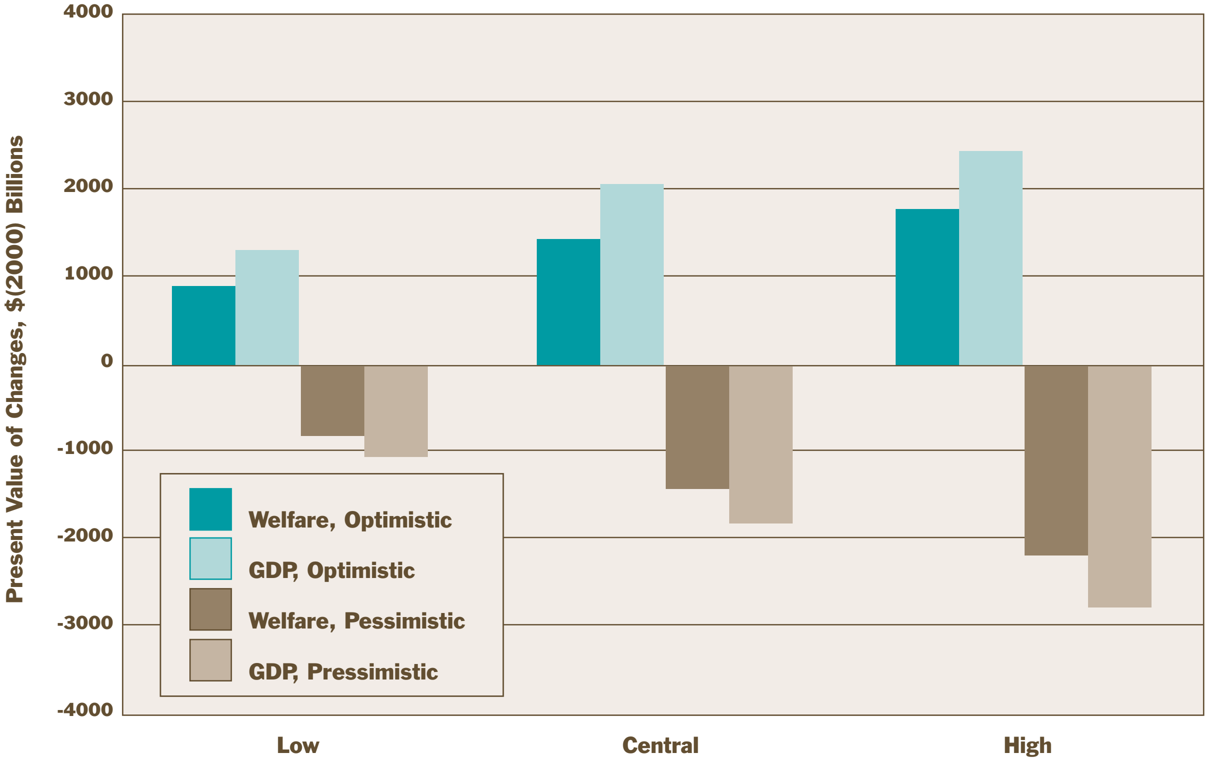
C. Welfare Impacts

Climate change in IGEM alters economic welfare in addition to income, production and spending. Here, aggregate social welfare reflects either (1) society's willingness to pay for a new and improved situation or (2) what is foregone in the move to a new but inferior situation. These welfare gains or losses are expressed as changes in total household consumption of goods, services and leisure evaluated at current (or "base case") market prices.

Figure 9 presents estimated welfare gains and losses for the low, central and high climate change scenarios, under both optimistic and pessimistic assumptions, and compares these welfare effects to the GDP effects. In general, these results suggest that the market effects of climate change will have smaller implications for economic welfare than for overall income, spending and production. The differences relate to what is included or excluded from measures of welfare versus GDP. For example, GDP includes investment, which yields future consumption, and government or public spending on goods and services. GDP captures the income from labor supply but excludes leisure as a desirable commodity that may be chosen over additional income or additional consumption. Welfare, as defined in IGEM, includes private consumption involving goods, services *and* leisure, but excludes government purchases. In addition, current investment is excluded because of its role in creating future consumption. Overall, the estimated welfare consequences of climate change average about three quarters of the magnitude of estimated real GDP effects under both optimistic and pessimistic conditions. Welfare effects are a slightly smaller fraction of GDP effects under optimistic conditions because changes in investment and capital reinforce the

Figure 9

Impacts on **GDP and Household Welfare**



impacts from greater consumption and leisure. Conversely, welfare effects are a slightly larger fraction of GDP effects under pessimistic conditions because investment and capital effects partially offset the impacts from reduced consumption and leisure.

D. Comparing Optimistic and Pessimistic Cases

The optimistic and pessimistic results generated in this analysis clearly lack symmetry (see Figures 3 and 8). Optimistic impacts are larger in absolute magnitude than pessimistic impacts in the low climate change scenario. Conversely, optimistic impacts are smaller in absolute magnitude than pessimistic impacts in the high climate change scenario. They are approximately equal under central warming conditions. It might be tempting, therefore, to infer a mildly optimistic view of the likely implications of climate change for the U.S. economy if optimistic and pessimistic outcomes are taken as equally likely and if warming proceeds along a trajectory roughly consistent with the central scenario developed for this analysis (Smith, 2004). However, this inference would be unwarranted. First, it ignores the fundamentally temporary nature of market benefits, under optimistic assumptions. In the best case, economic costs are only postponed; they are not avoided. Again, the key question is when—not if—thresholds are reached, benefits reverse and adverse market outcomes materialize.

Second, narrowing the range of expected outcomes from these results requires more information than is currently available. As a first step, one would need to be able to assign probabilities to various scenarios concerning the future trajectory of climate change. There may be a growing consensus on the most likely range of future temperatures (Smith, 2004), but there appears to be no such consensus on future changes in precipitation. In light of the variability surrounding future climate paths and because interactions between temperature and precipitation are not well defined it remains difficult to determine which of several possible climate scenarios is most likely to materialize. There is next the need to assign probabilities to the range of optimistic versus pessimistic market outcomes associated with each climate change scenario. A reasonable expectation might be that optimistic impact assumptions are more likely to prevail if climate change proceeds along a moderate trajectory. Conversely, pessimistic outcomes might be more likely to prevail if future climate shifts are more extreme. Unfortunately, the current literature is again of little help in assigning probabilities to impact assumptions. The Intergovernmental Panel on Climate Change (IPCC) and the Energy Modeling Forum (EMF), among others, have constructed "stories" or scenarios for future climate change; however these scenarios tend to be relatively independent and free of any prior expectations. This analysis is no different. A more definitive estimate of expected market impacts cannot be offered absent better information about the relative probabilities associated with different climate trajectories and their likely impacts.

Third, and perhaps most important, adding market impacts from other sectors is likely to produce lower benefits in the optimistic scenarios, while adding higher costs in the pessimistic scenarios. For example, if estimates of climate-related impacts on livestock, fisheries and storm, flood and hurricane damages from earlier efforts (Scheraga et al., 1993) are included in the mix of direct effects, the results indicate higher benefits on the optimistic side and higher costs on the pessimistic side. As shown in Table 5, the increments are comparable in absolute magnitude under low warming conditions. However, when these additional market sectors are included in the high warming scenario, the positive change in GDP estimated for optimistic outcomes is small ($98 billion) compared to the negative change in GDP estimated for pessimistic outcomes ($1,125 billion).

Table 5

Summary of the Estimated Direct and Indirect Impacts of Climate Change on Livestock, Fisheries and Storm, Flood and Hurricane Damages

	Optimistic		Pessimistic	
	Low	High	Low	High
Real GDP Effects From Figures 3, 8 and 9				
Percent change	+0.4	+0.7	-0.3	-0.9
Present value	+1,307	+2,449	-1,035	-2,752
Direct Effects				
Livestock	+5.7	+2.7	-8.8	-40.5
Fisheries	-1.3	-3.7	-3.2	-9.2
Storms, Floods and Hurricanes	-89	-301	-446	-1,505
Revised Real GDP Effects				
Percent change	+0.5	+0.8	-0.5	-1.3
Present value	+1,543	+2,548	-1,383	-3,877
Incremental Contributions of Livestock, Fisheries, Storms, Floods and Hurricanes to GDP				
Percent change	+0.1	+0.1	-0.1	-0.4
Present value	+336	+98	-348	-1,125

Values represent annual changes, 2000–2100.

Positive numbers indicate benefits and negative numbers indicate costs.

Values for real GDP, livestock and fisheries represent percent changes.

Direct effects of storms, floods and hurricanes are expressed in units of millions of constant 2000 dollars.

Present values are expressed in units of billions of constant 2000 dollars.

Livestock production benefits from climate change under optimistic assumptions but is adversely affected under pessimistic assumptions. There are no benefits to fisheries or to storm, flood and hurricane damages under either optimistic or pessimistic assumptions. For these impact categories, global warming is presumed to involve economic costs in all situations, with the timing and magnitude of these costs being the only variables. As temperature changes increase from low to high, the benefits to livestock production under optimistic outcomes diminish from 5.7 to 2.7 percent annually; at that point, livestock benefits only slightly offset the higher costs associated with fisheries and weather events. Conversely, the costs to livestock production from rising temperatures increase under pessimistic assumptions from 8.8 to 40.5 percent annually and add substantially to the higher damages associated with fisheries, storms, floods and hurricanes. The asymmetry of these effects illustrates the trend toward increasingly negative impacts on the U.S. market economy as temperatures continue to rise.

E. The Role of Discounting

Climate change poses a special policy problem because mitigative actions incur near-term social costs to secure social benefits that are much longer term.

Conventional discounting of benefits and costs over time can produce a bias against aggressive policy action if the present value of net benefits is negative or even small.

The discount rate applied to future social costs and benefits strongly influences estimated net benefits for any climate policy under consideration (Nordhaus, 1994). As in any present value determination, a lower discount rate increases the value of future net returns while a higher discount rate reduces it. In the case of climate change, lower discount rates tend to increase the value of policy intervention by allowing benefits that grow larger over time to weigh more heavily in present benefit-cost valuations. This prompts some analysts (e.g., Cline, 1992) to argue in favor of applying minimal discount rates in policy decisions that involve very long-term benefits.

Newell and Pizer (2001) demonstrate that simply accounting for the uncertainty in future interest (discount) rates has a large effect on valuations conducted over the very long term. These authors show that explicit introduction of this additional uncertainty increases the value of policy action. It is directionally equivalent, though less arbitrary, than relying on judgment to lower the discount rate.

Table 6 shows the effects of applying the Newell-Pizer methodology to the time paths of spot market interest rates generated in the IGEM simulations performed for this analysis. In general, incorporating uncertainty about future interest rates expands the boundaries of uncertainty for market outcomes estimated in this study. Under Newell-Pizer discounting, estimated gains under optimistic assumptions are larger, as are estimated costs under pessimistic assumptions. As climate changes become more pronounced, additional gains on the benefits side diminish while economic losses increase. Indeed, under the most extreme of the climate scenarios, the incremental benefit attributable to interest rate uncertainty in the optimistic case is less than half the magnitude of the incremental cost of that same uncertainty in the pessimistic case. This result offers additional evidence of the downside bias of likely climate impacts on the market economy.

Table 6

The Effect of Interest Rate Uncertainty on the Present Value of GDP Changes

Time Horizon: Infinite	**Optimistic**	**Pessimistic**
Low	+17.6%	-18.1%
Central	+16.2%	-19.7%
High	+9.7%	-20.8%
Time Horizon: 2000–2100		
Low	+6.0%	-6.1%
Central	+5.7%	-6.9%
High	+3.4%	-7.0%

Values represent percent changes in the present value of GDP impacts from climate change due to interest rate uncertainty.

F. Future Carbon Emissions

The impact of climate change on baseline projections of future carbon emissions depends on interactions involving both the size of the economy and its structure. As the economy grows or contracts and as the economic contribution of specific sectors becomes more or less important because of climate change, model projections of carbon emissions will change.

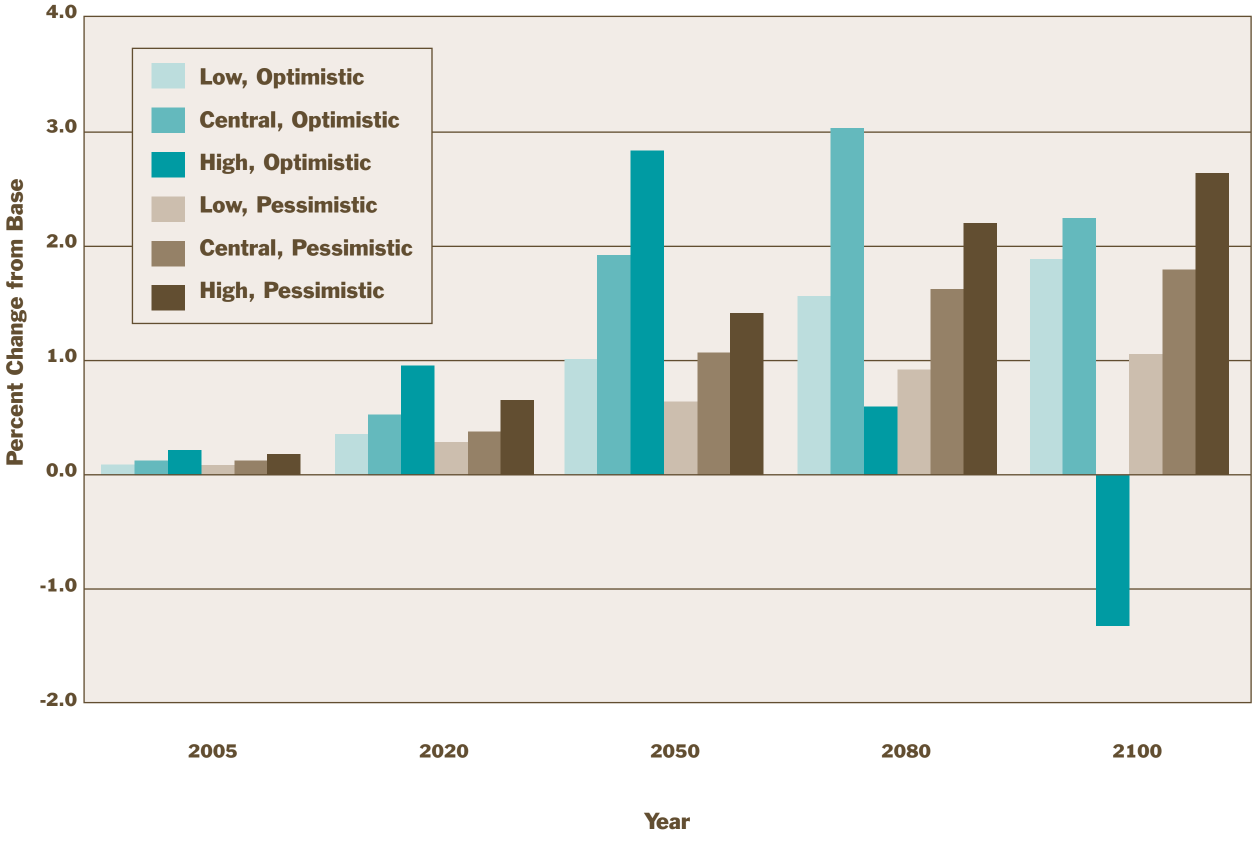
Climate change affects the level of economic activity (scale effects) and its composition or structure (substitution effects). In the model simulations performed for this analysis, interactions between these scale and substitution effects leads to the surprising observation that simulated carbon emissions continue to increase over the long run as warming progresses. This increase, illustrated in Figure 10, occurs irrespective of whether the model predicts that climate change secures benefits or imposes costs on the overall economy. Under optimistic outcomes, carbon emissions are higher by an average of 0.9, 1.7 and 1.1 percent in the low, central and high climate change scenarios, respectively. Under pessimistic outcomes, carbon emissions are estimated to increase by an average of 0.6, 1.0 and 1.4 percent, respectively across the same three scenarios. These results reflect the combined and offsetting influences of observed changes in the scale and structure of economic activity. Both types of changes are important to the emissions outcome and either can dominate the net emissions effect.

Under optimistic outcomes, there are two forces that promote an increase in carbon emissions and two forces that work toward reducing emissions. Driving emissions upward are the scale changes related to a larger economy with greater productivity, more consumers and more time available for work and leisure. Substitution toward relatively cheaper energy services also promotes higher emissions. The eventual reversal in energy benefits discussed previously has a dampening impact on this substitution effect beginning in 2077 in the central climate change scenario and in 2055 in the high change scenario. Indeed, the fact that the high climate change scenario shows a smaller increase in average emissions than the central climate change scenario is due entirely to this phenomenon.

The mechanisms working to reduce emissions arise from the restructuring of economic activity toward agriculture and away from capital goods which tend to be more energy-intensive and emissions-producing. Because of relative price reductions, agriculture and its related industries become relatively

Figure 10

Impacts on Carbon Emissions



more important while saving, investment and capital accumulation become relatively less important. As a result, while there is more capital available overall, the capital intensity of the economy and capital per worker are less. These substitution effects partially offset the upward pressures on emissions that arise from scale effects and cheaper energy.

Under pessimistic outcomes, these forces reverse but their impacts are such that substitution effects dominate scale effects. The forces working to increase emissions arise from a pattern of substitution away from agriculture and toward saving, investment and capital goods. The shift away from agriculture occurs as climate change adversely affects productivity and costs within that sector. The shift toward saving, investment and capital goods follows from the reduction in time available for work and leisure, which in turn tends to increase returns to capital relative to returns to labor. Each of these effects causes economic restructuring toward more energy-intensive industries and tends to increase emissions.

Working in the opposite direction to reduce emissions are the scale effects associated with a smaller economy, a smaller population and less time available for work and leisure. In addition, there are substitution effects related to slightly more expensive energy services. However, these opposing effects are not enough to offset predicted emissions increases arising from agricultural displacement and capital substitution.

While all scenarios show continued growth in carbon emissions, at least initially, Figure 10 also indicates that these projected increases are likely to be temporary over the very long run. Under optimistic outcomes, the economy eventually deteriorates due to the existence of threshold effects which cause benefits in the agriculture and energy sectors to reverse at a certain point as temperatures continue to rise. A smaller economy with more expensive energy ultimately leads to lower emissions. This occurs in the central and high climate change scenarios toward the year 2100. Under pessimistic outcomes, the emissions-reducing scale effects of a smaller economy should ultimately overwhelm the substitution effects from more expensive agriculture and relatively cheaper capital, although these trends are not displayed in Figure 10.

Box 1

Scale and Substitution Effects

The results of this analysis demonstrate the importance of general equilibrium considerations in projecting the time paths of future emissions. Substitution effects govern the structure of economic activity, promoting—on balance—emissions-generating activities or encouraging emissions-reducing activities. Scale effects govern the level of overall economic activity with larger economies generating more emissions and smaller economies generating fewer emissions. It is therefore both possible and plausible that over some time interval, differing combinations of these effects can lead to identical outcomes—as in the current case of higher emissions under both optimistic and pessimistic circumstances. What actually occurs in any given model simulation depends on assumptions about market responses to price changes inherent in the methodology and on the magnitude of impacts estimated for different levels of climate change.

V. Findings

In distilling the details and informational content of these model simulations, five key observations emerge. Each has relevance for future modeling efforts and for ongoing policy discussions over climate change.

1) Climatic changes of the types and magnitudes considered here have the potential to either impose considerable costs or produce temporary benefits for the U.S. market economy and for the economic welfare of U.S. residents. Under pessimistic assumptions, climate change imposes immediate economic costs on the market economy. These costs increase as warming becomes more pronounced both within and across different climate change scenarios (Figure 8). In fact, costs increase almost monotonically because of the assumed linearity of the underlying damage functions. Under pessimistic scenarios, real U.S. GDP under the full range of warming trajectories considered (i.e., the low, central, and high climate change scenarios) is 0.6 to 1.9 percent lower by 2100 relative to baseline conditions that assume no economic effects from climate change. However, under the additional "high and drier" climate scenario, GDP is 3.0 percent lower by 2100 relative to baseline conditions.

Under optimistic assumptions, climate change produces immediate benefits to the market economy. These benefits may well last through the 2100's, depending on the trajectory of future climate shifts. In the optimistic case, real U.S. GDP by 2100 is 0.7 to 1.0 percent higher than baseline conditions across the low, central, and high climate change scenarios. However, these benefits are not sustainable. In the high climate change scenario, they peak around mid-century. In the central climate change scenario, they peak around century's end. Even in the low scenario, they ultimately peak—albeit after 2100. Thereafter, the benefits from climate change increasingly diminish and, eventually, give way to costs (Figure 3).

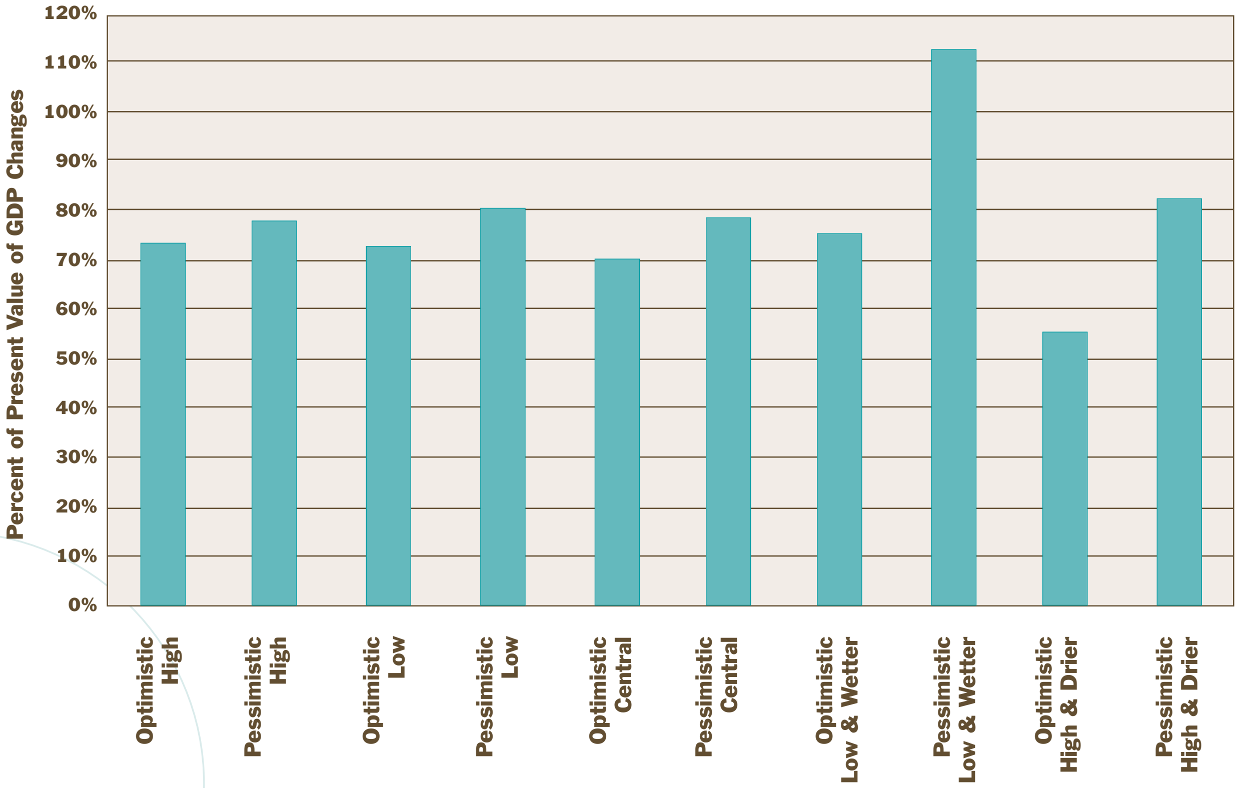
2) Due to climate thresholds in certain key sectors, the economic benefits simulated for the 21st century under optimistic conditions are not sustainable and economic damages are inevitable. Figures 3 and 8 (and Figures 13 and 14) illustrate this point. Under pessimistic assumptions, the economy steadily worsens as temperature and precipitation steadily increase. Prevailing trends evolve smoothly over time consistent with the varying severity of underlying climate shifts in the low, central and high warming scenarios.

However, under optimistic assumptions, there are inflection points or thresholds in the central and high climate change scenarios. In the latter, the benefit trend slows and peaks noticeably around mid-century whereas, in the central climate scenario, this transition appears toward century's end. The timing of these discontinuities follows directly from the damage functions relating to agriculture and energy services (see Section III and Appendix A). When temperature increases reach key thresholds, a reversal occurs in the damage functions for these sectors; instead of rising continually in concert with warming temperatures, benefits begin to erode—as do their positive effects on overall economic performance. After 2055 in the high climate change scenario and around 2100 in the central case, there is a flattening in the benefit trend. Indeed, in the high and drier scenario, market benefits are completely eroded by 2100 and climate change begins to impose net costs on the economy, even under optimistic assumptions.

3) The effects on U.S. agriculture dominate the effects in other market sectors when estimating the net impacts of climate change on the nation's overall economic performance. Currently, the agriculture, forestry and fisheries industries represent about 2.0 percent of total U.S. industrial output and about 3.5 percent of total final spending (real GDP). However, agriculture's role in determining the estimated total market impact of climate change is far more substantial. Figures 2 and 6 show the consequences of warming for

Figure 11

Contribution of Agriculture to Changes in GDP



domestic industries in the year 2050 under the central climate change scenario. Under optimistic assumptions (Figure 2), agriculture and energy are the primary drivers of estimated benefits. Agriculture, food, tobacco and lumber share the spotlight with electricity and gas services as the sectors most influenced by climate change. Under pessimistic assumptions, on the other hand (Figure 6), agriculture, food, tobacco and lumber are alone in experiencing dramatic impacts.

Additional simulations help to clarify agriculture's impact on the overall structure of the economy. A summary of these results appears in Figure 11. Ignoring for a moment the scenarios that include extreme changes in precipitation, agriculture accounts for 70 to 73 percent of the total effect on real GDP in the optimistic cases and 78 to 80 percent of the total effect on real GDP in the pessimistic cases. These figures increase by about 5 percentage points when the effects on livestock production and commercial fisheries are included. Clearly, significant changes in comparatively small sectors can exert an enormous influence on the impacts estimated for the overall economy.

When considering variations in precipitation, the role of agriculture becomes more interesting and more complex. Absent flooding and other extreme events, additional precipitation is viewed as favorable to agriculture. Moreover, its contribution to the total estimated change in real GDP increases as precipitation increases. Under optimistic assumptions in the low climate change scenario, additional precipitation increases agriculture's share of the total economic impact from 73 percent to 75 percent. Under pessimistic assumptions and the same low climate change conditions, additional precipitation increases agriculture's share of the total impact from 81 percent to 112 percent. In this case, agricultural changes from increased precipitation benefit the economy whereas other climate effects impose costs, so that agriculture's share of the total effect exceeds 100 percent.

As precipitation decreases with higher temperatures, total damages associated with pessimistic outcomes increase and agriculture's share of these damages also increases, from 78 to 83 percent. By contrast, with optimistic outcomes, agriculture's share of the total economic effect falls from 73 percent to 56 percent. This is because non-linearities within the damage response function for agriculture involve both temperature and precipitation changes. Under optimistic assumptions, reduced precipitation rapidly erodes predicted benefits to crop agriculture and those for forestry, albeit at a much slower rate. The effect of these non-linearities is to reverse and eventually eliminate climate related benefits to agriculture, such that this sector's presence in the portfolio of market impacts being considered matters significantly less to estimated effects for the economy as a whole.

4) For the economy, wetter is better. Moving from wetter to drier climate conditions involves significant costs that worsen as damages become more severe. Figure 12 shows the average impact of precipitation on real GDP for the period 2000–2100 under pessimistic versus optimistic assumptions and across different climate change scenarios. The comparative time paths of GDP changes over this period for the low and high climate change scenarios are displayed graphically in Figures 13 and 14.

Several observations emerge from these results. First, everything else being equal, more precipitation is better for the economy than is less precipitation. With optimistic outcomes, the “low and wetter” climate change scenario yields greater economic benefits than does the low climate change scenario. Similarly, the high climate change scenario yields greater economic benefits than does the “high and drier” scenario. Under pessimistic assumptions, there is an identical pattern of effects favoring more precipitation. In fact, under pessimistic assumptions, an actual economic benefit is predicted for the “low and wetter” scenario.

Second, the effects of less precipitation are more costly at higher temperatures than they are at lower temperatures. In the optimistic cases, benefits decline as precipitation decreases. This erosion of benefits is greater in moving from the high to the “high and drier” climate change scenario

Figure 12

Contribution of Precipitation to Impacts on Real GDP, Low and High Rates of Warming

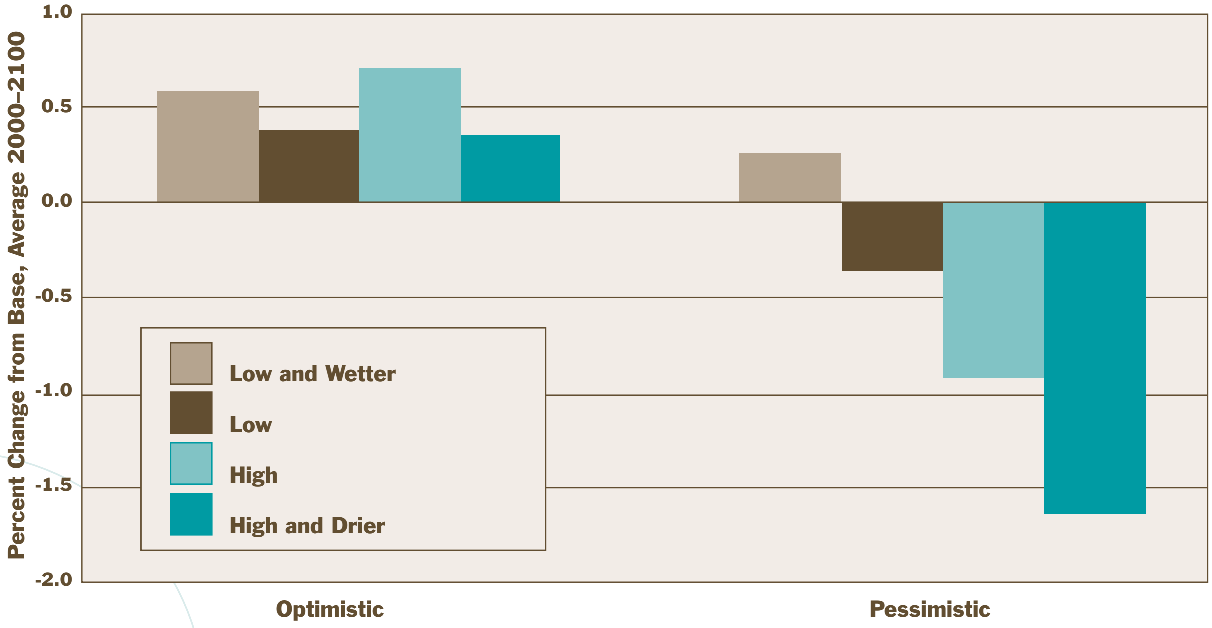
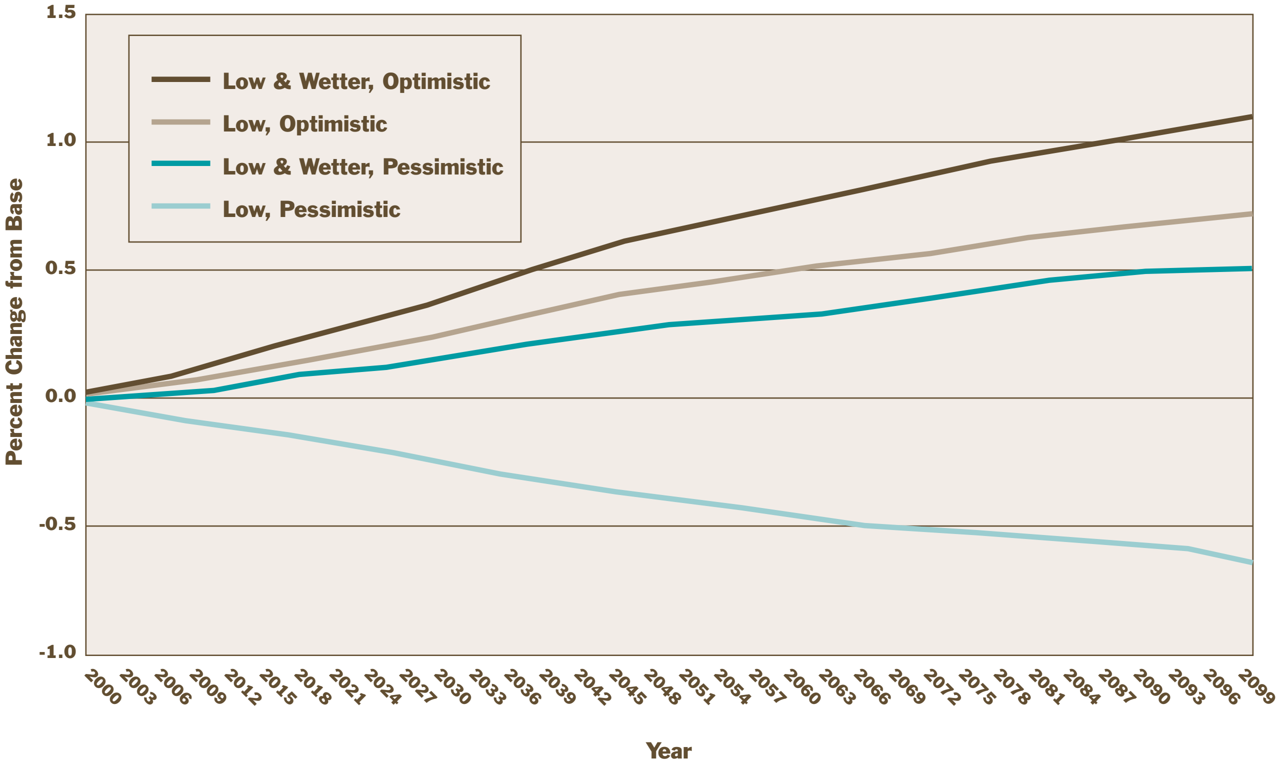


Figure 13

Impacts on Real GDP with Varying Precipitation, Low Climate Change Scenarios



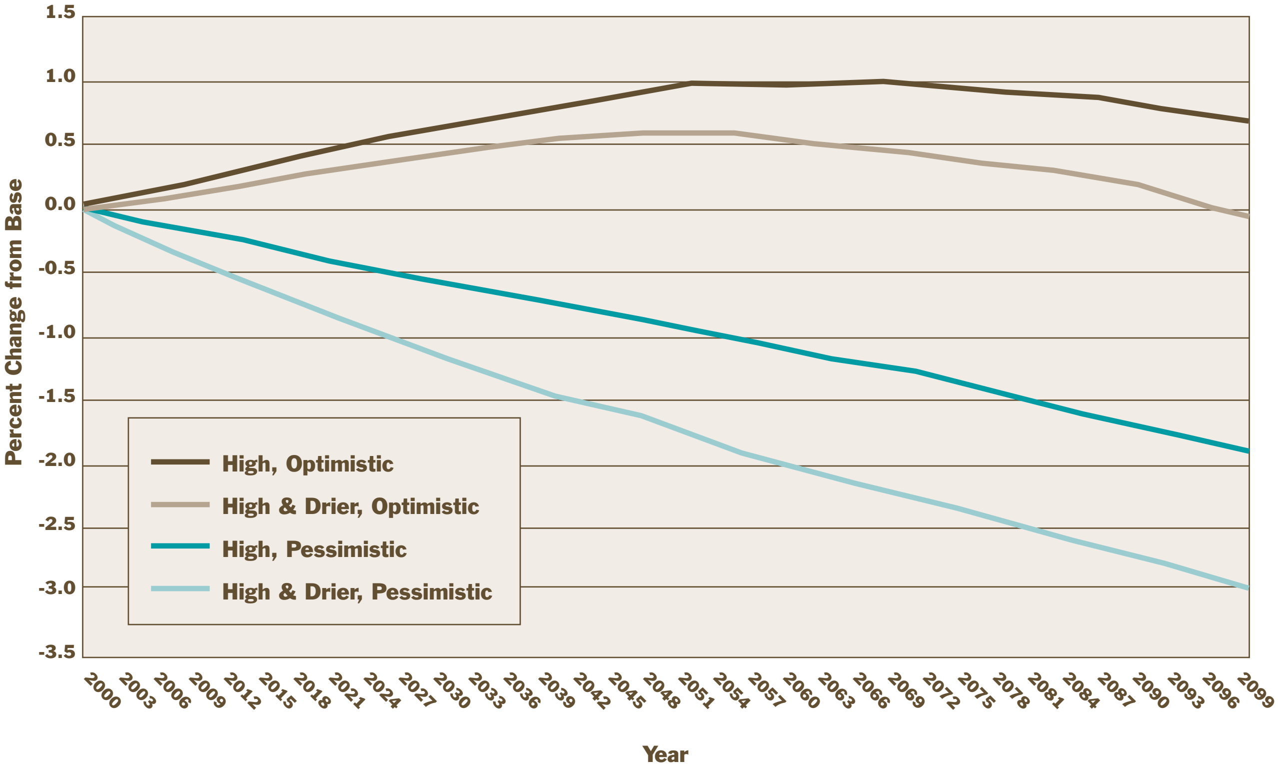
(0.36 percentage points) than it is in moving from the "low and wetter" scenario to the low scenario (0.20 percentage points). Similarly, with pessimistic outcomes, the economic costs of moving from the high to the "high and drier" climate change scenario are greater than those of moving from the "low and wetter" scenario to the low scenario (0.72 versus 0.57 percentage points).

Third, the marginal effects of reduced precipitation increase as the outlook for market consequences becomes more pessimistic. Not surprisingly, the economic costs of moving to drier climate conditions are greater under pessimistic assumptions than they are under optimistic assumptions. This occurs both in moving from the "low and wetter" climate change scenario to the low scenario and in moving from the high to the "high and drier" scenario.

It is clear from these observations that increased attention needs to be paid to the precipitation changes that accompany any given climate scenario. It is also important to note that these results follow solely from the agricultural consequences of more or less rainfall. The damages considered here make no

Figure 14

Impacts on Real GDP with Varying Precipitation, High Climate Change Scenarios

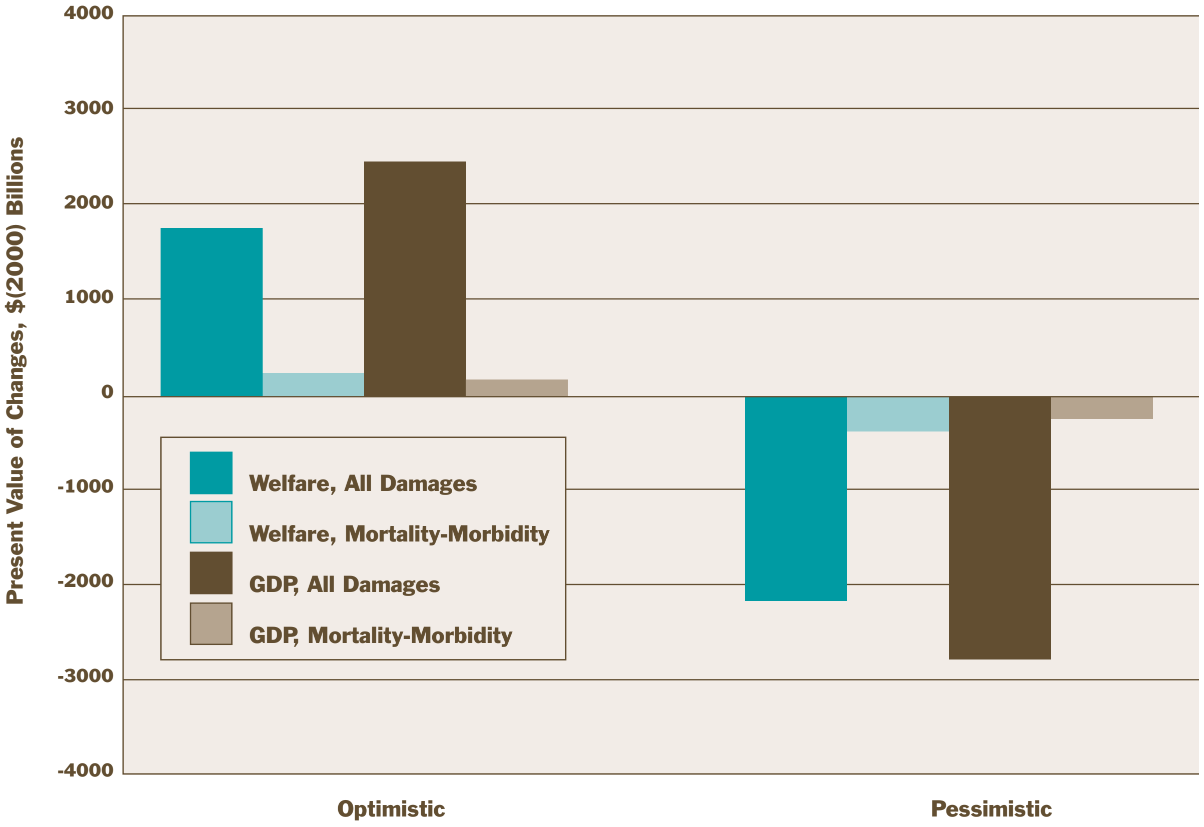


allowance for the effects of increased storm and flood activity. In addition, the potential impacts of increased volatility in precipitation patterns or of regional variations in precipitation changes are not explicitly considered here. However, it is worth pointing out that the incremental costs of flooding attributable to climate change are extremely small in comparison to the benefits to agriculture and the economy from increased precipitation; it is a matter of comparing the millions of dollars in storm, flood and hurricane damages in Table 5 to the billions of dollars implied in Figure 12.

5) The effects of climate change on mortality and morbidity are small but important determinants of the predicted changes in economic activity (GDP) and household welfare, with the estimated impacts on welfare almost twice as large as the estimated impacts on GDP. As noted previously, welfare is taken to represent society's willingness to pay for an altered situation and is defined to include goods, services and leisure. Figure 15 presents the effects on real GDP and household welfare for the high climate change scenarios under both optimistic and pessimistic assumptions. Figure 15 further isolates the effects of mortality and morbidity on these measures. Note that mortality and morbidity account for 6 to 9 percent of the GDP effect, but 13 to 16 percent of the welfare effect.

Figure 15

Contributions of Mortality and Morbidity to Impacts on GDP and Welfare, High Climate Change Scenarios



Under optimistic assumptions, warming reduces mortality and morbidity such that there are additional consumers and, because there are more people, additional time available for both work and leisure. These changes help promote consumption at the expense of saving and investment. In addition, with more time available the proportional increase in work is greater than the increase in leisure as available capital is relatively scarcer. Increased consumption and labor income, which are reflected in GDP, are augmented by an increase in leisure for both workers and non-workers, thereby producing the welfare gains observed in Figure 15.

Under pessimistic assumptions, the opposite occurs. Warming increases mortality and morbidity such that there are fewer consumers and less time available for the now smaller working-aged population. In this case, changes in relative scarcity favor capital accumulation over labor input. There is both less work and less leisure, with work again showing the larger proportional change. Lower consumption and lower leisure combine to generate an overall reduction in household welfare.

Box 2

Valuing Mortality Impacts

The relative importance of mortality and morbidity in assessments of the economic and welfare impacts of climate change depend on the values assigned to human life and health and on the assumptions underlying this valuation. The welfare effects considered in this analysis are limited to market phenomena. Gains reflect additions to consumption and leisure, while losses reflect consumption and leisure forgone—all at market prices. These changes include none of the willingness-to-pay considerations that characterize much of the value-of-life literature.

The most common approaches to valuing mortality attempt to define a given reduction in risk and an individual's willingness to pay to reduce that risk. The better estimates incorporate changes in life expectancy, risks of dying and relevant demographic considerations. Estimates are developed either by examining wage differentials and occupational risks or by sophisticated survey techniques.

A perspective on these market valuations of mortality is provided by the U.S. Environmental Protection Agency (U.S. EPA 1997, 1999 and 2000). In assessing the benefits and costs of U.S. environmental policies, EPA uses a value of a statistical life (VSL) saved that is drawn from a survey of the literature on willingness-to-pay for avoiding a premature death or for an additional life-year. The survey covers numerous research efforts with estimates (in year 2000 U.S. dollars) ranging from a low of $1.0 million to a high of $21.7 million. An estimated distribution of these research estimates has an average or mean value of $7.7 million and a standard deviation of $5.1 million. EPA uses this mean value of $7.7 million as the value of a statistical life saved or lost due to the presence or absence of a particular policy.

The simulation results from this exercise, based solely on market considerations, generate a value in the range of $1.5 million per life gained under the optimistic outcomes and a value in the range of $1.6 million per life lost under the pessimistic outcomes. These figures are at the low end of the range in EPA's survey, implying that the premiums willingly paid to avoid premature death or to prolong productive life are considerably larger than the benefits arising from market effects alone. Adding a willingness-to-pay premium to IGEM's market estimates for mortality and morbidity would clearly increase the relative importance of these effects in estimating the overall impacts of climate change on real GDP and welfare.

VI. Conclusions

A critical question that naturally emerges from this analysis concerns the degree to which potential damages arising from climate change are sufficiently large as to warrant more aggressive and more immediate mitigative actions. Most climate change policies achieve their greatest benefits far in the future, while incurring potentially substantial costs nearer term. As a result, traditional benefit-cost analysis can inspire a wait-and-see attitude toward such initiatives. The very existence of potential market benefits for the U.S. under some climate change scenarios and for some amount of time, together with the increasing gap between best- and worst-case impacts as warming progresses, would seem to lend further support to the wait-and-see approach. However, this conclusion ignores one of the most important results of this analysis, namely, that any benefits from climate change are temporary. Predicted trends in market outcomes become less optimistic and more pessimistic as warming occurs both within and across climate change scenarios. This suggests that some short-term mitigative actions would undoubtedly provide positive net benefits. It also highlights the risk that inaction today could increase the likelihood and magnitude of future damages. Moreover, to the extent that pessimistic outcomes prevail and steep emissions reductions become necessary over time, near-term efforts to begin phasing in moderate greenhouse gas reductions may avoid the need for more costly measures later.

The findings also support more immediate actions for other regions of the world. Economies in which agriculture provides a larger fraction of national income and particularly in regions that are likely to move from cooler and wetter climate conditions to hotter and drier conditions are obviously at greater risk. For these economies, short-term mitigative actions will appear more favorable because the benefits of these actions are likely to lie near or above their current social costs.

Failure to include climate-related impacts on mortality and morbidity understates the effects of climate change on overall economic welfare together with the true magnitude of likely benefits associated with mitigative policies. To the extent that adverse health effects are more likely than beneficial ones under all plausible scenarios for long-term climate change, the net benefits of such policies are again higher than they are often currently perceived. Add to this the fact that the market impacts estimated here for mortality and morbidity effects are at the low end of valuations reported in the available literature and, in each case, the arguments for deferring policy action diminish.

The results of this analysis also suggest a number of priorities for future research on the likely impacts of climate change. First, the kinds of market consequences evaluated here must be integrated to a greater extent with assessments of non-market consequences. Second, there is an essential need to clarify the likely range of market outcomes arising in a given sector (or area of economic activity) from a given level of climate change. Moreover, it is highly likely that trends in response functions will vary with changing climate conditions as opposed to remaining fixed. A better understanding of the relationship between market response and climate at the sector or activity level would allow for a better determination of the distribution of likely outcomes for a given climate scenario. With an improved understanding of response functions, it would be possible to better estimate the impacts of alternative climate scenarios on both income and welfare measures (with the latter—welfare impacts—being arguably more relevant). These scenarios could then be combined probabilistically to yield a likely distribution of market outcomes that better characterizes the full range of potential U.S. market impacts from climate change.

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Appendix A: The Modeling of Sector Impacts for Use in Assessing the Overall Market Impacts of Climate Change

This appendix describes the relationships introduced into IGEM to estimate the overall impacts of climate change. These damage functions or response-surface estimates are based on available data from a variety of impact studies. By using their results to estimate and scale impacts, this study adds empirical content to what often has been an exercise in applying expert judgment (e.g., Nordhaus, 1991; Cline, 1992; Fankhauser, 1995; Tol, 1999; Nordhaus and Boyer, 2000). The response functions portray the degree to which economic processes might be affected through the coming century as climate change trends continue or changes begin to appear. Recognizing the inherent uncertainties reflected in the literature, both optimistic and pessimistic estimates are developed for each sector's response to each of three evolving climate change scenarios.

These relationships are sensitive to the climate variables of temperature, precipitation and sea-level rise. Most of the estimates depict changes in the unit costs of production for various sectors within the economy. Others affect levels of productive spending on investment goods and others influence the quantity and quality of life for U.S. residents. The estimated response functions are applied to the trajectory of climate changes implied by a specific climate change scenario.

The sectors of the economy for which a broad range of outcomes on cost changes due to climate change are available are:

Crop agriculture
Livestock
Forestry
Fisheries
Space heating and cooling
Coastal protection
Storms, floods and hurricanes
Water supply
Air quality
Health

Omission of a sector is not meant to imply that no effects are expected, but rather that the net effect of these changes on the market economy currently cannot be adequately or broadly assessed from the available literature.

Estimating impact responses to changes in climate variables is difficult in several respects. First, available studies typically estimate impacts for only a very limited set of climate scenarios. This means that there are only a few data points available for the purposes of estimation. Second, the limited span of the data allows the use of only very simple functional forms, e.g., linear versus non-linear forms. Third, these are inherently dynamic processes with possible discontinuous changes (such as threshold effects). With limited data, these relationships often cannot be adequately characterized. As a result, some studies rely on expert judgment to postulate non-linear relationships. For example, Scheraga et al. (1993) and Nordhaus and Boyer (2000) both hypothesize underlying non-linear relationships. While this can also provide important insights, the difficulty with this approach is its non-empirical subjectivity.

For consistency within IGEM, impact estimates for most of the sectors, including agriculture, forestry, and energy, measure the change in the unit cost of production, holding output or production constant. Figure A-1 illustrates the principle that underlies these impact estimates.

Figure A-1

Conceptual Economic Framework

for Measuring the Change in Production Costs

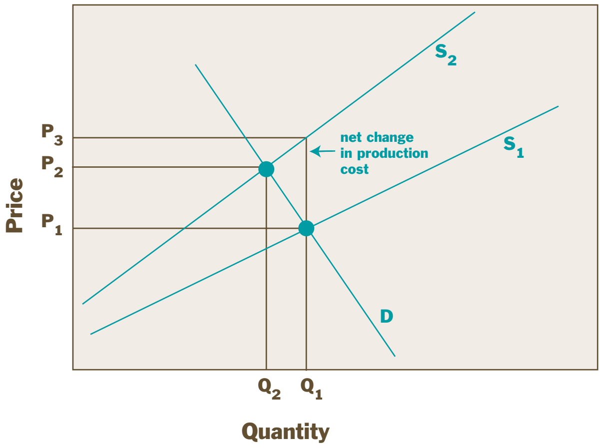

Figure A-1 shows a general supply and demand relationship, with demand given by D and two different supply curves, S1 and S2. S1 represents the supply or the locus of long-run marginal production costs under baseline climate conditions. S2 illustrates the effects of climate change that has served to increase marginal production costs or, equivalently, to decrease productivity implying that the same output now requires more inputs. For the purposes of modeling climate change, interest focuses on the distance corresponding to the change in price from P1 to P3.

The following sections provide details on the development of the impact relationships for each of the sectors.

A.1. Crop Agriculture

The optimistic estimate is derived from an evaluation of the estimated production changes presented in Table 3.3b of the U.S. National Assessment (USNCCA, 2001). This table gives national average changes in dry land production for all the major crops (assuming adaptation) for both the Canadian Climate (CC) and Hadley Center (HC) models for 2030 and 2090. Several steps were taken to develop estimates using these data so that temperature and precipitation changes could drive the estimated response:

- Changes in annual average temperature and precipitation associated with both the CC and HC models for 2030 and 2090 were developed based on data received from Dr. Benjamin Felzer (NCAR).
- Using crop area data from the 1995 Census of Agriculture (USDA), a weighted average of production changes across crops was developed to estimate an annual average change in total production for the U.S. National Assessment data.
- Then, using the production estimates as a direct proxy for the change in unit production costs, regression coefficients were estimated for temperature and precipitation changes.
- The coefficients then were used to estimate impacts associated with the temperature and precipitation changes under the timelines for each of the three climate change scenarios.

The estimated optimistic relationship between agricultural productivity and climate is:

$$\begin{aligned} \text{dCost} &= [0.016 * \text{dTemperature}] - [0.025 * (\text{dTemperature})^2] \\ &+ [1.453 * \text{dPrecipitation}] - [0.553 * (\text{dPrecipitation})^2] \end{aligned}$$

where dCost, dTemperature, and dPrecipitation are the change in unit production cost, the change in temperature (in °C), and the percentage change in precipitation (in percent), respectively. Note that this is quadratic in changes in both temperature and precipitation and includes the effects of CO_2 fertilization in the underlying data upon which it is based.

There is a great deal of uncertainty in identifying a particular temperature-related threshold for the agricultural sector as a whole at a national scale. Agronomic theory, evidence from field experiments, and crop simulation models all suggest the existence of such thresholds for individual crops under region-specific conditions. Heterogeneity across crops, regions, conditions, and water availability makes an accurate determination quite difficult. Techniques such as meta-analysis (which examines multiple studies and models, and controls for variation in crops, regions, and conditions) might offer some additional clarity, but are beyond the current scope. Furthermore, necessary aggregation procedures to produce a specific nation-wide value applicable to agriculture, in general, entails the strong assumption of no adaptation on the part of farmers. That is to say, such a national-scale threshold estimate, were it ever to be identified, would be subject to change and drift as cropping patterns and conditions varied over time and, more importantly, as climate changed and farmers adapted.

For the current purposes of bounding national-scale estimates based on a range of plausible scenario assumptions, it is not necessary that a definitive threshold estimate be identified. It is, however, clearly important that the nature of such a threshold as identified in the existing literature be reflected in the modeling of impacts, so as to best represent and account for important characteristics of the underlying processes.

The objective is to provide IGEM with a specification and set of results for simulating the optimistic scenario for the agricultural sector, while linking this scenario as closely and as consistently as possible to the results and scenarios given by the U.S. National Assessment (2001). The equation above accomplishes this.

The pessimistic scenario is based on the modeling of Adams et al. (1990) in one of the earlier attempts to model the agricultural response to climate change. This study examined agricultural response under two general circulation models (GCMs) for doubled CO_2 conditions, the GISS and GFDL models. As before, U.S. average changes in temperature and precipitation from the two GCMs were used to orient the model results to the climate scenarios. Adams et al (1990) present results in the form of price and quantity indices that express the aggregate impacts on the agricultural sector across regions and commodities. These indices can be used to estimate the unit cost changes associated with the two GCMs.

However, given just two data points, there are insufficient statistical degrees of freedom to estimate response coefficients for both temperature and precipitation. To address this limitation, a proxy measure is used to express both the change in temperature and precipitation in a single scalar. With assistance from Dr. David Yates and his 1997 article (Strzepek and Yates, 1997), a water balance model was developed. This model expresses annual run-off as a function of temperature and precipitation. Given the strong relationship observed in data from Adams et al. (1990) between precipitation and agricultural productivity, run-off changes appear a suitable proxy for soil moisture. In turn, this leads to a single-variable model that reasonably associates climate change and agricultural impacts based on the Adams et al. (1990) data.

The water balance relationship given in Strzepek and Yates (1997) appears as:

$$Q_a = P_a \left[1 - \frac{L_a}{\sqrt{cL_a^2 + P_a^2}} \right]$$

where Q_a is run-off (mm/yr), P_a is annual precipitation, $L_a = 300 + 25T_a + 0.05T_a^3$, c is a calibration constant (equal to 0.9 for uncalibrated watersheds), and T_a is annual average temperature (°C).

The effects of climate changes on run-off are given by the differentials of the run-off equation with respect to temperature and precipitation changes. A regression model of the change in cost and the change in run-off then is estimated. The estimated pessimistic relationship between agricultural productivity and climate is given as:

$$dCost = -0.013 * dQ_a$$

where dCost is the change in the unit cost of production and dQ_a in millimeters per year is the estimated change in run-off using the water balance relationship given above. As the cost equation indicates, the costs of maintaining agricultural output fall as run-off rises.

A.2. Livestock

Scheraga et al. (1993) also draw on the earlier efforts of Adams et al. (1993) in constructing models of the impacts of climate change on productivity in livestock production. The optimistic model for livestock production is based on Adams et al. (1993) results for the GISS climate scenario and includes the direct benefits of CO_2 fertilization. Formally, the model developed to interpolate and extrapolate the impacts on livestock production is given as:

$$\text{Cost} = (100+1.4 * (\text{dTemperature})^{1.5}) * (1-0.16 * L)$$

where Cost is an index of unit cost (relative to a base of 100), dTemperature is the change in the global mean temperature in °C, and L is the logistic function $L=1/(1+\exp(-(0.022*(CO_2-330)-5))$. The logistic function is designed to capture the beneficial effects of CO_2 fertilization in agriculture. Its parameters are set so that its point of inflection occurs at a CO_2 concentration of 555 parts per million (ppm). Below 555 ppm, values for L are increasing at an increasing rate while, above 555 ppm, values are increasing at a decreasing rate. The interaction of temperature change and CO_2 effects are such that cost benefits for livestock production are sustainable through 2100 and beyond under low warming conditions but erode, beginning in 2080, under high warming conditions. This benefit reversal, like the quadratic expression for crop agriculture, introduces another threshold effect into the set of optimistic driving assumptions.

The pessimistic model for livestock production is based on the Adams et al. (1993) results in the absence of benefits from CO_2 fertilization. Here, the index of relative unit cost depends solely on the change in global mean temperature as:

$$\text{Cost} = 100+13.49 * (\text{dTemperature})^{1.5}$$

Using this formulation, unit production costs are almost 20 percent higher under low warming conditions and more than double under the higher warming trends. Stated another way, the same inputs generate only 80 percent of the “base” output of livestock under low warming trends and less than 50 percent of the base output under the more severe conditions.

A.3. Forestry

Forest sector impacts are estimated from the results of Callaway et al. (1995) and Sohngen and Mendelsohn (1999). As with the agriculture estimates, the objective is to estimate the change in the unit cost of production associated with a given change in climate. The best proxy for this is the yield change associated with a change in climate. As in agriculture, yield is the fundamental productivity characteristic that is affected by climate.

The optimistic scenario is derived from data compiled by Dr. Brent Sohngen for the VEMAP project and used to analyze the forest sector in Sohngen and Mendelsohn (1999). The VEMAP project examined the response of ecosystem productivity to changes in climate. Both biogeochemical and biogeographical processes were simulated in the VEMAP project to examine ecosystem productivity changes. The former simulates the fundamental changes in chemical cycling and net primary productivity while the latter simulates the geographic response of vegetation and ecosystem types as they migrate in response to climate change. Of the nine combinations of model types explored in Sohngen and Mendelsohn, this study adopts the combination of the TEM (Melillo et al., 1993) biogeochemical model and the DOLY biogeographical model (Woodward et al., 1995) because this combination is at the higher range of the yield estimates.

Optimistic forestry impact estimates were developed as follows. First, regional productivity changes were averaged, weighted by regional harvests in 1991 (Haynes et al., 1995). Next, annual changes in temperature and precipitation associated with the VEMAP GCMs were constructed based on data provided by Sohngen. Finally, a regression was fit to estimate the coefficients for changes in temperature and precipitation on unit costs (the negative of yield changes). The estimated relationship is given as:

$$\text{dCost} = -0.052 * \text{dTemperature} + 0.078 * \text{dPrecipitation}$$

where the variables are the same as defined earlier. Note here that higher temperatures reduce unit costs while higher precipitation increase unit costs.

The pessimistic scenario is derived from the data used in Callaway et al. (1995). The yield data used in this study were derived from gap model studies that do not explore the results of changes in biogeographical distribution.[1] As a consequence, the estimated effects of climate change are often quite negative.

Callaway et al. give estimated percentage changes in regional softwood and hardwood growing stock (yield) for each of four climate scenarios, 2.5°C with and without CO_2 effects, and 4°C with and without CO_2 effects. Their study is based on GCM outputs which include precipitation changes consistent with changes in temperature.

Assuming CO_2 effects, a weighted average yield change is estimated using regional harvest share data from Haynes et al. (1995). This provides two estimates with two different temperature change

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[1] In addition, gap models do not take CO_2 changes into account and, therefore, Callaway et al. (1995) constructed an adjustment factor that is used to mitigate some of the estimated losses.

assumptions. Regressing on temperature provided the following relationship for estimating pessimistic unit cost changes:

$$dCost = 0.041 * dTemperature$$

A.4. Fisheries

Rising sea levels due to global warming and measures to protect developed shorelines are expected to result in losses of coastal wetlands. In turn, these will have negative consequences for fish harvests and harvest costs. Titus et al. (1991) estimate the loss of wetlands for 50 centimeter (cm) and 100 cm increases in sea levels. In Scheraga et al. (1993), these results are approximated by:

$$Loss = A * (dSea\text{-}Level)^{0.6}$$

where Loss is the proportion of wetlands lost, dSea-Level is the sea level rise in cm and A is a model parameter. Scheraga et al. estimate that a 50 percent reduction in marsh productivity raises average harvest costs by 12.5 percent. Assuming a linear, one-for-one relationship between the loss in wetlands and the reduction in marsh productivity (Frankhauser, 1993), the effect of sea level rise on harvest costs is given as:

$$Cost = 1+0.25 * Loss = 1+0.25 * (A * (dSea\ Level)^{0.6})$$

where Cost is an index of unit cost for the aggregate commercial fish harvest. In Scheraga et al., the model parameter, A, takes on the value of 0.016 under optimistic conditions and 0.040 for pessimistic outcomes. Under low warming trends, unit costs for commercial fisheries are 2.2 and 5.5 percent higher by 2100 under optimistic and pessimistic conditions, respectively. Under the high warming trends, these percentages rise to 6.3 and 15.7 percent, respectively. On the down side, these results are consistent with more recent estimates by Markowski et al. (1999). However, unlike the smaller optimistic "costs" of Scheraga et al., these authors identify potential cost and production benefits (i.e., lower costs and higher output) in the range of 3.0 to 10.0 percent. While measurable, the impact of fisheries on the overall economy is extremely small as commercial fishing is around 1.1 percent of total agriculture and agriculture is around 3.2 percent of final spending. At a share of 0.03 percent, truly dramatic changes for better or worse will be of little consequence to overall incomes and welfare; they will matter most only to those directly involved in these markets.

A.5. Space Heating and Cooling

Climate change is expected to change energy use by affecting space heating and cooling requirements (i.e., space conditioning) for both residential and commercial environments. Space conditioning is an important component of energy use, accounting for about 15 percent of total energy expenditures in 1990 (Rosenthal et al., 1995). In the United States, heating expenditures are about 2.3 times those for cooling. Therefore, a moderate general warming is widely expected to generate an average cost savings for space conditioning, particularly in the short run, in which the stock of houses and buildings remains constant. There is also agreement on the existence of a theoretical threshold beyond which cooling cost increases dominate heating cost savings. Additionally, in the long run, adjustments to the stock of houses and buildings may affect the rate at which temperature changes affect energy costs. For example, Morrison and Mendelsohn (1999) suggest that, in a warmer climate, it may be more efficient to reduce investments in capital improvements, such as insulation, which would marginally increase energy use compared to the case where house and building characteristics were held constant.

The goal here is to identify how climate change may affect the energy requirements to produce the level of services currently expected by the control of indoor temperatures. Attempts to measure the impact of warming on energy use have produced a range of results. Rosenthal et al. (1995) estimate energy savings of 6 percent under a 1°C warming and 13 percent under a 2.5°C warming. Nordhaus (1991) and Cline (1992) estimate cost increases of 1 percent and 11 percent, respectively, for a 2.5°C warming. These latter estimates are based largely on changes in electricity use, the primary energy source for space cooling.

Rosenthal et al. (1995) are comprehensive in their examination of energy use. Their model takes into account differences in the use of various energy sources to produce space-conditioning services. The model is regional and considers how warmer temperatures affect the demand for heating and cooling as measured by changes in heating- and cooling-degree days. The model draws on the U.S. Department of Energy's Commercial Buildings Energy Consumption Survey (Energy Information Administration, 1992), and its Residential Energy Consumption Survey (Energy Information Administration, 1993) to estimate the relationships between energy costs and space conditioning demands in the residential and commercial sectors.

Morrison and Mendelsohn (1999) model energy costs and climate change using some of the same dataset as Rosenthal et al. (1995). Their analysis derives from both short- and long-run theoretical models that capture the substitution effects between energy and construction investment. Consistent with the Rosenthal et al. (1995) findings, climate change is likely to reduce unit energy costs in the short-run. However, taking into account long-run changes in house and building characteristics, energy costs could in fact climb by 2 to 4 percent under a 2.5°C warming.[2] While Rosenthal et al. (1995) do not consider changes in building characteristics, there is agreement that, if temperatures rise much beyond 2.5°C, long-run energy costs would rise because cooling cost increases would dominate heating cost savings.

In constructing estimates for IGEM, data were developed from both the Rosenthal et al. (1995) study and from the Morrison and Mendelsohn (1999) study. From Rosenthal et al. (1995), data on space conditioning costs and their estimated change under a 1°C global average warming for both residential and commercial sectors energy and across energy sources (i.e., electricity, natural gas, petroleum, and coal and wood) were used to estimate the cost change associated with a 1°C increase in global average temperature. The percentage changes in costs are weighted by the share of total energy used from each source and by the two sectors, residential and commercial. The result is -5.766 percent per °C change in global average warming. The optimistic estimate appears as follows:

for temperature changes up to 2°C

dCost = -5.766% * dglobal average temperature,

and, for temperature changes beyond 2°C

dCost = 5.766% * (dglobal average temperature - 2°C) + (2°C * -5.766%)

Reversing the weighting scheme in Rosenthal et al. (1995) leads to estimates of cost changes by fuel type. Under optimistic conditions, electricity-based costs increase while space conditioning from coal, wood, oil and gas becomes relatively less expensive and more than compensating.

The overall impact on energy is a two-piece linear relationship, where average costs fall over temperature increases up to 2°C. As temperature changes rise above a 2°C increase, energy costs rise linearly

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(2) Mendelsohn and Morrison argue that changes in the capital stock will most likely result from climate change. For example, insulation requirements will likely fall as a result of climate change and, therefore, consumers can be expected to shift expenditures away from building costs and into higher energy bills, with the understanding that total space conditioning costs, including capital, would be lower.

at the same rate they were falling. Because Rosenthal et al. (1995) do not identify the point at which the trend reverses, the threshold change identified in Morrison and Mendelsohn (1999) is employed here.

Like agriculture, the threshold assumption and behavior are uncertain. The true threshold may be above or below 2°C and there is no reason that the rates of change in energy costs should be equal above and below this threshold. However, there are no available estimates to suggest something other than a symmetrical relationship and this represents a more plausible assumption than simply continuing the linear fall in energy costs with ever increasing temperatures.

The pessimistic estimates of energy cost changes due to climate change are based on the model and work of Morrison and Mendelsohn (1999). Building on this effort, Mendelsohn and Schlesinger (1999) estimate a reduced-form relationship summarizing the fuller model. The reduced-form equation appears as:

$$\text{Welfare (millions of \$1995)} = -\left[(251{,}000 + 7380 * \text{Temp} - 368*\text{Temp}^2) * (\text{GDP}/\text{GDP}_{2060})\right].$$

From this, the percentage change in the unit cost of energy, dCost, is given as:

$$\text{dCost} = [\text{Welfare (climate change)} / \text{Welfare (baseline)} - 1] / 0.7$$ [3]

Strictly interpreted, IGEM does not represent space heating and cooling among its economic activities. However, within the market demands for coal, wood, refined petroleum products, electricity and natural gas are the uses of these commodities for the purposes of space conditioning. In accounting for the energy effects of climate change, the direct effects are applied to the total outputs of commodities (coal, wood, oil, electricity and gas) in proportion to their use in supplying residential and commercial heating and cooling. Implicit in this scheme is the presumption that the producers in these sectors include those who own and operate the equipment in which these energy inputs are consumed. Also implicit in this scheme is the notion that the outputs of these sectors are not really commodities but, rather, the services these commodities provide (e.g., space conditioning, water and process heating, cooking, motive power, etc.). Viewed in this manner, IGEM can portray the economy-wide adjustments to the energy changes arising from global warming. Success in this portrayal depends on the extent to which a) the relative responsiveness implied for these energy users to price and cost changes is accurate and b) the inability of IGEM to strictly isolate energy products and end

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(3) The scale adjustment dividing the expression by 0.7 is made to reflect the difference between using measures of welfare, which are based on producer and consumer surplus, and changes in the marginal cost of production. The adjustment is exact when demand is relatively inelastic (i.e., -0.35) and when producers are willing to supply all that is demanded at prevailing prices.

uses (e.g., distillate oil for space heating versus gasoline for automobiles, natural gas for space heating versus natural gas for industrial processes, electricity for air conditioning versus electricity for lighting and appliances, etc.) does not seriously bias the estimated economic outcomes.

A.6. Water Supplies

Water resources provide a variety of services and have been the subject of many studies related to climate change. Two of the more recent studies that have attempted to estimate the changes in socioeconomic costs include Hurd et al. (1999) and Frederick and Schwarz (1999).

Optimistic estimates are based on market impacts estimated by Hurd et al. (1999). Here, detailed models of four selected watersheds (Colorado, Missouri, Delaware, and Apalachicola-Flint-Chattahoochee) were developed and used to assess the economic impacts of run-off and demand changes under alternative climate scenarios. The welfare changes then were extrapolated to other regions and all then were aggregated to the national level. Mendelsohn and Schlesinger (1999) then estimated a reduced-form equation, similar to the one developed for energy, to relate impacts to changes in precipitation and temperature. This relationship appears as follows:

$$\text{Welfare (millions of \$1995)} = 134{,}000 - (4124 * \text{Temperature}) + (67.4 * \text{Temperature})^2 + (4941 * \text{Average Monthly Precipitation}).^4$$

From this, the percentage change in the unit cost of energy, dCost, is given as:

$$\text{dCost} = -[\text{Welfare (climate change)} / \text{Welfare (baseline)} - 1] / 0.7$$

Pessimistic estimates are derived from Frederick and Schwarz (1999). Estimates of the potential impacts of climate change are developed under both the HC and CC GCMs used in the U.S. National Assessment. The authors report total annual additional costs of approximately $105 billion related to water resource services by 2030 under the relatively dry CC scenario and benefits of $4.7 billion under the relatively wet HC scenario. The methodology accounts for forgone opportunity costs associated with water

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(4) In the United States, the average annual temperature is around 10.7°C. Over the relevant range of temperatures and temperature changes, this function shows welfare declining. The linear term dominates the quadratic term until about 30.6°C, far beyond any projections of temperature rise.

redirected away from agriculture, for increased conservation efforts, and for ecological services related to streamflow. The costs in Frederick and Schwarz (1999) associated with providing additional supplies are estimated at $45 billion under the CC scenario and $0 under the HC scenario.

To provide a basis of comparison, 1995 water use rates by sector from Solley et al. (1998) combine with the costs by sector of new supplies estimated in Frederick and Schwarz (1999) to yield an average cost across sectors. Per acre foot (af) estimates by sector from Frederick and Schwarz (1999) and the average cost weighted by water use are as follows:

1. public supply	$538/af[5]
2. domestic	$538/af
3. commercial	$538/af
4. irrigation	$50/af
5. livestock	$50/af
6. industrial	$125/af
7. mining	$125/af
8. thermoelectric	$125/af
Average Use Weighted Value	**$151/af**

Using $151/af as the average baseline marginal cost of developing additional water supplies, the total baseline cost for current water services is estimated at $77.4 billion per year.[6] The estimated cost increase under the CC scenario is 58 percent (i.e., $45 billion / $77 billion), and under the HC scenario is 0 percent.

The run-off equation developed for agriculture again was applied to estimate the climate response function for these two data points. Run-off changes estimated from temperature and precipitation changes were used to estimate changes in water supply costs yielding the following:

$$dCost = -2.143 * dQ_a/Q_a$$

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(5) The estimated per acre foot costs for the public supply, domestic, and commercial sectors were based on the Frederick and Schwarz's estimated costs for other sectors, which reflect differences in relative regional scarcity, and averaged across all regions.

(6) This estimate is derived as the product of total average per capita water use (1,350 gallons per person per day), 365 days per year, 340 million people (projected in 2030), 325,851 gallons/af, and $151/af.

A.7. Coastal Protection

Accelerated sea-level rise is expected to impact coastal areas and increase costs to protect developed areas, beaches and other natural habitats. Estimates of the cumulative and annualized costs projected to occur with climate change are available from several sources including Smith and Tirpak (1989), Nordhaus (1991), Frankhauser (1995), and Yohe et al. (1996). As summarized recently in Yohe et al. (1999), these estimates can be used directly along with the estimated rise in sea-level to estimate the direct costs on the economy.

The optimistic estimate is based on the results in Yohe et al. (1996). Here, 50 and 100 centimeter (cm) increases in sea-level yield annualized costs of $0.06 billion and $0.16 billion, respectively. Accordingly, the estimated coefficient for sea-level rise is $1.52 million per centimeter.

The pessimistic estimate is based on Nordhaus (1991), which builds on an earlier EPA effort. In this case, the estimated range of cumulative impacts with a 100 cm rise by 2100 is $73 to $111 billion, which Nordhaus annualizes to approximately $5.0 billion. Therefore, the estimated annualized cost for sea-level rise is $50 million per centimeter.

A.8. Storms, Floods and Hurricanes

Scheraga et al. (1993) posit an increase in the damages from storms, floods and hurricanes attributable to global climate change. Damages over baseline amounts grow according to the following relation:

$$\text{dCost} = A * (\text{dTemperature}/4)^{1.2} * \text{Cost}$$

where dCost is the additional damage in a given year due to warming, dTemperature is the change in global mean temperature (°C), Cost is the baseline damage estimated for that same year and A is a model parameter. Under optimistic conditions, the value of A is taken as 0.1 and, under pessimistic outcomes, A is 0.5. In Scheraga et al. (1993), baseline damages were presumed to rise over time based on evidence of the increasing frequency, intensity and area of storm, flood and hurricane occurrences (Riebsame et al., 1986). However, in light of more current data (Changnon, 2003, National Climate Data Center, 2003, and Pielke and Landsea, 1998), this analysis assumes no such trend. From these sources, baseline expected damages are estimated at a constant annual average of $7 billion, in year 2000 dollars. Under this formulation and under the low warming trends assumed herein, global climate change increases the expected average annual damages from storms, floods and hurricanes by just over 1 percent, optimistically, and by just over 6 percent, pessimistically. Under the high warming trends of this analysis, these increases rise to 4 and 21 percent, respectively.

A.9. Health

Changes in temperature are related to fluctuations in the incidence of adverse cardiovascular and respiratory outcomes through thermal stress. Therefore, as temperatures rise, the number of premature cold-related deaths in winter is likely to fall, while the number of heat-related deaths is expected to increase. This section seeks to account for the net effect of these two changes.

Martens (1997) and Kalkstein and Greene (1997) estimate thermal stress mortality rates. Martens presents an optimistic relationship that shows net mortality rates declining in cold temperate regions. Specifically, Martens' (1997) relationship suggests that there will be a reduction of 3 cardiovascular deaths per 100,000 persons under 65 for approximately each 1.2°C warming. This mortality benefit translates into 2.5 net lives saved per 100,000 persons per 1°C warming.

In comparison, Kalkstein and Greene (1997) estimate an overall increase in mortality rates as a consequence of climate change. The Kalkstein and Greene analysis suggests that continued warming has a much greater effect on heat-related mortality in the summer than on cold-related mortality in the winter. Their study examined the effects of climate change on the change in the frequency of "unhealthy" air masses both in winter and summer. Their results for 2050 indicate a mortality cost of 3.8 net lives lost per 100,000 persons per 1°C warming.

A.10. Air Quality

This section summarizes the analytical efforts of Chestnut and Mills (2000).

Concentration-response functions derived from the epidemiological literature for the effects of changes in ambient ozone concentrations yield a range of health outcomes varying in severity from days where individuals experience minor restrictions in their normal activity, to hospitalizations, and, at the extreme, premature mortality (U.S. EPA, 1999).

Abt Associates (1999) reports estimates of the number of ozone-related hospitalizations, emergency room visits, and symptom days in the 37 Eastern states and the District of Columbia for April through October 1997. One percent of the Abt Associates (1999) values are taken as the starting point estimate of the number of adverse health outcomes that would be attributable to a 1 percent increase in ambient ozone concentrations. These starting values are scaled upward by a factor of 1.28 to account for the population of the remaining Western states not captured in the original Abt Associates (1999) estimates (U.S. Bureau of the Census, 1998). This population adjustment assumes the per capita incidence of these ozone-related outcomes is the same in the East and West.

In this analysis, people and time are the chosen metrics for examining the market consequences of changes in mortality and morbidity. Mortality affects the population as a whole and the discretionary time available to the working-aged population for work and leisure. Morbidity is assumed to affect only the latter.

Table A-1 shows the steps in developing the morbidity effects arising from ozone concentrations. Age distributions of the outcomes in Table A-1 were developed from the 1996 and 1997 National Hospital Discharge Survey, the 1996 and 1997 National Hospital Ambulatory Medical Care Survey and the 1996 National Health Interview Survey. The 1996 and 1997 data from these surveys were averaged to yield the age distributions of occurrences. The shares in column 2 assume that the age distribution of ozone-related outcomes is the same as the age distribution for all outcomes in the same category. For example, the survey data indicate that 33 percent of all cardiovascular hospital admissions in the U.S. are for patients of working age. Therefore, it is assumed that 33 percent of ozone-related cardiovascular hospital admissions also are for patients of working age.

Table A-1

Ozone-Related Labor-Leisure Days Lost From Morbidity Outcomes per 1% Increase in Ozone Concentration

Health outcome	Estimated ozone-related outcomes for all ages in U.S. (1,000s)	Share of outcomes realized by the working aged population	Labor-leisure days lost per outcome	Fraction of the year relevant to labor-leisure choice (235 days out of 365 days)	Total labor-leisure days lost
Cardiovascular hospital admissions	0.20	33%	4.7	0.644	200
Respiratory hospital admissions	0.68	33%	5.3	0.644	766
Respiratory emergency room visits	2.04	51%	1.0	0.644	670
Symptom days	1062.40	60%	0.25	0.644	102,628
Total loss in labor-leisure days per 1% increase in ozone concentration					**104,264**

From the National Hospital Discharge Surveys for 1996 and 1997, it is estimated that working-aged individuals had an average length of stay of 4.7 days for a cardiovascular hospitalization and 5.3 days for a respiratory hospitalization. Emergency room visits are assumed to result in the loss of 1 labor-leisure day per occurrence. Ozone-related symptom days are primarily respiratory-related and may include some restriction in activity. Lacking data on how much activity restriction occurs within an average minor restricted activity day, an assumption is made that each occurrence represents the loss of 1/4 of a labor-leisure day.

Finally, it is assumed that ozone-related outcomes occur on both work and non-work days. This results in a 0.644 adjustment assuming 235 out of 365 days are work days. For IGEM, this scalar adjusts the morbidity effects for the assumed fraction of a year over which households make discretionary labor-leisure choices. Table A-1 combines the information on ozone-related outcomes, age-based allocation shares, and labor-leisure days lost per occurrence to produce an annual estimate of the total national ozone-related loss in labor-leisure for a 1 percent change in ozone concentration.

Table A-2

Relationship of Ozone-Related **Premature Mortality** and Respiratory Hospital Admissions

Premature mortality concentration-response parameter	5.1×10^{-9}
Respiratory hospital admissions concentration-response parameter	16.0×10^{-9}
Ratio of mortality to respiratory hospital admissions parameters	0.32
National estimate of ozone-related respiratory hospital admissions	67,840
Estimated ozone-related premature mortalities	21,624

Ozone-related premature mortalities were calculated using the ratio of the central concentration-response parameter estimate for ozone-related premature mortality and the low concentration-response parameter estimate for ozone-related respiratory hospital admissions provided in BenMod 1.0 Benefits Model for Air Quality Documentation Report (Chestnut et al., 1997). The latter is equivalent to the pooled parameter estimate used in Abt Associates (1999) to calculate respiratory hospital admissions attributable to ozone. This concentration-response parameter ratio was then multiplied by the national estimate of ozone-related hospital admissions (see Table A-1) to estimate ozone-related premature mortalities for 1997. The information used to estimate the number of ozone-related mortalities in 1997 is presented in Table A-2.

From this, Chestnut and Mills (2000) estimate that a 1 percent increase in ozone concentrations is responsible for 216 to 217 premature mortalities.

The ozone-related premature mortality parameter used in this process is a weighted average of the results from a group of nine studies that satisfied a set of study selection criteria such as including controls for particulate matter and using year round data. As a group, these studies found both statistically significant and insignificant effects for ozone on premature mortality. Plausible alternative estimates for the impact of ozone on premature mortality include a lower bound "no effect" estimate, which is supported by the statistically insignificant results in the group and upper bound estimates based on alternative groupings of the statistically significant results. The decision to use the weighted average result from the entire group of studies reflects a desire to incorporate all the data from the studies.

Evidence suggests that some aspects of air quality are strongly affected by climate. Elevated urban and regional oxidant concentrations, in particular ozone, are the result of complex interactions between sunlight, NO_x, and other precursors. Given the relationship between oxidant formation and sunlight, ambient ozone concentrations tend to increase with temperature (Penner et al., 1989). This assumes that the increased temperature raises marginal ambient concentrations and does not result in greater efforts to control emissions. Penner et al. (1989) estimate that ambient ozone concentrations could increase between 1 and 2 percent per °C increase in temperature. This analysis assumes the midpoint of this range is 1.5 percent per °C.

For the optimistic scenarios, it is assumed that ozone levels are controlled below standards in the future and that the marginal effect of climate change on ozone formation is negligible. Therefore, there are no labor-leisure days lost or premature mortalities under these conditions.

Assuming that a 1°C increase leads to a 1.5 percent rise in ozone, the pessimistic relationship for morbidity effects is given as:

$$\text{labor-leisure days lost} = 104{,}264 * 1.5\% * \text{dOzone}/1°\text{C} * \text{dTemperature}.$$

The pessimistic relationship for ozone-related mortality effects appears as:

$$\text{premature mortalities} = 216.24 * 1.5\% * \text{dOzone}/1°\text{C} * \text{dTemperature}.$$

Each of these impose costs on the economy as they reduce the household sector's time endowment for labor-leisure choice and/or the nation's population.

A.11. Modeling Mortality Effects

The mortality effects related to thermal stress (section A.9) and air quality (section A.10) appear as annual changes to the base population and, depending on the person's age, the amount of time available for discretionary work and leisure decisions. These changes are either upward or downward as optimistic or pessimistic circumstances prevail. A premature death avoided is a benefit to the economy until such a time as that person dies anyway, presumably unaffected by climate change. Similarly, a premature death is a cost to the economy until such a time as the person would have died anyway, again, presumably unaffected by climate change. Accordingly, the annual changes in population due to climate change first must be distributed by age group. These, then, are accumulated, also by age group. The annual cumulative benefits or costs are adjusted downward by the cumulative number of persons that just either have (benefit side) or would have (cost side) died anyway. This is a crude overlapping generations calculation in that it does not account for changes in births or actuarial deaths along the way but, nevertheless, avoids large overstatements of the mortality benefits or costs.

The age distribution of mortalities is assumed to be the same as for all respiratory and cardiovascular mortalities reported for 1997 by the Centers for Diseases Control and Prevention (2000). This subset of all deaths is selected because climate-related health outcomes are assumed to be generally associated with respiratory and cardiovascular conditions. Table A-3 shows the age distribution of premature mortalities for ozone-related deaths. The weights implicit in these data are applied to the net lives saved or lost due to thermal stress and to ozone-related deaths to arrive at the age distribution of annual benefits and costs to the population. In turn, these are accumulated to yield the total effects of climate change unadjusted for when these persons should no longer be counted in the stream of benefits or costs.

Table A-3

Age Distribution of Ozone-Related Premature Mortalities

Age group	Estimated premature mortalities in 1997
Less than 1 year	33
1–4	12
5–9	6
10–14	8
15–19	14
20–24	22
25–29	35
30–34	67
35–39	132
40–44	235
45–49	374
50–54	534
55–59	712
60–64	1,057
Age 65+	18,383
Total	**21,624**

The departure of individuals from the mortality benefit-cost streams is a lagged reduction in the cumulative deaths avoided or incurred. Table A-4 shows the assumptions used to perform this adjustment. For example, persons aged 20 to 24 are represented by an average 22 year old. This individual is presumed to have 52 years remaining before retirement and 59 years of remaining life. Thus, a 22 year old entering the benefit or cost stream in the year 2020 is no longer counted as a benefit or cost after the year 2072 for labor-leisure decisions, and after the year 2079 for population considerations.

Table A-4

Years Remaining in the Mortality Benefit-Cost Pool

Age group	Assumed age	Number of remaining working years	Number of remaining years
Less than 1 year	1	73	80
1–4	3	71	78
5–9	7	67	74
10–14	12	62	69
15–19	17	57	64
20–24	22	52	59
25–29	27	47	54
30–34	32	42	49
35–39	37	37	44
40–44	42	32	39
45–49	47	27	34
50–54	52	22	29
55–59	57	17	24
60–64	62	12	19
Age 65+	70	4	11

Appendix B: Description of the Intertemporal General Equilibrium Model (IGEM): Industries and Commodities, Model Organization and Model Flows

In IGEM, production is disaggregated to 35 separate commodities produced by one or more of 35 industries. The industries are listed in Table B-1 and generally match two-digit sectors in the North American Industry Classification System (NAICS). Each industry produces one primary product and may produce one or more additional goods or services.

Table B-1

Definitions of **Industries-Commodities**

Number	Description
1	Agriculture, forestry and fisheries
2	Metal mining
3	Coal mining
4	Crude oil and natural gas extraction
5	Non-metallic mineral mining
6	Construction
7	Food and kindred products
8	Tobacco manufactures
9	Textile mill products
10	Apparel and other textile products
11	Lumber and wood products
12	Furniture and fixtures
13	Paper and allied products
14	Printing and publishing
15	Chemicals and allied products
16	Petroleum refining
17	Rubber and plastic products
18	Leather and leather products
19	Stone, clay and glass products
20	Primary metals
21	Fabricated metal products
22	Non-electrical machinery
23	Electrical machinery
24	Motor vehicles
25	Other transportation equipment
26	Instruments
27	Miscellaneous manufacturing
28	Transportation and warehousing
29	Communications
30	Electric utilities (services)
31	Gas utilities (services)
32	Wholesale and retail trade
33	Finance, insurance and real estate
34	Other personal and business services
35	Government enterprises

Economic activity is organized in an inter-industry framework in which the demands for and supplies of each commodity, as well as those of capital and labor, balance in both value and quantity terms. This inter-industry framework consists of the thirty-five producing sectors, the household or consumer sector, a business investment sector, the federal, state and local governments sector and a foreign sector. The organization of annual use and make tables is shown in Figure B-1; these are "spreadsheets" at the industry and commodity level of detail. The use tables show commodity purchases by industries and final demand while the make tables show the commodities made by industries. Figure B-1 also shows the inputs of capital and labor into each producing and consuming sector.

Figure B-1

Organization of the **Use and Make Tables**

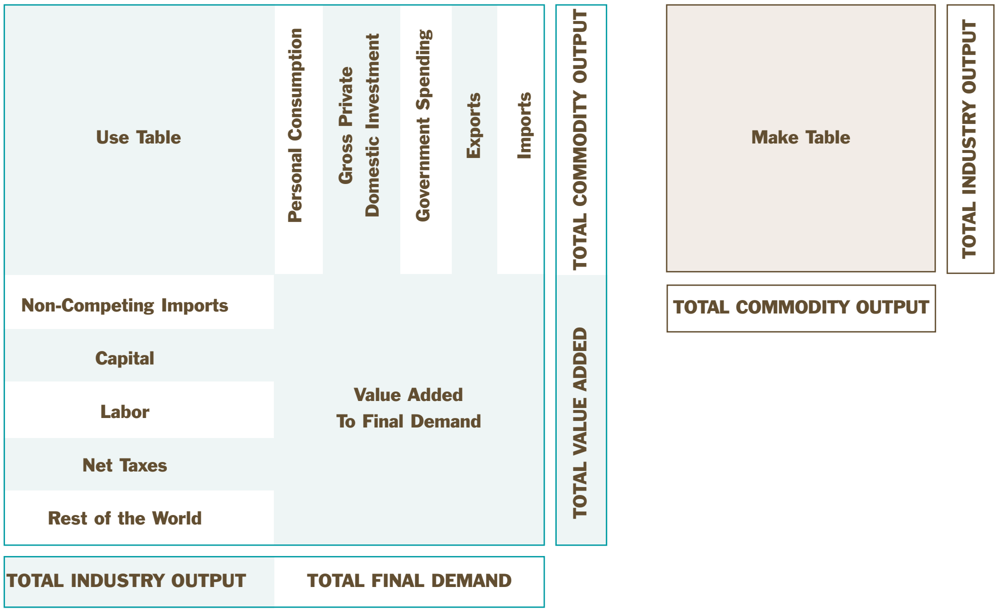


Figure B-2 depicts production and supply. Inputs of the thirty-five commodities plus capital, labor and non-competing imports are combined to produce domestic industrial outputs. In turn, these outputs are mapped into domestic commodity outputs through use of the make table. Combining the domestic commodities with competitive foreign imports gives rise to the available supplies that are purchased as intermediate inputs or finished goods (final demand).

Finally, household consumption by commodity is shown as the result of a three-stage, multi-period optimization process in Figure B-3. Households choose the amount of full consumption (goods, services and leisure) they are going to consume in each period. They then allocate this between the consumption of goods and services and the consumption of leisure. Given the time endowment for each period, the choice of leisure simultaneously determines the labor supply that, with prevailing compensation rates, interest, profits and other capital income, determines total income. The difference between income and consumption is private domestic saving which, with foreign saving, funds private domestic investment and the government deficit. Consumption then is allocated among the thirty-five commodities, including the service flows from consumer durable goods. Investment is allocated similarly across the various categories of capital goods as households and businesses use saving to purchase additions to the capital stock. Government additions to capital are part of government purchases.

Figure B-2

The Model Flows of **Production and Commodity Supply**

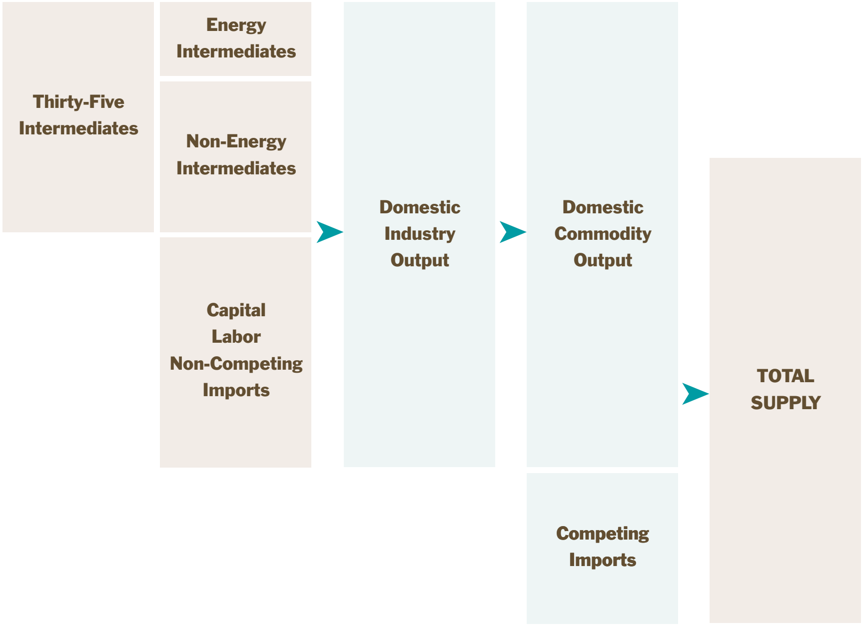
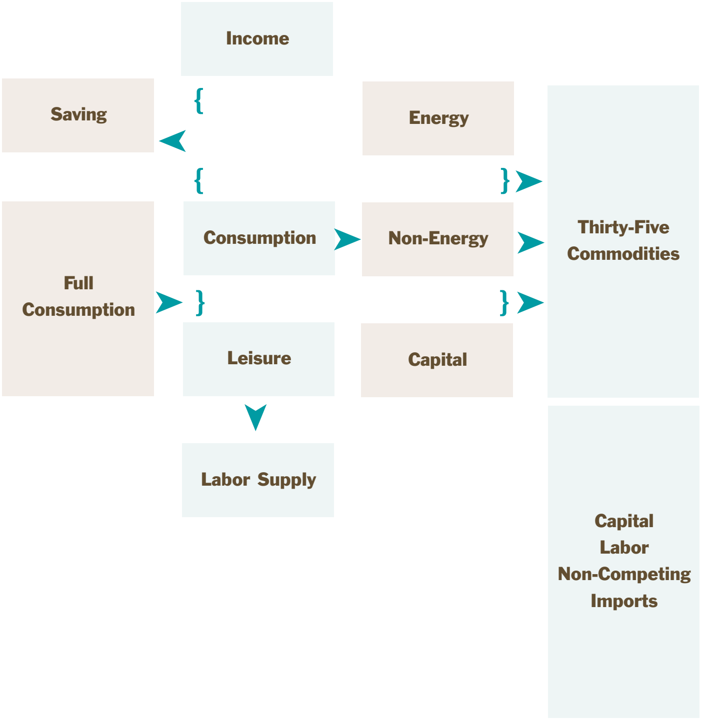


Figure B-3

The Model Flows of **Household Behavior**



This report develops an integrated assessment of the potential impacts of climate change on the U.S. economy. The Pew Center on Global Climate Change was established by the Pew Charitable Trusts to bring a new cooperative approach and critical scientific, economic, and technological expertise to the global climate change debate. We intend to inform this debate through wide-ranging analyses that will add new facts and perspectives in four areas: policy (domestic and international), economics, environment, and solutions.

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