Climate Change and the U.S. Economy: The Costs of Inaction

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1. Introduction

The scientific consensus is in: The earth's climate is changing for the worse, as a result of anthropogenic (human-caused) changes to the composition of the atmosphere. If we can, all around the world, work together to reduce the concentration of greenhouse gases in our atmosphere, we can slow and even stop climate change. If we fail to do so, the consequences will be increasingly painful – and expensive.

The Intergovernmental Panel on Climate Change (IPCC), an international organization of thousands of scientists, including numerous prominent U.S. scholars, issues periodic assessments of what we know about climate change; the latest and most ominous assessment appeared in 2007. If greenhouse gas emissions continue to grow unimpeded, the latest IPCC reports predict an increase of as much as 12-13°F in the mainland United States and 18°F in Alaska by 2100.[1] Recent studies by leading scientists among the IPCC's panel of experts predict sea-level rise of nearly 4 feet by 2100. The IPCC also considers more erratic weather, storms, droughts, hurricanes and heat waves to be likely consequences of business-as-usual emissions.

It is hard to imagine these climatic changes *not* having serious economic consequences, but in many ways, the economic impacts of climate change have proved more difficult to project than the future climate itself. A number of economists have conducted studies in which they take scientific predictions about climate change and use them to estimate future economic conditions. But the results of these studies don't agree, any more than the economists themselves do.

The problem is that economic analysis is not science: economic models use crucial but untestable assumptions based on the set of values held by the economist. In an empirically based science, results would be expected to converge toward a consensus over time, as has happened in climate science. Indeed, reproducible empirical research is a cornerstone of the scientific method. Economics, in contrast, offers results driven by theories that differ from researcher to researcher, with no obvious empirical tests that could settle the disputes.

Many of the most widely cited economic analyses of climate change are severely out of step with the gravity of the scientific consensus, which predicts an unrecognizable future climate unless action is taken quickly. Those economic analyses are equally out of step with the world's ethical consensus, as expressed in international negotiations, which views climate change as a problem of the utmost seriousness for our own and future generations.

At the same time, there are many empirical studies of industries, sectors, and states, identifying damages that will be caused by unchecked climate change. Multi-billion-dollar losses have resulted from many droughts, floods, wildfires, and hurricanes – events that will likely become more frequent and more devastating as the climate continues to worsen. Tourism, agriculture, and other weather-dependent industries will suffer large losses, but no one will be exempt. A thorough review of such studies for the United States has recently been produced by the University of Maryland's Center for Integrative Environmental Research (CIER 2007). This report complements the CIER research, attempting to develop a single "bottom line" economic impact for several of the largest categories of damages – and to critique the misleading economic models that offer a more complacent picture of climate costs for the United States.

In this report, we begin by highlighting just a few categories of costs, which, if present trends continue, will add up to a bottom line of almost $1.9 trillion (in today's dollars), or 1.8 percent of U.S. output per year by 2100. Chapter 2 describes four types of costs: economic damages caused by the increasing intensity of Atlantic and Gulf Coast hurricanes; damaged or destroyed residential real estate as a result of rising sea levels; increasing need for, and expenditure on, energy throughout the country; and the costs of providing water to the driest and most water-stressed parts of the United States as climate change exacerbates drought conditions and disrupts existing patterns of water supply.

In Chapter 3, we calculate the cost to the United States of climate inaction. A future with no economic consequences of climate change is no longer available to us, but it is still possible to slow climate change and to hold the damages to a fraction of the level described in Chapter 2. The cost of inaction is the difference between the economic damages in the best climate future that is still achievable, as described in Chapter 3, and the damages in the business-as-usual climate future described in Chapter 2. The cost of climate inaction (or, put another way, the potential savings from taking action to reduce greenhouse gas emissions) for the same four categories of costs, is $1.6 trillion per year by 2100, more than 1.5 percent of U.S. output.

These estimates – gross costs from climate change of 1.8 percent of U.S. output in 2100, or a net cost of inaction of 1.5 percent of output – are for just four categories of damages; an estimate of the total costs of climate change would be much larger. Many of the most widely published economic analyses of climate change, however, predict significantly lower costs for the United States. Indeed, some have predicted net benefits for the United States, and even for the world as a whole. In Chapter 4 we look at what's under the hood of some well-known economic analyses of the consequences of climate change. Chapter 4 explains some of the more bizarre assumptions that lead economists to make predictions that are out of step with the scientific consensus and with commonly shared values.

Among recent economic analyses the Stern Review (2006) stands out in its attempt to incorporate the inescapable uncertainty that surrounds climate predictions, and in its ethical judgments about how to value future costs and benefits. The PAGE model of climate impacts, used in the Stern Review, offers a unique approach to these important questions. The Stern Review did attempt to sum up worldwide costs and benefits across a vast range of impacts; nonetheless, it remains incomplete and imperfect in a number of areas. While the Stern Review represents an important advance in bringing economic analysis in step with climate science and commonly held values, its economic modeling still shows damages in the United States (and in many other industrialized countries) to be relatively small: just 1 percent of U.S. output by 2100, despite the inclusion in this estimate of monetary values placed on non-economic damages (like human lives lost or ecosystems destroyed) and on the risk of catastrophic damages (like a complete melting of the Greenland or West Antarctic Ice Sheets).

The Stern Review's results for the United States are examined in detail in Chapter 5. A new analysis, prepared for this report by Chris Hope, the developer of the PAGE model, changes the

Stern Review's assumptions about the United States' ability to protect itself from climate impacts and about the likelihood of catastrophic climate impacts. These changes have a big effect on estimates of U.S. damages from climate change. In our preferred PAGE model runs, climate costs reach 3.6 percent of U.S. output by 2100, including economic, non-economic, and catastrophic damages. Of course, many consequences of climate change cannot be priced: loss of human lives and health, extinction of species and losses of unique ecosystems, increased social conflict, and other impacts extend far beyond any monetary measure of losses.

Focusing on the losses that have prices, damage on the order of a few percentage points of GDP each year would be a serious impact for any country, even a relatively rich one like the United States. And we will not experience the worst of the global problem: The sad irony is that while richer countries like the United States are responsible for much greater per person greenhouse gas emissions, many of the poorest countries around the world will experience damages that are much larger as a percentage of their national output.

For countries that have fewer resources with which to fend off the consequences of climate change, the impacts will be devastating. The question is not just how we value damages to future generations living in the United States, but also how we value costs to people around the world – today and in the future – whose economic circumstances make them much more vulnerable than we are. Decisions about when and how to respond to climate change must depend not only on our concern for our own comfort and economic well-being, but on the well-being of those who share the same small world with us. Our disproportionate contribution to the problem of climate change should be accompanied by elevated responsibility to participate, or even to lead the way, in its solution.

2. The high costs of business-as-usual emissions: Four case studies

How much difference will climate change make for the U.S. economy? In this report we compare two possible climate futures for the United States. This chapter presents the *business-as-usual* case, combining the assumption that emissions continue to increase over time, unchecked by public policy, with the worst of the likely outcomes from uncertain climate impacts. An alternative, *rapid stabilization* case will be presented in the next chapter, along with a comparison of the costs of the two scenarios.

The business-as-usual case is based on the high end of the "likely" range of outcomes under the IPCC's A2 scenario (their second highest scenario), which predicts a global average temperature increase of 10°F and (with a last-minute amendment to the science, explained below) an increase in sea levels of 35 to 55 inches by 2100.[2] This high-impact future climate, however, should not be mistaken for the worst possible case. Greenhouse gas emissions could increase even more quickly, as represented by the IPCC's A1FI scenario. Nor is the high end of the IPCC's "likely" range a worst case: 17 percent of the full range of A2 predictions were even worse. Instead, our business-as-usual case combines the probable outcome of current trends in emissions with the climate outcomes that are unfortunately likely to result.

In this chapter, we consider four case studies under the business-as-usual climate scenario for the United States: 1) increasing intensity of Atlantic and Gulf Coast hurricanes; 2) inundation of coastal residential real estate with sea-level rise; 3) changing patterns of energy supply and consumption; and 4) changing patterns of water supply and consumption, including the effect of these changes on agriculture. In the business-as-usual scenario the annual costs of these four effects alone adds up to almost $1.9 trillion in 2100, or 1.8 percent of U.S. gross domestic product (GDP), as summarized in Table 1 below. The total cost of these four types of damages, however, only represents a lower bound of the total cost of the business-as-usual scenario; many other kinds of damages, while also likely to have important effects on the U.S. economy, are more difficult to estimate. Damage to commercial real estate from inundation, damage to or obsolesce of public and private infrastructure from rapidly changing temperatures, and losses to regional tourism industries as the best summer and winter vacation climates migrate north – just to name a few – are all likely effects of climate change that may be costly in the United States.

Table 1: Business-As-Usual Case: Summary Damages of Four Case Studies for the U.S.

	in billions of 2006 dollars				*as a percentage of GDP*			
	2025	**2050**	**2075**	**2100**	**2025**	**2050**	**2075**	**2100**
Hurricane Damages	$10	$43	$142	$422	0.05%	0.12%	0.24%	0.41%
Real Estate Losses	$34	$80	$173	$360	0.17%	0.23%	0.29%	0.35%
Energy Sector Costs	$28	$47	$82	$141	0.14%	0.14%	0.14%	0.14%
Water Costs	$200	$336	$565	$950	1.00%	0.98%	0.95%	0.93%
Total Costs for Four Categories	**$271**	**$506**	**$961**	**$1,873**	**1.36%**	**1.47%**	**1.62%**	**1.84%**

Business-as-usual: High emissions, bad outcomes

Climatologists predict a range of outcomes that could result from business-as-usual (meaning steadily increasing) emissions. The business-as-usual case is the worst of what the IPCC calls its "likely" predictions for the A2 scenario.[3] With every day that current trends in greenhouse gas emissions continue, the business-as-usual case becomes more probable.

The average annual temperature in most of the mainland 48 states will increase 12 to 13°F by 2100 – a little more in the nation's interior, a little less on the coasts. For a few areas of the United States, the average annual temperature increase will be near or below the global mean: for the Gulf Coast and Florida, 10°F by 2100; and for Hawaii and U.S. territories in the Pacific and the Caribbean, 7°F by 2100. Alaska, like all of the Arctic, will experience an even greater increase in average temperature than the U.S. mainland. On average, Alaska's annual temperature will increase by a remarkable 18°F by 2100, but temperature increases may be even higher in the northernmost reaches of Alaska. Table 2 shows the progression of these temperature changes over time.

Table 2: Business-As-Usual Case: U.S. Annual Average Temperatures by Region

in degrees Fahrenheit above year 2000 temperature

	2025	2050	2075	2100
Alaska	4.4	8.8	13.2	17.6
U.S. Central	3.3	6.6	9.9	13.1
U.S. East	3.1	6.1	9.2	12.2
U.S. West	3.1	6.1	9.2	12.2
U.S. Gulf Coast and Florida	2.4	4.9	7.3	9.7
Global Mean	2.2	4.3	6.5	8.6
Hawaii and the Pacific	1.8	3.6	5.4	7.2
Puerto Rico and the Caribbean	1.8	3.6	5.4	7.2

Sources: IPCC (2007b); authors' calculations.

These temperature increases represent a fundamental change to the climate of the United States. In the business-as-usual case, the predicted annual average temperature for Anchorage, Alaska in 2100 – 53°F – is the historical average temperature for New York City. Under this scenario, the northern tier of mainland states from Washington to Maine will come to have the current climate of the mid-latitude states, those stretching from Northern California to New Jersey. Those middle tier states will take on the climate of the southern states, while the southern states will become more like Mexico and Central America. Table 3 shows a comparison of U.S. city temperatures today and in 2100, ignoring the effects of humidity. Annual average temperatures in Honolulu and Phoenix will match some of the hottest cities in the world today – Acapulco, Mexico and Bangkok, Thailand. The United States' hottest cities, Miami and San Juan, Puerto Rico will reach an annual average of 85 and 87°F, respectively – hotter than any major city in the world today.

Table 3: Business-As-Usual Case: U.S. Cities Annual Average Temperatures in 2100

in degrees Fahrenheit

	Historical Average	Predicted in 2100	Is like…today
Anchorage, AK	35	53	New York, NY
Minneapolis, MN	44	57	San Francisco, CA
Milwaukee, WI	46	59	Charlotte, NC
Albany, NY	47	60	Charlotte, NC
Boston, MA	50	62	Memphis, TN
Detroit, MI	49	62	Memphis, TN
Denver, CO	50	63	Memphis, TN
Chicago, IL	50	64	Los Angeles, CA
Omaha, NE	51	64	Los Angeles, CA
Columbus, OH	52	65	Las Vegas, NV
Seattle, WA	52	65	Las Vegas, NV
Indianapolis, IN	52	65	Las Vegas, NV
New York, NY	53	65	Las Vegas, NV
Portland, OR	53	65	Las Vegas, NV
Philadelphia, PA	54	66	Las Vegas, NV
Kansas City, MO	54	67	Houston, TX
Washington, DC	56	68	Houston, TX
Albuquerque, NM	56	68	Houston, TX
San Francisco, CA	57	69	New Orleans, LA
Baltimore, MD	58	70	New Orleans, LA
Charlotte, NC	60	73	Honolulu, HI
Oklahoma City, OK	60	73	Honolulu, HI
Atlanta, GA	61	74	Honolulu, HI
Memphis, TN	62	75	Miami, FL
Los Angeles, CA	64	76	Miami, FL
El Paso, TX	63	76	Miami, FL
Las Vegas, NV	66	78	San Juan, PR
Houston, TX	68	79	San Juan, PR
Jacksonville, FL	69	79	San Juan, PR
New Orleans, LA	69	80	San Juan, PR
Honolulu, HI	75	82	Acapulco, Mexico
Phoenix, AZ	71	83	Bangkok, Thailand
Miami, FL	75	85	*no comparable city*
San Juan, PR	80	87	*no comparable city*

Sources: IPCC (2007b); http://www.worldclimate.com/; authors' calculations.

Along with temperature, regional variations in precipitation and humidity are important determinants of local climates. Hot temperatures combined with high humidity levels are often more unpleasant, and worse for human health, than a hot but dry climate. The perceived heat of each local climate will be determined by annual average temperatures, temperature extremes – heat waves and cold snaps – and precipitation levels, as well as some ecosystem effects. We assume that in the business-as-usual case, heat waves will become more frequent and more intense (IPCC 2007b). Changes in precipitation patterns are likely to differ for each region of the United States. Alaska's precipitation will increase by 10 to 20 percent, mostly from increased snowfall. The Great Lakes and Northeast states will receive 5 percent more precipitation each year, mostly in winter. The U.S. Southwest, including California and Texas will experience a decrease in precipitation, down 5 to 15 percent, mostly from less winter rain. The U.S. Gulf Coast and Florida will also receive 5 to 10 percent less rain each year.[4] There will also be a higher risk of winter flooding, earlier peak river flows for snow and glacier-fed streams; lower summer soil moisture and river flows; and a shrinkage of sea ice, glaciers and permafrost (IPCC 2007b).

Climate change also affects storm intensity in the business-as-usual case; specifically, Atlantic hurricanes and Pacific typhoons will become more destructive. The specific changes to hurricane intensity assumed in the business-as-usual case are discussed in detail later on in this report. In general, we assume that hurricanes striking the mainland Atlantic and Gulf coasts of the United States maintain their historical frequency but become more intense. We do not include any changes to Pacific typhoon impacts in our calculations, although these impacts may be important for Hawaii in particular.

Estimates for sea-level rise under the business-as-usual case diverge somewhat from the A2 scenario as presented in the most recent IPCC report. The authors of the IPCC 2007 made the controversial decision to exclude one of the many effects that combine to increase sea levels – the risk of accelerated melting of the Greenland and Antarctic ice sheets caused by feedback mechanisms such as the dynamic effects of meltwater on the structure of ice sheets. Without the effects of these feedback mechanisms on ice sheets, the high end of the likely range of A2 sea-level rise is 20 inches, down from approximately 28 inches in the IPCC 2001 report (IPCC 2007b).

Melting ice sheets were excluded from the IPCC's predictions not because they are thought to be insignificant – on the contrary, these effects could raise sea levels by dozens of feet over the course of several centuries – but because they are extremely difficult to estimate.[5] Indeed, the actual amount of sea-level rise observed since 1990 has been at the very upper bound of prior IPCC projections that assumed high emissions, a strong response of temperature to emissions, *and* included an additional ad hoc amount of sea-level rise for "ice sheet uncertainty" (Rahmstorf 2007).

This area of climate science has been developing rapidly in the last year, but, unfortunately, the most recent advances were released too late for inclusion in the IPCC process (Kerr 2007a; b; Oppenheimer et al. 2007). A January 2007 article by Stephan Rahmstorf in the prestigious peer-reviewed journal *Science* proposes a new procedure for estimating melting ice sheets' difficult-to-predict contribution to sea-level rise (Rahmstorf 2007). For the A2 emissions scenario on which our business-as-usual case is based, Rahmstorf's estimates of 2100 sea-level rise range from 35 inches, the central estimate for the A2 scenario, up to 55 inches, Rahmstorf's high-end figure including an adjustment for statistical uncertainty. For purposes of this report, we use an intermediate value that is the average of his estimates, or 45 inches by 2100; we similarly interpolate an average of Rahmstorf's high and low values to provide estimates for dates earlier in the century (see Table 4).

Because of these added uncertainties, Table 4, below, presents two estimates of sea-level rise for the business-as-usual case, as well as the predicted sea-level rise used for the business-as-usual case throughout this report. The low estimate for the business-as-usual case is Rahmstorf's 18 inches by 2050 and 35 inches in 2100. The high estimate is the top of the range predicted by Rahmstorf's recent work, 28 inches by 2050 and 55 inches in 2100. The business-as-usual prediction is the average of these two estimates: 23 inches in 2050 and 45 inches in 2100. Sea-level rise for most of the United States is likely to be at or near the global mean, but northern Alaska and the northeast coast of the mainland United States may be somewhat higher (IPCC 2007b).

Table 4: Business-As-Usual Case: U.S. Average Sea-Level Rise

in inches above year 2000 elevation	2025	2050	2075	2100
Sea-Level Rise - low estimate	8.9	17.7	26.6	35.4
Sea-Level Rise - high estimate	13.8	27.6	41.3	55.1
Sea-Level Rise - business-as-usual prediction	11.3	22.6	34.0	45.3

Sources: IPCC (2007b); authors' calculations.

Cost calculations

Projecting economic impacts almost a century into the future is of course surrounded with uncertainty. Any complete projection, however, would include substantial effects due to the growth of the U.S. population and economy. With a bigger, richer population, there will be more demand for energy and water – and quite likely, more coastal property at risk from hurricanes.

In order to isolate the effects of climate change, we have made three projections: a forecast for business as usual, based on the scenario just described; another for the rapid stabilization scenario described in the next chapter; and a third for an unrealistic scenario with no climate change at all, holding today's conditions constant. All three use the same economic and population projections, an assumption which is probably not realistic, but is helpful in isolating the effects of climate change alone. The costs described in this chapter are the differences between the business-as-usual and the no climate change scenarios; that is, they are the effects of the business-as-usual climate changes alone, and not the effects of population and economic growth. The costs in the next chapter for the rapid stabilization case are likewise the differences between our projections for that scenario and the no climate change scenario.

Case Study #1: More intense hurricanes

In the business-as-usual scenario, hurricane intensity will increase, with more Category 4 and 5 hurricanes occurring as sea-surface temperatures rise. Greater damages from more intense storms would come on top of the more severe storm surges that will result from higher sea levels (Henderson-Sellers *et al.* 1998; Scavia *et al.* 2002; Anthes *et al.* 2006; Webster *et al.* 2006; IPCC 2007b). In this chapter, we predict annual damages caused by increased intensity of U.S. hurricanes to be $422 billion in 2100 in the business-as-usual case; this is the increase over annual damages that would be expected if current climate conditions remained unchanged.

Tropical storms and hurricanes cause billions of dollars in economic damages, and tens or even hundreds of deaths each year along the U.S. Atlantic and Gulf coasts. Tropical storms, as the name implies, develop over tropical or subtropical waters. To be officially classified as a hurricane, a tropical storm must exhibit wind speeds of at least 74 miles per hour. Hurricanes are categorized based on wind speed, so that a relatively mild Category 1 hurricane exhibits wind speeds of 74 to 95 miles per hour, while an extremely powerful Category 5 hurricane has wind speeds of at least 155 miles per hour (Williams and Duedall 1997; Blake *et al.* 2007).

Atlantic tropical storms do not develop spontaneously. Rather, they grow out of other disturbances, such as the "African waves" that generate storm-producing clouds, ultimately seeding the hurricanes that hit the Atlantic and Gulf Coasts of the United States. Sea-surface temperatures of at least 79°F are essential to the development of these smaller storms into hurricanes, but meeting the temperature threshold is not enough. Other atmospheric conditions, such as dry winds blowing off the Sahara or the extent of vertical wind shear – the difference between wind speed and direction near the ocean's surface and at 40,000 feet – can act to reduce the strength of U.S.-bound hurricanes or quell them altogether (Nash 2006).

While climate change is popularly associated with more frequent and more intense hurricanes (Dean 2007), within the scientific community there are two main schools of thought on this subject. One group emphasizes the role of warm sea-surface temperatures in the formation of hurricanes and points to observations of stronger storms over the last few decades as evidence that climate change is intensifying hurricanes. The other group emphasizes the many interacting factors responsible for hurricane formation and strength, saying that warm sea-surface temperatures alone do not create tropical storms.

The line of reasoning connecting global warming with hurricanes is straightforward; since hurricanes need a sea-surface temperature of at least 79°F to form, an increase of sea-surface temperatures above this threshold should result in more frequent and more intense hurricanes (Landsea *et al.* 1999). The argument that storms will become stronger as global temperatures increase is closely associated with the work of several climatologists, including Kerry Emanuel, of MIT, who finds that rising sea-surface temperatures are correlated with increasing wind speeds of tropical storms and hurricanes since the 1970s, and Peter J. Webster, of Georgia Tech, who documents an increase in the number and proportion of hurricanes reaching Categories 4 and 5 since 1970 (Emanuel 2005; Webster *et al.* 2005).

Climatologist Kevin E. Trenberth reports similar findings in the July 2007 issue of *Scientific American*, and states that, “Challenges from other experts have led to modest revisions in the specific correlations but do not alter the overall conclusion [that the number of Category 4 and 5 hurricanes will rise with climate change]” (2007). While these scientists predict increasing storm intensity with rising temperatures, they neither observe nor predict a greater total number of storms. Thus the average number of tropical storms that develops in the Atlantic each year would remain the same, but a greater percentage of these storms would become Category 4 or 5 hurricanes.

Scientists who take the opposing view acknowledge that sea-surface temperatures influence hurricane activity, but emphasize the role of many other atmospheric conditions in the development of tropical cyclones, such as the higher wind shears that may result from global warming and act to reduce storm intensity. In addition, since hurricane activity is known to follow multidecadal oscillations in which storm frequency and intensity rises and falls every 20 to 40 years, some climate scientists – including Christopher W. Landsea, Roger A. Pielke, and J.C.L. Chan – argue that Emanuel and Webster’s findings are based on inappropriately small data sets (Landsea 2005; Pielke 2005; Chan 2006). Pielke also finds that past storm damages, when “normalized” for inflation and current levels of population and wealth, would have been as high or higher than the most damaging recent hurricanes (Pielke and Landsea 1998; Pielke 2005). Thus, he infers that increasing economic damages are likely due to more development and more wealth, not to more powerful storms.

The latest IPCC report concludes that increasing intensity of hurricanes is “likely” as sea-surface temperatures increase (IPCC 2007b). A much greater consensus exists among climatologists regarding other aspects of future hurricane impacts. Even if climate change were to have no effect on storm intensity, hurricane damages are very likely to increase over time from two causes. First, increasing coastal development will lead to higher levels of damage from storms, both in economic and social terms. Second, higher sea levels, coastal erosion, and damage of natural shoreline protection such as beaches and wetlands will allow storm surges to reach farther inland, affecting areas that were previously relatively well protected (Anthes *et al.* 2006).

In our business-as-usual case, the total number of tropical storms stays the same as today (and the same as the rapid stabilization case), but storm intensity – and therefore the number of major hurricanes – increases. In order to calculate the costs of U.S. mainland hurricanes over the next 100 years for each scenario, we took into account coastal development and higher population levels, sea-level rise as it impacts on storm surges, and greater storm intensity.

Hurricane damage projections

We used historical data to estimate the expected number of hurricanes, and the damages per hurricane, in each category. Under current climate conditions, the average number of hurricanes hitting the U.S. mainland per 100 years would be 71 in Category 1, 46 in Category 2, 49 in Category 3, 12 in Category 4, and 2 in Category 5; this is based on the hurricane trends of the last 150 years. We then used damages from hurricanes striking the mainland U.S. from 1990 to

2006 as a baseline in estimating the average economic damages and number of deaths for each category of hurricanes. These damages per hurricane were applied to the average number of hurricanes in each category in order to estimate the impacts of an "average hurricane year." If there is no change in the frequency or intensity of hurricanes, the expected impact from U.S. hurricanes in an average year is $12.4 billion (in 2006 dollars) and 121 deaths (at the 2006 level of population).[6]

Table 5: Hurricanes Striking the Mainland U.S. from 1990 to 2006

Hurricane Category	Average Impacts 1990 to 2006: Damages (billions of 2006 $)	Average Impacts 1990 to 2006: Deaths (scaled to 2006)	Annual Probability of Occurance	Impacts in an Average Year: Damages (billions of 2006 $)	Impacts in an Average Year: Deaths (scaled to 2006)
1	$0.5	4	0.71	$0.4	3
2	$3.6	25	0.46	$1.6	12
3	$15.6	209	0.49	$7.6	102
4	$15.8	31	0.12	$1.8	4
5	$52.0	76	0.02	$1.0	1
Expected Value			**1.79**	**$12.4**	**121**

Sources: The large majority of data were taken from (Blake et al. 2007; National Hurricane Center 2007); a few data points were added from (NCDC CNN 1998; 2005; National Association of Insurance Commissioners 2007).[7]

We consider three factors that may increase damages and deaths resulting from future hurricanes; each of these three factors is independent of the other two. The first is coastal development and population growth – the more property and people that are in the path of a hurricane, the higher the damages and deaths (Pielke and Landsea 1998). Second, as sea levels rise, even with the intensity of storms remaining stable, the same hurricane results in greater damages and deaths from storm surges, flooding, and erosion (Pielke Jr. and Pielke Sr. 1997). Third, hurricane intensity may increase as sea-surface temperatures rise; this assumption is used only for the business-as-usual case (Emanuel 2005; Webster *et al.* 2005; IPCC 2007b). (For a detailed account of this model see Appendix A of this report.)

Table 6: Business-As-Usual Case: Increase in Hurricanes Damages to the U.S. Mainland

	2025	2050	2075	2100
Annual Damages				
in billions of 2006 dollars	$10	$43	$142	$422
as a percentage of GSP	0.05%	0.12%	0.24%	0.41%
Annual Deaths	74	228	437	756

Source: Authors' calculations

Combining these effects together, hurricane damages due to business as usual for the year 2100 would cause a projected $422 billion of damages – 0.41 percent of GDP – and 756 deaths above the level that would result if today's climate conditions remained unchanged (see Table 6).

Case Study #2: Real estate losses and sea-level rise

The effects of climate change will have severe consequences for low-lying U.S. coastal real estate. If nothing were done to hold back rising waters, sea-level rise would simply inundate many properties in low-lying coastal areas. In this section we estimate that annual U.S. residential real estate losses due to sea-level rise will amount to $360 billion in 2100 in the business-as-usual case.

Even those properties that remained above water would be more likely to sustain storm damage, as encroachment of the sea allows storm surges to reach inland areas that were not previously affected. More intense hurricanes, in addition to sea-level rise, will increase the likelihood of both flood and wind damage to properties throughout the Atlantic and Gulf coasts.

To estimate the value of real estate losses from sea-level rise we have updated the detailed forecast of coastal real estate losses in the 48 states, by James Titus and co-authors (1991).[8] In projecting these costs into the future we assume that annual costs will be proportional to sea-level rise and to projected GDP. We calculate the annual loss of real estate from inundation due to the projected sea-level rise, which reaches 45 inches by 2100 in the business-as-usual case. The annual losses in the 48 mainland states rise to $360 billion, or 0.35 percent of GDP, by 2100, as shown in Table 7.

Table 7: Business-As-Usual Case: U.S. Real Estate at Risk from Sea-Level Rise

	2025	2050	2075	2100
Annual Increase in Value at Risk				
in billions of 2006 dollars	$34	$80	$173	$360
as percent of GDP	0.17%	0.23%	0.29%	0.35%

Source: Titus et al. (1991), and authors' calculations

Florida sea-level rise case study

This summary calculation is broadly consistent with the more detailed estimate we developed in a recent study of climate impacts on Florida, where we used a similarly defined business-as-usual case (Stanton and Ackerman 2007). For that study we used a detailed map of areas projected to be at risk from sea-level rise, and data for the average value of homes, for each Florida county. We assumed that damages would be strictly proportional to the extent of sea-level rise, and to the projected growth of the Florida economy. In each county, we projected that the percentage of homes at risk equaled the percentage of the county's land area at risk, and valued the at-risk homes at the county median value (adjusted for economic growth). Under those assumptions, the annual increase in Florida's residential property at risk from sea-level rise reached $66 billion by 2100, or 20 percent of our U.S. estimate in this study.

Sea-level rise will affect more than just residential property. In Florida, the area vulnerable to 27 inches of sea-level rise, which would be reached soon after 2060 in the business-as-usual case, covers 9 percent of the state's land area, with a current population of 1.5 million. In addition to residential properties worth $130 billion, Florida's 27-inch vulnerable zone includes:

- 2 nuclear reactors;
- 3 prisons;
- 37 nursing homes;
- 68 hospitals;
- 74 airports;
- 82 low-income housing complexes;
- 115 solid waste disposal sites;
- 140 water treatment facilities;
- 171 assisted livings facilities;
- 247 gas stations
- 277 shopping centers;
- 334 public schools;
- 341 hazardous materials sites, including 5 superfund sites;
- 1,025 churches, synagogues, and mosques;
- 1,362 hotels, motels, and inns;
- and 19,684 historic structures.

Similar facilities will be at risk in other states with intensive coastal development as sea levels rise in the business-as-usual case.

<u>Adaptation to sea-level rise</u>

No one expects coastal property owners to wait passively for these damages to occur; those who can afford to do so will undoubtedly seek to protect their properties. But all the available methods for protection against sea-level rise are problematical and expensive. It is difficult to imagine any of them being used on a large enough scale to shelter all low-lying U.S. coastal lands from the rising seas of the 21st century, under the business-as-usual case.

Elevating homes and other structures is one way to reduce the risk of flooding, if not hurricane-induced wind damage. A FEMA estimate of the cost of elevating a frame-construction house on a slab-on-grade foundation by two feet is $58 per square foot, after adjustment for inflation, with an added cost of $0.93 per square foot for each additional foot of elevation (FEMA 1998). This means that it would cost $58,000 to elevate a house with a 1,000 square foot footprint by two feet. It is not clear whether building elevation is applicable to multistory structures; at the least, it is sure to be more expensive and difficult.

Another strategy for protecting real estate from climate change is to build seawalls to hold back rising waters. There are a number of ecological costs associated with building walls to hold back the sea, including accelerated beach erosion and disruption of nesting and breeding grounds for important species, such as sea turtles, and preventing the migration of displaced wetland species (NOAA 2000). In order to prevent flooding to developed areas, some parts of the coast would require the installation of new seawalls. Estimates for building or retrofitting seawalls range widely, from $2 million to $20 million per linear mile (Yohe *et al.* 1999; U.S. Army Corps of Engineers 2000; Kirshen *et al.* 2004).

In short, while adaptation, including measures to protect the most valuable real estate, will undoubtedly reduce sea-level rise damages below the amounts shown in Table 7, protection measures are expensive and there is no single, believable technology or strategy for protecting the vulnerable areas throughout the country.

Case Study #3: Changes to the energy sector

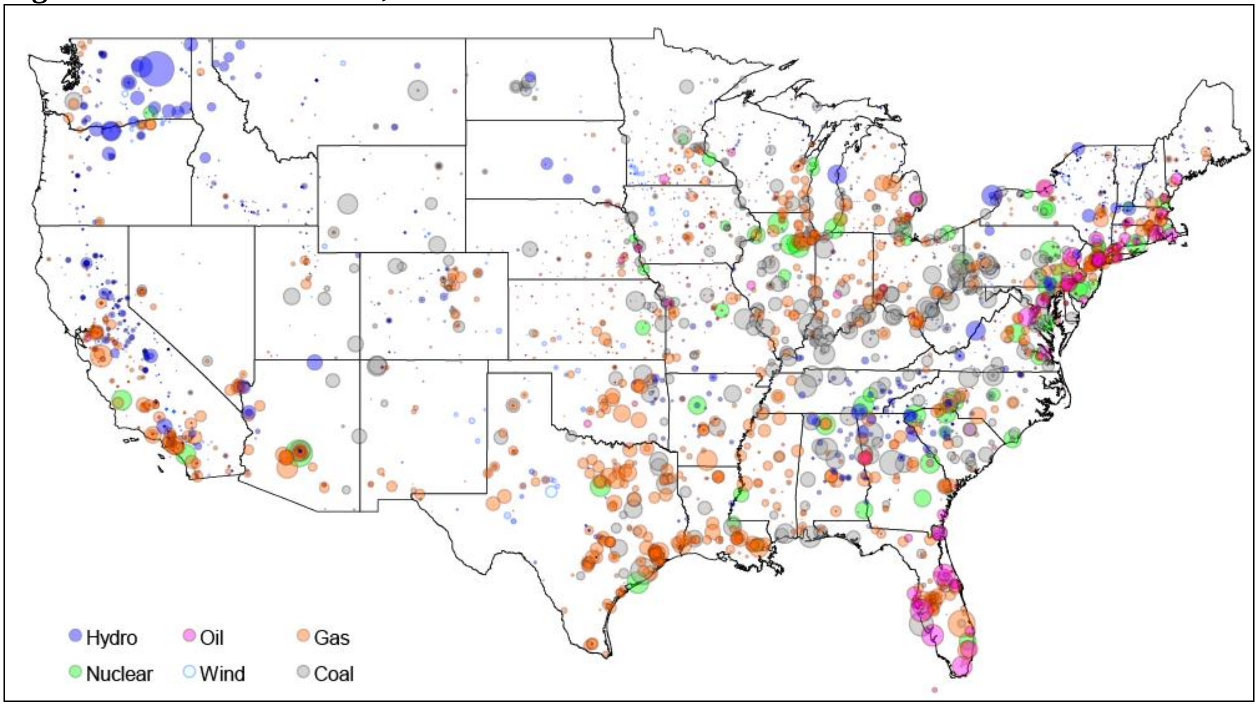
Climate change will affect both the demand for and the supply of energy: hotter temperatures will mean more air conditioning and less heating for consumers – and more difficult and expensive operating conditions for electric power plants. In this section, we estimate that annual U.S. energy expenditures (excluding transportation) will be $141 billion higher in the 2100 in the business-as-usual case than they would be if today's climate conditions continued throughout the century.

Although we include estimates for direct use of oil and gas, our primary focus is on the electricity sector. Electricity in the United States is provided by nearly 17,000 generators with the ability to serve over one thousand gigawatts (EIA 2007c Table 2.2). Currently, nearly half of U.S. electrical power is derived from coal, while natural gas and nuclear each provide one-fifth of the total. Hydroelectric dams, other renewables – such as wind and solar-thermal – and oil provide the remaining power (EIA 2007c Table 1.1).

As shown in Figure 1, power plants are distributed across the country. Many coal power plants are clustered along major Midwest and Southeast rivers, including the Ohio, Mississippi, and Chattahoochee. Natural gas-powered plants are located in the South along gas distribution lines and in the Northeast and California near urban areas. Nuclear plants are clustered along the eastern seaboard, around the Tennessee Valley, and along the Great Lakes. Hydroelectric dams provide most of the Northwest's electricity, and small to medium dams are found throughout the Sierras, Rockies, and Appalachian ranges. Since 1995, new additions to the U.S. energy market have primarily come from natural gas.

Higher temperatures associated with climate change will place considerable strain on the U.S. power sector as currently configured. Across the country, drought conditions will become more likely, whether due to greater evaporation as a result of higher temperatures, or – in some areas – less rainfall, more sporadic rainfall, or the failure of snow-fed streams. Droughts clearly reduce hydroelectric output. Perhaps less obviously, droughts and heat waves put most generators at risk, adding stress to transmission and generation systems and thereby reducing efficiency and raising the cost of electricity.

Figure 1: U.S. Power Plants, 2006



Source: North American Electric Reliability Corporation (NERC 2007b)
Note: Colors correspond to the primary fuel type, and sizes are proportional to plant capacity (output in megawatts). Only plants operational as of 2006 are included.

<u>Power plants and water requirements</u>

Coal, oil, nuclear, and many natural gas power plants use steam to generate power, and rely on massive amounts of water for boiling, cooling, chemical processing, and emissions scrubbing. Most plants have a "minimum water requirement" – when water is in short supply, plants must reduce generation or shut down altogether.

When power plants boil water in industrial quantities to create steam, the machinery gets hot; some system for cooling is essential for safe operation. The cheapest method, when water is abundant, is so-called "open-loop" or "once-through" cooling, where water is taken from lakes, rivers, or estuaries, used once to cool the plant, and then returned to the natural environment. About 80 percent of utility power plants require water for cooling purposes and of these, almost half use open-loop cooling (NERC 2007a). The "closed-loop" alternative is to build cooling towers that recirculate the water; this greatly reduces (but does not eliminate) the need for cooling water, while making the plant more expensive to build. It is possible to retrofit plant cooling towers to reduce their water intake even more ("dry cooling"), but these retrofits are costly, and can reduce the efficiency of a generator by up to 4 percent year round, and nearly 25 percent in the summer during peak demand (Puder and Veil 1999; U.S. DOE 2006).[9] Dry cooling is common only in the most arid and water-constrained regions. Yet if drought conditions persist or become increasingly common, more plants may have to implement such high-cost, low-water cooling technologies, dramatically increasing the cost of electricity production.

When lakes and rivers become too warm, plants with open-loop cooling become less efficient. Moreover, the water used to cool open-loop plants is typically warmer when it returns to the natural environment than when it came in, a potential cause of damage to aquatic life. The Brayton Point Power Plant on the coast of Massachusetts, for example, was found to be increasing coastal water temperatures by nearly two degrees, leading to rapid declines in the local winter flounder population (Gibson 2002; Fisher and Mustard 2004).

In 2007, severe droughts reduced the flows in rivers and reservoirs throughout the Southeast and warmed what little water remained. On August 17, 2007, with temperatures soaring towards 105°F, the Tennessee Valley Authority shut down the Browns Ferry nuclear plant in Alabama to keep river water temperatures from passing 90 degrees, a harmful threshold for downstream aquatic life (Reeves 2007). Even without the environmental restriction, this open-loop nuclear plant, which circulates three billion gallons of river water daily, cannot operate efficiently if ambient river water temperatures exceed 95°F (Fleischauer 2007).

Browns Ferry is not the only power plant vulnerable to drought in the Southeast; we estimate that over 320 plants, or at least 85 percent of electrical generation in Alabama, Georgia, Tennessee, and North and South Carolina are critically dependent on river, lake, and reservoir water.[10] The Chattahoochee River – the main drinking water supply for Atlanta – also supports power plants supplying more than 10,000 megawatts, over 6 percent of the region's generation (NERC 2007b). In the recent drought, the river dropped to one-fifth of its normal flow, severely inhibiting both hydroelectric generation and the fossil fuel-powered plants which rely on its flow.[11] As the drought wore on, the Southern Company, a major utility in the region, petitioned the governors of Florida, Alabama, and Georgia to renegotiate interstate water rights so that sufficient water could flow to four downstream fossil-fuel plants and one nuclear facility.[12]

Extended droughts are increasingly jeopardizing nuclear power reliability. In France, where five trillion gallons of water are drawn annually to cool nuclear facilities, heat waves in 2003 caused a shutdown or reduction of output in 17 plants, forcing the nation to import electricity at over ten times the normal cost. In the United States, 41 nuclear plants rely on river water for cooling, the category most vulnerable to heat waves.[13]

The U.S. Geological Survey estimates that power plants accounted for 39 percent of all freshwater withdrawals in the United States in 2000, or 136 billion gallons per day (U.S. DOE 2006). Most of this water is returned to rivers or lakes; water consumption (the amount that is not returned) by power plants is a small fraction of the withdrawals, though still measured in billions of gallons per day. The average coal-fired power plant consumes upwards of 800 gallons of water per megawatt hour of electricity it produces. If power plants continue to be built using existing cooling technology, even without climate change, the energy sector's consumption of water is likely to more than double in the next quarter century, from 3.3 billion gallons per day in 2005 to 7.3 billion gallons per day in 2030 (Hutson *et al.* 2005).[14]

Droughts reduce hydroelectric output

Droughts limit the amount of energy that can be generated from hydroelectric dams, which supply six to ten percent of all U.S. power. U.S. hydroelectric generation varies with precipitation, fluctuating as much as 35 percent from year to year (U.S. DOE 2006). Washington, Oregon, and Idaho – where dams account for 70, 64, and 77 percent of generation, respectively – are particularly vulnerable to drought.

The 2007 drought in the Southeast had a severe impact on hydroelectric power. At the time of this writing, the latest data on hydroelectric production, for September 2007, showed that it had fallen by 15 percent nationwide from a year earlier, and by 45 percent for the Southeastern states (EIA 2007d).[15] At about the same time, the Federal Regulation and Oversight of Energy commission was considering reducing flows through dams in the Southeast to retain more water in reservoirs for consumption (White 2007).

Heat waves stress transmission and generation systems

Heat waves dramatically increase the cost of producing electricity and, therefore, the price to end-users. During periods of normal or low demand, the least expensive generators are run. During peak demand, increasingly expensive generators are brought online. During a heat wave, when demand for air-conditioning and refrigeration spikes, operators are forced to bring extremely expensive and often quite dirty plants (such as diesel engines) online to meet demand. At these times, the cost of electricity can be more expensive by several orders of magnitude than during normal operations. In dire circumstances, even with all existing power plants in use, there still may not be enough electricity generated to meet demand, resulting in rolling blackouts that may cause health problems for households left without air conditioners or fans, as well as creating costs for business and industry.

Transmission lines, which transport energy from generators to end-users, can become energy sinks during a heat wave. When temperatures rise, businesses and residents turn on air conditioners, increasing the flow of electricity over the power lines. As the lines serve more power, resistance in the lines increases – converting more of the energy to waste heat – and the system becomes less efficient. During normal operation, about 8 to 12 percent of power is lost over high-voltage transmission lines and local distribution lines; during heat waves, transmission losses can add up to nearly a third of all the electricity generated.

The increased resistance in the lines also causes them to heat up and stretch, sagging between towers. Warmer ambient temperatures, as well as low wind speeds, prevent lines from cooling sufficiently, increasing their sag and the potential for a short circuit as the lines contact trees or the ground. Damaged lines force power to be shunted onto other lines, which, if near capacity, may also sag abnormally. Large-scale blackouts in the Northeast and on the West Coast have been attributed to transmission lines sagging in heat waves (U.S.-Canada Power System Outage Task Force 2003). On August 14, 2003, much of the Northeast and eastern Canada was cast into darkness in a 31-hour blackout, which exacted an economic cost estimated at $4-6 billion (AP 2003).

Like transmission lines, generators that use air for cooling become significantly less efficient when ambient temperatures rise. Air-cooled gas-powered turbines can see efficiency losses of as much as 20 percent when air temperatures rise above 59°F, and therefore are used as little as possible during summer months (Kakaras *et al.* 2004; Erdem and Sevilgen 2006). Ironically, these same gas turbines running at low efficiency are most likely to be needed when temperatures and air conditioning use spike.

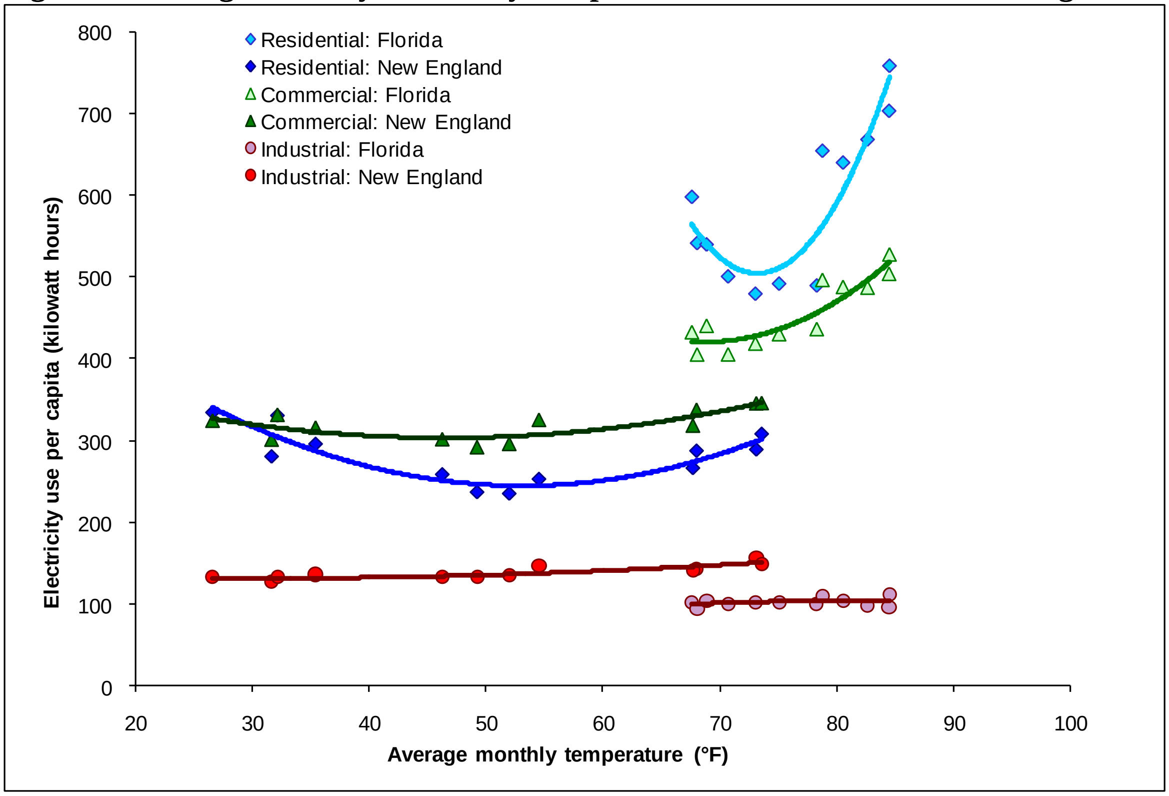
Energy consumption

In the United States, monthly regional electricity consumption is closely related to average monthly temperatures.[16] This relationship often follows a bowed, or slightly U-shaped, curve where the highest demand for electricity is at low and high temperatures for heating and cooling. At mild temperatures, when neither heating nor cooling is required, electricity demand is at its lowest.

The shape of the curve showing electricity demand vs. temperature is quite different across regions, as shown in Figure 2 below. In Florida, residential customers are highly sensitive to both warm and cool temperatures, using significantly more energy when temperatures fall above or below 67ºF. The residential sector of New England is less temperature sensitive (note the wider, less-bowed curve), and has a minimum at 53ºF.[17] This is partially due to the differing rates of use of air conditioning across the country. In the Atlantic states from Maryland to Florida, 95 percent of homes have air conditioning, compared to less than sixty percent in New England. Only one-third of all air conditioned homes in New England have central AC systems, compared to 80 percent in Florida (EIA 2001 Tables HC4 9a & 11a). Therefore, it makes sense that energy usage is tightly coupled to warming temperatures in Florida, and will become increasingly coupled in New England as temperatures rise.

On the flip side, less heating will be required as winters become warmer, particularly in northern states. More than half of households in the South use electricity to heat their homes, while in New England just 10 percent use electricity, half use heating oil, and about 40 percent use natural gas (EIA 2001 Tables HC3 9a & 11a). Winter warming will reduce electricity use in Florida, but this will be outweighed by the increased electricity demand for air conditioning. In New England, reductions in natural gas and fuel oil consumption are likely in winter, as is increasing demand for electricity as summers warm. In our analysis, summarized below, we find that northern states nearly break even on changes in energy costs due to warming, while southern states increase energy consumption dramatically, due to the rising use of air conditioning.

Figure 2: Average Monthly Electricity Use per Person in Florida and New England, 2005



Source: EIA (2007f) and NCDC (2007) authors' calculations

High energy costs in the business-as-usual case

To estimate the energy costs associated with climate change, we examined the projected relationship between energy consumption and temperature in 20 regions of the United States (Amato *et al.* 2005; Ruth and Lin 2006). Monthly demand for residential, commercial, and industrial electricity, residential and commercial natural gas (EIA 2007g), and residential fuel oil deliveries were tracked for 2005 and compared to average monthly temperatures in the largest metropolitan area (by population) in each region (NCDC 2005; EIA 2007f; 2007e). To estimate the effects of the business-as-usual scenario, we increased regional temperatures every decade by the expected temperature change from the Hadley CM3 climate model.[18] We used 2006 state-specific electricity, gas, and fuel prices to estimate the future costs of energy, assuming a continuation of the temperature/energy consumption patterns from 2005 (EIA 2007b). We assume that the 2006 retail electricity prices, used throughout our projections, are high enough so that utilities are able to recover the cost of required new plants as well as the cost of fuel.

In addition, we include a secondary set of costs for the purchase of new air conditioning systems, following the current national distribution of air conditioning. Although we include both the energy costs of decreases in heating and increases in cooling, the two are not symmetrical in their impacts on equipment costs: those who enjoy decreased heating requirements cannot sell part of their existing furnaces (at best, there will be gradual decreases in heating system costs in new structures); on the other hand, those who have an increased need for cooling will buy additional air conditioners at once.

In the business-as-usual case, increasing average temperatures drive up the costs of electricity above population and per-capita increases. Not surprisingly, electricity demand rises most rapidly in the Southeast and Southwest, as those regions experience more uncomfortably hot days. By the same token, our model projects that while the Northeast and Midwest also have rising air conditioning costs, those costs are largely offset by reduced demand for natural gas and heating oil expenditures.

Overall, we estimate that by 2100 in the business-as-usual case, climate change will increase the retail cost of electricity by $167 billion, and will lead to $31 billion more in annual purchases of air conditioning units. At the same time, warmer conditions will lead to a reduction of $57 billion in natural gas and heating oil expenditures. Overall costs in the energy sector in the business-as-usual case add up to $141 billion more in 2100 due to climate change alone, or 0.14 percent of projected U.S. GDP in 2100.

Table 8: Business-As-Usual Case, in 2100: Energy Cost Increases above 2005 Levels

in billions of 2006 dollars

	Southwest	South	Southeast	Northeast	Midwest	West, Northwest	Total
Electricity	$62.3	$20.4	$58.9	$10.5	$10.2	$4.7	$166.9
Heating Oil	$0.0	$0.0	-$0.2	-$3.1	$0.0	$0.0	-$3.4
Natural Gas	-$9.5	-$4.0	-$6.7	-$10.7	-$16.8	-$5.9	-$53.7
AC Units	$4.0	$2.5	$7.3	$6.2	$7.5	$3.5	$30.9
Total	$56.8	$18.9	$59.2	$2.8	$0.9	$2.2	$140.7

Source: Authors' calculations; see Appendix B.
Note: AC Units refers to the purchase of additional air conditioning units.

<u>The "lowball" average</u>

Our model is constructed around averages: average temperature changes, average monthly temperatures, and aggregate monthly energy use in large regions. In reality, however, the capacity of the energy sector must be designed for the extremes: we rely on air conditioning on the hottest of days, and we demand natural gas for power production, space heating, and cooking. Since energy costs climb rapidly when demand is high and the system is stretched, many costs will be defined by extremes as well as average behavior.

One of the most severe climate strains on the electricity sector will be intensifying heat waves. During a heat wave, local grids can be pushed to the limits of their capacity just by virtue of many air conditioning units operating simultaneously. Heat waves and droughts (both expected to become more common conditions, according to the IPCC) will push the costs of electricity during times of shortage well beyond the costs included in our model. Therefore, a full cost accounting must consider not only the marginal cost of gradually increasing average temperatures, but electricity requirements on the hottest of days, when an overstressed energy sector could be fatal. Similarly, savings in natural gas and fuel oil in the North could be quickly erased by extended cold snaps even as the average temperature rises. In addition, this model cannot quantify the substantial costs of reduced production at numerous hydroelectric facilities, nuclear facilities which are not able to draw enough cooling water to operate, conflicts between water-intensive power suppliers, the costs of retrofitting numerous plants for warmer conditions, and reduced power flow from decreasingly efficient natural gas plants.

Case Study #4: Problems for water and agriculture

In many parts of the country, the most important impact of climate change during the 21st century will be its effect on the supply of water. Recent droughts in the Southeast and in the West have underscored our dependence on the fluctuating natural supply of fresh water. Since five out of every six gallons of water used in the United States are consumed by agriculture, any changes in water supply will quickly ripple through the nation's farms as well.[19] Surprisingly, studies from the 1990s often projected that the early stages of warming would boost crop yields. This section surveys the effects of climate change on water supply and agriculture, finding that the costs of business as usual for water supply could reach almost $1 trillion per year by 2100, while the anticipated gains in crop yields may be small, and would in any case vanish by mid-century.

Water trends

Precipitation in the United States increased, on average, by 5-10 percent during the 20th century, but this increase was far from being evenly distributed, in time or space. Most of the increase occurred in the form of even more precipitation on the days with the heaviest rain or snow falls of the year.[20] Geographically, stream flows have been increasing in the eastern part of the country, but decreasing in the west. As temperatures have begun to rise, an increasing percentage of precipitation in the Rockies and other western mountains has been falling as rain rather than snow (IPCC 2007a Ch. 14).

While there have been only small changes in average conditions, wide year-to-year variability in precipitation and stream flows has led to both droughts and floods with major economic consequences. The 1988 drought and heat wave in the central and eastern United States caused $69 billion of damages (in 2006 dollars), and may have caused thousands of deaths. One reason for the large losses was that the water level in the Mississippi River fell too low for barge traffic, requiring expensive alternative shipping of bulk commodities. In recent years, the 1988 drought is second only to Hurricane Katrina in the costs of a single weather disaster (NCDC 2007).[21]

Growing demand has placed increasing stresses on the available supplies of water, especially – but not exclusively – in the driest parts of the country. The spread of population, industry, and irrigated agriculture throughout the arid West has consumed the region's limited sources of water; cities are already beginning to buy water rights from farmers, having nowhere else to turn (Gertner 2007). The huge Ogallala Aquifer, a primary source of water for irrigation and other uses in several of the Plains states, is being depleted, with withdrawals far in excess of the natural recharge rate (e.g., Glantz and Ausubel 1984; Terrell *et al.* 2002). In the Southwest, battles over allocation and use of the Colorado River's water have raged for decades (Reisner 1986). The wetter states of the Northwest have seen conflicts between farmers who are dependent on diversion of water for irrigation, and Native Americans and others who want to maintain the river flows needed for important fish species such as salmon. In Florida, one of the states with the highest annual rainfall, the rapid pace of residential and tourist development, and the continuing role of irrigated winter agriculture, have led to water shortages – which have been amplified by the current drought (Stanton and Ackerman 2007).

Rising costs for water supply

Water use per capita is no longer rising, as more and more regions of the country have turned to conservation efforts, but new supplies of water are required to meet the needs of a growing population, and to replace unsustainable current patterns of water use. Thus even if there were no large changes in precipitation, much of the country would face expensive problems of water supply in the course of this century. Responses are likely to include intensified water conservation measures, improved treatment and recycling of wastewater, construction and upgrading of cooling towers to reduce power plant water needs, and reduction in the extent of irrigated agriculture.

In a study done as part of the national assessment of climate impacts, conducted by the U.S. Global Change Research Program in 1999-2000, Kenneth Frederick and Gregory Schwartz (1999; 2000) estimated the costs of future changes in water supply for the 48 coterminous states, with and without climate change. In the absence of climate change, i.e. assuming that the climate conditions and water availability of 1995 would continue unchanged for the next century, Frederick and Schwartz projected an annual water cost increase (in 2006 dollars) of $50 billion by 2095. They calculated water availability separately for 18 regions of the country, projecting a moderate decline in irrigated acreage in the West and an increase in some parts of the Southeast and Midwest. Since the lowest-value irrigated crops would be retired first, the overall impact on agriculture was small.

Forecasting scarcity

In the business-as-usual future, problems of water supply will become more serious, as much hotter, and in many areas drier, conditions will increase demand. The average temperature increase of 12-13^{o}F across most of the country, and the decrease in precipitation across the South and Southwest, as described above, will lead to water scarcity and increased costs in much of the country.

Projecting future water costs is a challenging task, both because the United States consists of many separate watersheds with differing local conditions, and because the major climate models are only beginning to produce regional forecasts for areas as small as a river basin or watershed. A recent literature review of research on water and climate change in California commented on the near-total absence of cost projections (Vicuna and Dracup 2007). The estimate by Frederick and Schwartz appears to be the best available national calculation, despite limitations that probably led them to underestimate the true costs.

The national assessment by the U.S. Global Change Research Program, which included the Frederick and Schwartz study, used forecasts to 2100 of conditions under the IPCC's IS92a scenario, a midrange IPCC scenario which involves slower emissions growth and climate change than our business-as-usual case. Two general circulation models were used to project regional conditions under that scenario; these may have been the best available projections in 1999, but are quite different from the current state of the art (e.g., IPCC 2007b). One of the models discussed by Frederick and Schwartz (the Hadley 2 model) was at that time estimating that climate change would increase precipitation and reduce problems of water supply across most of the United States. This seems radically at odds with today's projections of growing water scarcity in many regions.

The other model included in the national assessment – the Canadian Global Climate Model – projected drier conditions for much of the United States, seemingly closer to current forecasts of water supply constraints. The rest of this discussion relies exclusively on the Canadian model forecasts. Yet that model, as of 1999, was projecting that the Northeast would become drier, while California would become wetter – the reverse of the latest IPCC estimates (see the detailed description of the business-as-usual scenario earlier in this chapter).

Frederick and Schwartz estimated the costs for an "environmental management" scenario, assuming that each of the 18 regions of the country needed to supply the lower of the desired amount of water, or the amount that would have been available in the absence of climate change. The cost of that scenario was $612 billion per year (in 2006 dollars) by 2095.[22] Most of the nationwide cost was for new water supplies in the Southeast, including increased use of recycled wastewater and desalination. The climate scenario used for the analysis projected a national average temperature increase of 8.5^{o}F by 2100, or about two-thirds of the increase under our business-as-usual scenario. Assuming the costs incurred for water supply are proportional to temperature increases, the Frederick and Schwartz methodology would imply a cost of $950 billion per year by the end of the century as a result of business-as-usual climate change, compared to the costs that would occur without climate change.[23]

Table 9: Business-As-Usual Case: Increased U.S. Water Costs above 2005 Levels

	2025	2050	2075	2100
Annual Increase in Costs				
in billions of 2006 dollars	$200	$336	$565	$950
as percent of GDP	1.00%	0.98%	0.95%	0.93%

Sources: Frederick and Schwartz (2000), and authors' calculations.

Although these costs are large, they still omit an important impact of climate change on water supplies. The calculations described here are all based on annual supply and demand for water, ignoring the problems of seasonal fluctuations. In many parts of the west, the mountain snowpack that builds up every winter provides a natural reservoir, gradually melting and providing a major source of water throughout the spring and summer seasons of peak water demand. With warming temperatures and the shift toward less snow and more rain, areas that depend on snowpack will receive more of the year's water supply in the winter months. Therefore, even if the total volume of precipitation is unchanged, less of the flow will occur in the seasons when it is most needed. In order to use the increased winter stream flow later in the year, expensive (and perhaps environmentally damaging) new dams and reservoirs will have to be built. Such seasonal effects and costs are omitted from the calculations in this section.

Moreover, there has been no attempt to include the costs of precipitation extremes, such as floods or droughts, in the costs developed here (aside from the hurricane estimates discussed above). The costs of extreme events are episodically quite severe, as suggested by the 1988 drought, but also hard to project on an annual basis.

Despite these limitations, we take the Frederick and Schwartz estimate, scaled up to the appropriate temperature increase, to be the best available national cost estimate for the business-as-usual scenario. There is a clear need for additional research to update and improve on this cost figure.

Agriculture

Agriculture is the nation's leading use of water, and the U.S. agricultural sector is shaped by active water management: nearly half of the value of all crops comes from the 16 percent of U.S. farm acreage that is irrigated (USDA 2004). Especially in the west, any major shortfall of water will be translated into a decline in food production.

As one of the economic activities most directly exposed to the changing climate, agriculture has been a focal point for research on climate impacts, with frequent claims of climate benefits, especially in temperate regions like much of the United States.

The initial stages of climate change appear to be beneficial to farmers in the northern states. In the colder parts of the country, warmer average temperatures mean longer growing seasons. Moreover, plants grow by absorbing carbon dioxide from the atmosphere; so the rising level of carbon dioxide, which is harmful in other respects, could act as a fertilizer and increase yields. A few plant species, notably corn, sorghum, and sugar cane, are already so efficient in absorbing carbon dioxide that they would not benefit from more; but for all other major crops, more carbon could allow more growth. Early studies of climate costs and benefits estimated substantial gains to agriculture from the rise in temperatures and carbon dioxide levels (Mendelsohn *et al.* 1994; Tol 2002b). As recently as 2001, in the development of the national assessment by the U.S. Global Change Research Program, the net impact of climate change on U.S. agriculture was projected to be positive throughout the 21st century (Reilly *et al.* 2001).

Recent research, however, has cast doubts on the agricultural benefits of climate change. More realistic, outdoor studies exposing plants to elevated levels of carbon dioxide have not always confirmed the optimistic results of earlier greenhouse experiments.[24] In addition, the combustion of fossil fuels which increases carbon dioxide levels will at the same time create more tropospheric (informally, ground-level) ozone – and ozone interferes with plant growth. A study that examined the agricultural effects of increases in both carbon dioxide and ozone found that in some scenarios, ozone damages outweighed all climate and carbon dioxide benefits (Reilly *et al.* 2007). In this study and others, the magnitude of the effect depends on the speed and accuracy of farmers' response to changing conditions: do they correctly perceive the change and adjust crop choices, seed varieties, planting times, and other farm practices to the new conditions? In view of the large year-to-year variation in climate conditions, it seems unrealistic to expect rapid, accurate adaptation. The climate "signal" to which farmers need to adapt is difficult to interpret. But errors in adaptation could eliminate any potential benefits from warming.

The passage of time will also eliminate any climate benefits to agriculture. Once the temperature increase reaches 6°F, crop yields everywhere will be lowered by climate change.[25] Under the business-as-usual scenario, that temperature threshold is reached by mid-century. Even before that point, warmer conditions may allow tropical pests and diseases to move further north, reducing farm yields. And the increasing variability of temperature and precipitation that will accompany climate change will be harmful to most or all crops (Rosenzweig *et al.* 2002).

One recent study (Schlenker *et al.* 2006) analyzed the market value of non-irrigated U.S. farmland, as a function of its current climate; the value of the land reflects the value of what it can produce. For the area east of the 100th meridian, where irrigation is rare, the value of an acre of farmland is closely linked to temperature and precipitation.[26] Land value is maximized – meaning that conditions for agricultural productivity are ideal – with temperatures during the growing season, April-September, close to the late 20th century average, and rainfall during the growing season of 31 inches per year, well above the historical average of 23 inches.[27] If this relationship remained unchanged, then becoming warmer would increase land values only in areas that are colder than average; becoming drier would decrease land values almost everywhere.

For the years 2070-2099, the study projected that the average value of farmland would fall by 62 percent under the IPCC's A2 scenario, the basis for our business-as-usual scenario. The climate variable most strongly connected to the decline in value was the greater number of degree-days above 93°F, a temperature that is bad for virtually all crops. The same researchers also studied the value of farmland in California, finding that the most important factor there was the amount of water used for irrigation; temperature and precipitation were much less important in California than in eastern and midwestern agriculture (Schlenker *et al.* 2007).

It is difficult to project a monetary impact of climate change on agriculture; if food becomes less abundant, prices will rise, partially or wholly offsetting farmers' losses from decreased yields. This is also an area where assumptions about adaptation to changing climatic conditions are of great importance: the more rapid and skillful the adaptation, the smaller the losses will be. It appears likely, however, that under the business-as-usual scenario, the first half of this century will see either little change or a small climate-related increase in yields from non-irrigated agriculture; irrigated areas will be able to match this performance if sufficient water is available. By the second half of the century, as temperature increases move beyond 6°F, yields will drop everywhere.

In a broader global perspective, the United States, for all its problems, will be one of the fortunate countries. Tropical agriculture will suffer declining yields at once, as many crops are already near the top of their sustainable temperature ranges. At the same time, the world's population will grow from an estimated 6.6 billion today to 9 billion or more by mid-century – with a large portion of the growth occurring in tropical countries. The growing, or at least non-declining, crop yields in temperate agriculture over the next few decades will be a valuable, scarce global resource. The major producing regions of temperate agriculture – the United States, Canada, northern China, Russia, and northern Europe, along with Argentina, Chile, Australia, New Zealand, and South Africa – will have an expanded share of the world's capacity to grow food, while populations are increasing fastest in tropical countries where crop yields will be falling. The challenge of agriculture in the years ahead will be to develop economic and political mechanisms which allow us to use our farm resources to feed the hungry worldwide. At the same time, while we may fare better than other nations, climate change threatens to damage American agriculture, with drier conditions in many areas, and greater variability and extreme events everywhere.

3. The costs of inaction

Chapter 2 described the impacts of the business-as-usual scenario, the worst of the likely outcomes that would be expected if past emission trends continue unchecked. The costs in just four areas that we could quantify – hurricane damages, sea-level rise, energy costs, and water supply costs – are projected to rise rapidly, reaching a combined total of 1.8 percent of U.S. GDP per year by 2100; these are the costs over and above the costs that would result from population and economic growth in the absence of climate change.

How much effect can we have on reducing these climate-induced losses by limiting our emissions of greenhouse gases? It is, unfortunately, no longer possible to avoid all adverse climate impacts. Some change from the pre-industrial climate has already taken place, and more is bound to occur as a result of greenhouse gases in the atmosphere, as well as the additional emissions that will be released in the very near future (too soon for policy changes to take effect). This chapter presents our four case studies using an alternative scenario, the *rapid stabilization case*, designed to represent the best we can realistically hope for at this point. The difference between business-as-usual and rapid stabilization is the cost of inaction, or the potential savings that can come from reducing greenhouse gas emissions, just from these four types of damages.

As noted in Chapter 2, we assume that the size of the U.S. economy and population will be the same in both cases. This (perhaps unrealistic) assumption is useful in clarifying the meaning of our two cases, and the contrast between them: all the economic differences between the business-as-usual and rapid stabilization cases reflect different climate impacts applied to the same economy, not changes in the underlying projections of GDP or population.

Rapid stabilization case: Low emissions, good outcomes

With immediate, large-scale reductions in greenhouse gas emissions, it is still possible for changes in the world's climate to remain relatively small. The rapid stabilization case is an optimistic estimate of the impacts of the most rigorous policy prescription under discussion today: "80 by 2050", or an 80 percent reduction in U.S. emissions by 2050, accompanied by a 50 percent reduction in total world emissions, and continuing reductions thereafter. The rapid stabilization case is the best of the likely impacts under that low emissions scenario. In the rapid stabilization case, global mean temperature rises 2ºF and sea levels rise 7 inches by 2100, but precipitation levels, hurricane intensity, and other climatic trends remain at their historical levels. It should be emphasized that this low-impact future climate is simply not possible unless we achieve significant reductions in greenhouse gas emissions, in the United States and around the world, in the next two decades.

If we want to keep the global average temperature from exceeding 2ºF above year 2000 levels and avoid a complete melting of the Greenland ice sheet and most other adverse climate impacts, we must stabilize the atmospheric concentration of carbon dioxide at 450ppm or lower.[28] In order to stabilize at 450ppm, global emissions of greenhouse gases must begin to decline by

2020, reaching one-half their current levels by 2050 and one-quarter of current levels by 2100. Because the United States' one-twentieth of world population bears responsibility for a full one-fifth of these emissions, U.S. emissions would have to decline 80 percent by 2050 in order to meet these goals (UCS 2007).

Of the six main scenarios that the IPCC describes as "equally probable" (Schenk and Lensink 2007), B1 has the lowest emissions, with atmospheric concentrations of CO_2 reaching 550ppm in 2100. The concentration levels and temperatures of the rapid stabilization case are below the low end of the likely range of B1 impacts. Because there is no IPCC scenario as low as the rapid stabilization case, we have approximated the low end of the likely temperature range for atmospheric stabilization at 450ppm of carbon dioxide using data from the Stern Review (2006).[29] Regional U.S. temperature increases above year 2000 levels are reported in Table 10.

Table 10: Rapid Stabilization Case: U.S. Annual Average Temperatures by Region

in degrees Fahrenheit above year 2000 temperature	2025	2050	2075	2100
Alaska	0.9	1.8	2.8	3.7
U.S. Central	0.8	1.5	2.3	3.0
U.S. East	0.7	1.4	2.2	2.9
U.S. West	0.7	1.4	2.2	2.9
U.S. Gulf Coast and Florida	0.6	1.1	1.7	2.2
Global Mean	0.4	0.9	1.3	1.8
Hawaii and the Pacific	0.4	0.8	1.2	1.6
Puerto Rico and the Caribbean	0.4	0.8	1.2	1.6

Sources: Stern (2006); IPCC (2007b); authors' calculations.

The concentration of greenhouse gases in the atmosphere will affect the climate of every city, state, and country somewhat differently. Most of the United States will experience a larger temperature increase than the global average. While global mean temperature rises a little less than 2ºF by 2100 in the rapid stabilization case, average annual temperatures in most of the U.S. mainland will increase by 3ºF and Alaska's annual average temperature by 4ºF. The average annual temperatures that we report are an average of day and nighttime temperatures for every day of the year. A small change in annual average temperatures can mean a big difference to a local climate. For example, the historical average annual temperature is 50ºF in Boston, 53ºF in New York City, and 56ºF in Washington D.C. The rapid stabilization scenario – with the lowest plausible emissions – still represents a significant change to local climates throughout the United States in the next century. Three degrees Fahrenheit is a big change, but if it happens at a slow enough pace, each locality should be able to adapt to its new climate. Of course, this adaptation will not be costless.

The area of the United States that will suffer the most extreme impacts, even in the rapid stabilization case, is Alaska, where glaciers, sea ice, and permafrost are already retreating today, and an even greater upheaval to ecosystems, infrastructure, and industry can be expected in the decades to come. U.S. Gulf states, Florida, Hawaii, and U.S. territories in the Pacific and the Caribbean, in contrast, will experience smaller temperature changes – much closer to the global mean – than the majority of U.S. states. On the other hand, island and coastal regions are more exposed than the interior of the country to other aspects of climate change, such as increased storm damages and sea-level rise. In our study of climate impacts on Florida (Stanton and Ackerman 2007), we found these factors, plus climate impacts on the tourism industry and the electricity sector, could lead to large aggregate damages to the state economy.

In the best case, rapid stabilization scenario, sea levels will still rise in the United States and around the world. Even if it were possible to stabilize the atmospheric concentration of carbon dioxide well below the target of 450ppm, sea levels would continue to rise for centuries, if not millennia, because of the slow but inexorable expansion of the ocean caused by the last 100 years of temperature increase. The rapid stabilization case includes the IPCC's best case for global mean sea-level rise, an increase of 7 inches by 2100 (see Table 11).[30]

Table 11: Rapid Stabilization Case: U.S. Average Sea-Level Rise

in inches above year 2000 elevation	2025	2050	2075	2100
Sea-Level Rise	1.8	3.5	5.3	7.1

Sources: IPCC (2007b); authors' calculations.

For the most uncertain impacts of climate change – precipitation levels, trends in storm intensity, frequency, and path, and ocean acidity levels – the rapid stabilization scenario assumes benign outcomes: in this optimistic case, the only impacts of climate change are temperature increases and sea-level rise. We assume that U.S. weather patterns and the condition of marine ecosystems – which are extremely sensitive to changes in temperature and ocean chemistry – remain constant.

Case Study #1: Hurricane damages in the rapid stabilization case

The rapid stabilization case will reduce hurricane damages, not to zero, but to something more closely resembling current conditions. As explained in Chapter 2, we started with the expected value of annual hurricane damages and deaths, based on recent experience and scaled to the population and GDP of 2006. We then modified this estimate for the modest sea-level rise expected in the rapid stabilization case, and for the expected growth of the U.S. economy and population. (For a more detailed explanation, see Appendix A.) U.S. hurricane damages for the rapid stabilization case are projected to be $13 billion and 23 deaths by 2100, over and above the damages that would be expected if current climate conditions continued unchanged.

Table 12: Rapid Stabilization Case: Increase in Hurricanes Damages to the U.S. Mainland

	2025	2050	2075	2100
Annual Damages				
in billions of 2006 dollars	$1	$2	$5	$13
as a percentage of GSP	0.00%	0.01%	0.01%	0.01%
Annual Deaths	4	11	17	23

Source: Authors' calculations

Case Study #2: Real estate losses in the rapid stabilization case

Our estimate of the value of real estate losses from sea-level rise is based on an update of the work of James G. Titus and co-authors (1991), as described in Chapter 2. The same methodology is used for the rapid stabilization case as for business as usual: we assume that the value of U.S. coastal real estate has grown in proportion to GDP, and that annual damages will be proportional to sea level and to GDP. For the rapid stabilization case we repeat the calculation, using the projected 7 inches of sea-level rise by 2100 in place of the business-as-usual projection of 45 inches by 2100. Thus, in the rapid stabilization case, damages rise to $46 billion by 2006 (see Table 13).

Table 13: Rapid Stabilization Case: U.S. Real Estate at Risk from Sea-Level Rise

	2025	2050	2075	2100
Annual Increase in Value at Risk				
in billions of 2006 dollars	$4	$10	$22	$46
as percent of GDP	0.02%	0.03%	0.04%	0.05%

Source: Authors' calculations

Case Study #3: Energy costs in the rapid stabilization case

In the rapid stabilization case, electricity demand rises throughout the country in pace with demographic growth and increasing demands for electricity from residential and commercial consumers.[31] At the same time, the slightly warmer temperatures reduce the demand for heating fuel. However, the increased energy demand is, in total only $8 billion more than what would be expected if current conditions continued. Our estimates for 2100 are shown in Table 14; in the summary of costs in Table 16 below, we assume energy costs are proportional to GDP throughout the century.

Table 14: Rapid Stabilization Case, 2100: Energy Sector Increased Costs above 2005 Levels

in billions of 2006 dollars

	Southwest	South	Southeast	Northeast	Midwest	West, Northwest	Total
Electricity	$5.3	$2.6	$6.0	$0.8	$0.8	$0.2	$15.6
Heating Oil	$0.0	$0.0	-$0.1	-$0.8	$0.0	$0.0	-$0.9
Natural Gas	-$3.7	-$1.0	-$1.6	-$2.2	-$3.3	-$1.5	-$13.3
AC Units	$0.8	$0.7	$1.8	$1.2	$1.4	$0.7	$6.6
Total	$2.4	$2.4	$6.2	-$1.0	-$1.2	-$0.7	$8.0

Note: AC Units refers to the purchase of additional air conditioning units.

Case Study #4: Water costs in the rapid stabilization case

The rapid stabilization scenario will entail somewhat increased water supply costs; even the modest projected warming of 3^{o}F across most of the United States by 2100 will increase the demand for water. As temperatures rise, more water will be needed for irrigation, power plant cooling, household needs, and other uses. Moreover, a higher air temperature leads to faster evaporation; this could outweigh the gains from a moderate increase in rainfall, leaving a smaller amount of water available in rivers and reservoirs. In the absence of modeling specifically tailored to these conditions, we estimate the costs of water supply in the rapid stabilization case by the same method used for the business as usual calculations in Chapter 2: we take the climate-related costs projected by Frederick and Schwartz, and scale them in proportion to the temperature increase. The result, as shown in Table 15, reaches $220 billion, or 0.22 percent of GDP, by 2100.

Table 15: Rapid Stabilization Case: Increased U.S. Water Costs above 2005 Levels

	2025	2050	2075	2100
Annual Increase in Costs				
in billions of 2006 dollars	$46	$78	$131	$220
as percent of GDP	0.23%	0.23%	0.22%	0.22%

Sources: Frederick and Schwartz (2000), and authors' calculations.

Summary: The cost of inaction

The cost of inaction is the difference between the estimates for the business-as-usual and rapid stabilization cases, summarized in Table 16 below. The costs in the business-as-usual scenario, in these four areas alone, reach 1.8 percent of GDP by 2100. The cost of inaction – the difference between the two cases – is almost $1.6 trillion, or more than 1.5 percent of GDP, by 2100. And there are many other categories of costs that will be imposed by climate change, beyond the four areas we have examined; the total cost of inaction is inevitably much greater.

Table 16: Costs of Inaction for Four Categories of Damages for the U.S.

	in billions of 2006 dollars				*as a percentage of GDP*			
	2025	**2050**	**2075**	**2100**	**2025**	**2050**	**2075**	**2100**
Hurricane Damages								
Business-as-Usual	$10	$43	$142	$422	0.05%	0.12%	0.24%	0.41%
Rapid Stabilization	$1	$2	$5	$13	0.00%	0.01%	0.01%	0.01%
Cost of Inaction	**$9**	**$41**	**$136**	**$409**	**0.05%**	**0.12%**	**0.23%**	**0.40%**
Real Estate Losses								
Business-as-Usual	$34	$80	$173	$360	0.17%	0.23%	0.29%	0.35%
Rapid Stabilization	$4	$10	$22	$46	0.02%	0.03%	0.04%	0.05%
Cost of Inaction	**$30**	**$69**	**$151**	**$314**	**0.15%**	**0.20%**	**0.25%**	**0.31%**
Energy Sector Costs								
Business-as-Usual	$28	$47	$82	$141	0.14%	0.14%	0.14%	0.14%
Rapid Stabilization	$2	$3	$5	$8	0.01%	0.01%	0.01%	0.01%
Cost of Inaction	**$26**	**$45**	**$77**	**$133**	**0.13%**	**0.13%**	**0.13%**	**0.13%**
Water Costs								
Business-as-Usual	$200	$336	$565	$950	1.00%	0.98%	0.95%	0.93%
Rapid Stabilization	$46	$78	$131	$220	0.23%	0.23%	0.22%	0.22%
Cost of Inaction	**$154**	**$258**	**$434**	**$729**	**0.77%**	**0.75%**	**0.73%**	**0.71%**
Total Costs for Four Categories								
Business-as-Usual	$271	$506	$961	$1,873	1.36%	1.47%	1.62%	1.84%
Rapid Stabilization	$53	$93	$163	$287	0.27%	0.27%	0.28%	0.28%
Cost of Inaction	**$218**	**$413**	**$798**	**$1,585**	**1.10%**	**1.20%**	**1.35%**	**1.55%**

The costs are not evenly distributed throughout the country. Hurricane damages are experienced almost entirely in the southeastern coastal states, on the Gulf Coast and the Atlantic (Pacific storms that affect Hawaii and the West Coast are not included in this calculation). Sea-level rise, of course, affects coastal areas. Energy costs are heavily concentrated in southern states; many northern states would enjoy reductions in winter heating costs that are roughly comparable to increased summer electricity expenses. Water supply costs are concentrated in areas that become drier than at present, particularly the Southeast and Southwest. Costs experienced in Alaska, Hawaii, Puerto Rico and other territories are almost entirely omitted from these calculations.

4. Why do economic models understate the costs of climate change?

Chapters 2 and 3 found that just four of the major impacts of climate change will cause damages projected to reach 1.8 percent of U.S. GDP by 2100 in the business-as-usual case, or 1.5 percent, if measured as the cost of inaction (or the savings from taking action to slow greenhouse gas emissions). Total damages to the U.S. economy, including many other impacts, will be larger than these estimates. Based on these findings, models that have predicted small climate costs, or even net benefits, to the U.S. economy appear to have underestimated the scale of the problem.

To the extent that climate policy relies on the predictions of economic models, it is built on what looks, to most people, like a "black box." This chapter examines what happens inside the black box of conventional economic models, finding a pattern of arbitrary and biased assumptions – with the bias almost always in the direction of minimizing the costs of climate change. The next chapter presents the model used in the British government's Stern Review, and explores its implications for the U.S.

To understand and respond to climate change, it is essential to forecast what will happen at carbon dioxide concentrations and temperature levels that are outside the range of human experience. In the realm of science there is substantial agreement, at least in broad outline, about the physical relationships that govern that these predictions. Reflecting that agreement, today's scientific models have achieved remarkably detailed forecasts of future climatic conditions, with a gradually increasing degree of consensus between models.

In the realm of economics, however, there is much less agreement about the laws and patterns that will govern future development. Numerous economic models weigh the costs of allowing climate change to continue against the costs of stopping or slowing it, and thus recommend a "best" course of action: one that, given the assumptions of a particular model, would cause the least harm. The problem lies in the choice of the assumptions.

Models of climate economics do not just swallow economic data and spit out predictions of future economic conditions. Inevitably, they embody ethical and political judgments; they make assumptions about how we value the lives, livelihoods, and natural ecosystems of future generations – how contemporary human society feels about those who will inherit the future. The models also make assumptions about future patterns of economic growth and technological change, technical questions on which economists do not all agree about the answers. Thus the economic results are driven by conjectures and assumptions that do not rest on empirical evidence, and often cannot be tested against data until after the fact.

More specifically, models that summarize the monetary value of climate damages are often inconsistent with the general public's understanding of how climate change will impact on society in several ways:

- Uncertain outcomes are disregarded, even when the possible impacts are catastrophic; instead, most economic models focus on the most likely climate impact.

- Costs to future generations are assumed to be much less important, and less valuable, than costs experienced today.
- Dubious price tags are given to non-economic losses, like damages to human health or the environment, for which no amount of money can adequately compensate.
- The early stages of warming are often assumed to be beneficial, even when the evidence is scant or contradictory.
- Surprisingly arbitrary methods are used to determine the overall scale of damages.

The following sections address each of these points in turn.

Uncertainty

Uncertainty is crucial to understanding climate change – both because of what we don’t know, and also because of what we do know. Temperature, rainfall, and other climate impacts are becoming more variable; floods, droughts, and storms are getting worse, although they are not predictable in detail. As temperatures rise, so does the risk of an irreversible catastrophe, such as the loss of a big ice sheet in Greenland or Antarctica, even though the probability of such catastrophes is not precisely known in advance.

Climate science now tells us both that we are uncertain about exactly what will happen next and that things are certain to get worse in general. The problem is that different levels of uncertainty are involved. No one knows how to predict next year's weather, and the year-to-year variation is enormous: there could be many hurricanes, or almost none; unusually hot temperatures, or unusually mild; more rain than average, or less. But scientists are increasingly certain that we are headed towards worsening conditions on average.

Picture each year’s weather as a card drawn from a deck of playing cards. There is no way of predicting next year's weather, any more than you can predict the next card you will draw from a well-shuffled deck. In an unchanging climate, however the probabilities of different outcomes are known in advance, just like the probabilities in drawing a card from a standard 52-card deck: there is one chance in 13 of drawing an ace, one chance in four of drawing a diamond, and so on.

Now imagine that the dealer changes one of the cards from time to time, so that you are no longer sure of the probabilities for your next draw. The weather in a changing climate is like drawing a card from a changing deck. The message of climate science is that the deck of climate possibilities is changing in disturbing directions, both toward more variability and more extreme outcomes, and toward worsening averages. The same logic applies in reverse: reducing greenhouse gas emissions will not guarantee better weather next year, but it will ensure that in the future we and our descendents will be able to draw from a better deck.

The nuances of uncertainty in predicting future outcomes can be difficult for both scientists and economists to convey to a wider audience. Many economic models estimate the most likely outcome and predict the economic consequences of that one possible future climate.

The Stern Review (2006), a study of climate economics from the British government (discussed more fully in the next chapter), takes a path-breaking approach: it explicitly includes uncertainty in its calculations of economic costs and benefits, using what is called "Monte Carlo analysis." Many critical features of climate science and economics are assumed to be uncertain; each time the model is run, the computer effectively rolls the dice and picks different values for the uncertain features. The model is run many times, and the results are averaged to produce the final estimates of climate damages. In some runs the impact of climate change is milder than the average expected value, and in some runs it is more severe.

Although Stern expanded the role of uncertainty in climate economics, another economist has argued that the problem goes even deeper. Martin Weitzman (2007) argues that in complex, changing systems such as the global climate (or financial markets), we are inevitably forecasting the future based on limited information. As a result, we cannot learn enough to be confident about how bad, and how likely, the worst-case possibilities may be. If, for example, we had to estimate how fast the average temperature will increase based on 100 experimental observations, we could not say much about the 99th percentile – that is, the worst case – of possible outcomes. Yet when faced with real, open-ended risks, people care a great deal about worst-case outcomes, out to the 99th percentile of possibilities and beyond.

The message for climate change, according to Weitzman, is that we should worry less about calibrating the most likely outcomes, and more about insurance against worst-case catastrophes. Thus IPCC (2007b) discusses "climate sensitivity," meaning the expected temperature change from a doubling of atmospheric carbon dioxide; this is relevant because the world is likely to reach twice the pre-industrial level of carbon dioxide within this century. (If current emission trends do not change, that level could be reached in the first half of the century.) The IPCC's best estimate of climate sensitivity is an increase of 5.4ºF as a result of a doubling of atmospheric carbon dioxide – well within the range of the ongoing debate over the impacts of predictable and expected damages. Weitzman argues, however, that the IPCC's reports also imply that the 99th percentile value for climate sensitivity is 18^{o}F. Discussing this worst case climate reaction to a doubling of carbon dioxide, he says:

> *Because such hypothetical temperature changes would be geologically instantaneous, it would effectively destroy planet Earth as we know it. At a minimum this would trigger mass species extinctions and biosphere ecosystem disintegration matching or exceeding the immense planetary die-offs associated with a handful of such previous geoclimate mega-catastrophes in Earth's history. (Weitzman 2007, p.9)*

This perspective suggests a profound reframing of the climate policy debate. When homeowners buy fire insurance, or when healthy young adults buy life insurance, they are spending money to insure against accidents that have annual probabilities of a few tenths of a percent. A 1 percent risk of disaster is, from some perspectives, very dangerous: the death rate for U.S. soldiers in the Iraq war is less than 1 percent per year, and no one views their job as a safe one. If expenditures on fire insurance for homeowners and life insurance for young adults are worthwhile, then perhaps climate economics should be talking more about the value of insurance against the 1 percent chance of 18ºF climate sensitivity, which would truly be a catastrophe, and less about average or likely results. What is the right price tag to put on a 1 percent chance of the end of life as we know it?

In the calculations for the four case studies presented in this report, we look at two ends of a range of likely estimates, from the 17th percentile and the 83rd percentile. We have not considered the possible economic impacts of catastrophic climatic change. While this approach is an improvement on presenting only the results of mean climate predictions, one could argue that the real cost of inaction is the failure to eliminate the risk of catastrophe, even if there is only a small chance of that catastrophe occurring.

Discounting the future

When costs are incurred to reduce emissions today, the greatest benefits of reduced climate change will take place decades or centuries from now. How much less valuable are those benefits, simply because they will happen in the future? Economists convert future amounts to their “present values,” meaning the amount of money you would have to put in the bank today to end up with the desired amount in the future. Leave $94 in a savings account paying 3 percent per year, and you will have approximately $100 in two years. Thus the present value of $100 two years from now is $94 today, assuming a discount rate of 3 percent. Put another way, in conventional economics $94 is the most that we should pay today to avoid damages of $100 in two years, at a discount rate of 3 percent. The present value depends on the discount rate: if the discount rate were higher than 3 percent, the present value of $100 two years from now would be lower than $94; if the discount rate were lower than 3 percent, the present value would be greater. The discount rate we choose for long-term public policy decisions depends entirely on how we value the future: it’s a matter of ethics, not science. The choice of discount rate is of particular importance when discounting values more than a few years into the future; in the long run, small differences in discount rates have big effects on present values.

At a discount rate near zero, future damages are considered to be almost as costly as if they occurred today, implying that it is “worth it” to take action now to stop those future damages from occurring (in the example above, a discount rate of precisely zero makes it worth spending $100 now to avoid $100 of future damages). At a high discount rate, future values fade rapidly into insignificance, implying that very little climate mitigation is “justified” by its (heavily discounted) benefits in generations to come. What, for instance, is it worth spending today to prevent $1,000 of damages that will occur 100 years from now? At a 1.4 percent discount rate (used in the Stern Review, as discussed in Chapter 5), the present value of that future $1,000 is $249, while at 5 percent the present value drops to less than $8.[32] Run the clock forward another century: what is it worth spending today to prevent $1,000 of damages 200 years from now? At a 1.4 percent discount rate, the answer is $62; at a 5 percent discount rate, it falls to $0.06. In short, damages that will occur one or two centuries from now are treated as important, albeit somewhat diminished, at a low discount rate; in contrast, they are all but invisible at a high discount rate.

For this reason, the choice of the discount rate dominates the results of climate economics. With exactly the same facts and assumptions about present and future costs and benefits, a low discount rate can imply high social costs and a strong rationale for active mitigation efforts, while a high discount rate implies low social costs and almost seems to justify inaction. But the choice of the discount rate for long-run climate studies is not a matter of objective scientific analysis. Rather, it is an expression of concern (or lack thereof) about the welfare of the generations that will follow us.

In the four case studies presented in this report, we do not calculate discounted present values; rather, we present annual costs in future years, both in dollars and as a percent of that year's projected GDP. In essence, we have avoided the question of discounting by looking at costs in a given year compared to that year's economy, rather than a cumulative stream of future costs compared to today's economy.

Pricing the priceless

How could a single number describe all the aspects of damages to human health and to the environment that will result from climate change? When the predicted impacts on ecosystems, human lives, and our enjoyment of our local climate are converted into monetary values and added together, much of what is most meaningful in these predictions gets lost.

Environmental damages have at times been monetized by calculating the price of building and operating replacements for lost ecosystem services – think of the costs of water purification, replacing once-clean rivers that have become polluted – and/or the subjective value that humans place on the existence of these ecosystems (as estimated by "contingent valuation" surveys, a specialized form of public opinion poll). But the values that current generations place on an ecosystem, even if accurately estimated, may not fully capture its true worth. Ecosystems may provide services and share interdependencies that are not yet fully understood. Future generations may place a higher value both on ecosystems services – like producing oxygen and filtering water – and on the existence of certain ecosystems. Surveys estimating values of ecosystems have only been carried out in a few locations, but these results are applied to ecosystems around the world – often with valuations weighted in proportion to the local per capita income (e.g., Tol 2002a). Endangered species that have the foresight to live in rich countries are thus declared to be "worth" more than those who have only low-income human neighbors. Large, well-known endangered animals are valued particularly highly, based on superficial aesthetics rather than ecological analysis or ethical judgments.

Human lives lost as a result of climate change can be monetized by assigning a – necessarily arbitrary – value to each life. In recent U.S. EPA cost benefit analyses, for example, this was often equivalent to $6 million under the Clinton administration, or less than $4 million under the Bush administration (Ackerman and Heinzerling 2004). But once a monetized value of lost lives has been added together with property damage, clean-up costs, and reduced production, what is the meaning of the resulting sum? If we use it to compare the cost of damages due to climate change to the cost of mitigation, what do trade-offs at the margin imply? This is really about deciding whether or not the research and development of an alternative fuel, for example, will cost too much in comparison to the amount of carbon that it can offset. How is the quality of decisions like this improved by lumping goods and services that can be bought and sold in a market – like steel girders or labor hours – together with human lives, which both legal and moral codes prevent us from trading? The dubious ethical import of monetizing human lives is further compounded when, as in some economic models such as Tol (2002a), the value of a life is made proportional to the income per capita in each region. Developing countries have, needless to say, reacted badly to the idea that their citizens' lives are "worth less" than those in rich countries.

In this report, we have not included any monetized value of human lives, saved or lost. The case study on hurricane damages reports additional lives lost as a separate, satellite account. If we were to assign a value to life our damage estimates would be even larger.

Benefits of moderate warming?

One reason why economic analysis often minimizes the importance of climate change is the assumption that a little bit of warming might be beneficial, especially for colder, northern areas. While this is at odds with the views of many climate scientists and advocates, it may resonate with some parts of public opinion.

The supposed benefits of warming loom large in the work of William Nordhaus, one of the best-known economists engaged in modeling climate change (Nordhaus 1999; Nordhaus and Boyer 2000). Based on the fact that Americans spend more on summer than on winter outdoor recreation, Nordhaus has concluded that there is a huge subjective desire, and willingness to pay, for hotter weather in cold northern countries. In his view, people worldwide feel that the optimal temperature is a year-round average of 68°F – the annual average temperature of Houston or New Orleans in the U.S., or Tripoli in Libya. His monetization of the assumed craving for heat is weighed against real damages caused by climate change in his cost-benefit analysis; in the 2000 version of his model, the result was that the world as a whole would experience a net benefit from warming through the first half of this century (Ackerman and Finlayson 2006).[33] Other survey research, examining actual attitudes toward temperature, has produced far smaller estimates of the psychological benefits of warming, suggesting that only a few of the northernmost countries will enjoy even the first decades of climate change (Rehdanz and Maddison 2005).

Another potential benefit which some economists anticipate from the early stages of warming is a large net reduction in temperature-related mortality. Bjorn Lomborg (2007), a leading anti-environmentalist,[34] highlights the mortality reduction from warming, drawing heavily on a study by Bosello *et al.* (2006) which makes the remarkable prediction that one degree of global warming will, on balance, save more than 800,000 lives annually by 2050. Deaths increase on both cold and hot days, but more temperature-related deaths occur when it is colder than the local ideal temperature. Note the importance of *local* temperatures: an uncomfortably cold day does not mean the same thing in Miami as in Chicago. As Chicago and other cold places heat up due to global warming, however, the local ideal temperature will gradually increase, following the warming trend in the climate. People do move from cold northern cities to Miami, and adapt relatively quickly to the new temperatures they experience. The prediction of Bosello *et al.* of lives saved by climate change assumes instead that human beings cannot adapt to new climates. (See Ackerman and Stanton (2007) for a detailed critique.)

A third, widely debated potential benefit of the early stages of climate change is the impact on agriculture in temperate regions. Longer and warmer growing seasons, plus the fertilization effect of increases in atmospheric carbon dioxide, could increase yields for some crops; early climate research suggested this could be a big effect, especially in northern states. The available research is contradictory, however, as discussed in Chapter 2, and the latest studies project little if any agricultural benefits from warming.

The one category of benefits of moderate warming that is significant in our calculations is the reduction in energy costs as winter heating costs decline. Roughly speaking, this benefit is comparable to the increase in electricity use for air conditioning for the northern half of the country, leaving little or no net change in (non-transportation) energy costs. In contrast, the southern half of the United States can expect a more substantial, negative impact from climate-related energy costs.

Arbitrary damage function

In the end, many economic analyses base their estimated damages from each degree of climate change not on detailed scientific and economic data, but instead on a more impressionistic, aggregated damage function relating damages to the increase in temperature above a base year. Letting T represent that temperature increase, the damage function is often as simple as

(1) $\text{Damages} = aT^N$

(where a and N are constants). These arbitrary damage functions are very often quadratic, that is, N=2, meaning that damages are proportional to the square of temperature increases. In Nordhaus (2007a), for example, the parameters and exponent of the damage function (a and N in equation (1)) are cited as having been set with the goal of matching as closely as possible two point estimates of damages from climate change: 1) at 4.5°F temperature increase above the 1900 level, damages would amount to 1.98 percent of gross world output; and 2) at 11°F, damages would be 11.27 percent of gross world output.

The 4.5°F damage costs on which Nordhaus' damage function is based are the sum of six categories of non-catastrophic climate change damage and an additional, modest estimate for catastrophic damage.[35] The data on which the 4.5°F damage costs are based are at best thin, and at worst presented without citation or other justification. One of the six categories is the enjoyment of warmer weather, which is assigned a monetary value as described above; at 4.5°F, all regions of the world except India, the Middle East, and Africa are assumed to experience a net benefit from warming.

Even less detail is presented on the damages from 11°F of warming, which lie beyond the bounds of easy extrapolation from current conditions. While the two estimates are conveniently close to fitting on the same quadratic curve (i.e. equation (1) with N=2), the development of the two data points hardly constitutes a proof that this is the right damage function. Indeed, there are countless functions that connect these two point estimates, as well as ample reasons to doubt the precision of both points.

As the Stern Review research team has demonstrated (Dietz *et al.* 2007), the choice of the exponent in the damage function makes an immense difference to the estimates. Set N=3 instead of 2 in equation (1), and damages climb much faster as temperatures rise, justifying far greater expenditures on climate protection. Since there is essentially no real information about whether N=2 or 3, or even whether the form of equation (1) is appropriate, the conclusion must be that economic models based on such a damage function do not produce reliable estimates of the value of climate damages.

The case studies presented in this report take a very different approach to estimating damages. Our estimates are built from the ground up using U.S. specific data about current costs and U.S. specific estimates, taken from the literature, of the likely change in these costs over time. We apply this information to the two IPCC climate scenarios, representing the high and low end of the likely range of climate futures.

5. U.S. climate impacts: Beyond the Stern Review

Economic analysis of climate change took a major step forward with the publication of the Stern Review, sponsored by the British government and directed by prominent British economist Nicholas Stern (2006). The Stern Review offered a thoughtful synthesis of the state of climate science, and presented the results of an innovative economic model of climate damages. The PAGE model,[36] used by Stern, avoids many of the shortcomings of traditional analyses described in Chapter 4, and estimates that climate damages from business-as-usual emissions through 2200 could be equivalent to 5 to 20 percent of world output each year on an ongoing basis.

This chapter discusses the results of the PAGE model for the United States, both in the form used in the Stern Review and with several new analyses and calculations, developed specifically for this report. The modeling results presented in this chapter were calculated by Chris Hope, the developer of the PAGE model, and Stephan Alberth, and are described in more detail in an accompanying background paper (Hope and Alberth 2007). The Stern Review predicted a 1 percent loss of U.S. GDP in 2100 for a scenario similar to our business-as-usual case, a serious underestimate in comparison to the loss of 1.8 percent of U.S. GDP, from just a sub-set of four climate impacts, documented in this report, but much less of an underestimate than many of the economic predictions that came before it.

Newly revised PAGE model results, produced for this report, project that U.S. damages will amount to 3.6 percent of GDP in 2100.[37] This estimate includes several categories of damages that are not included in our case studies; for the category of damages that includes our case studies, even the new PAGE results appear to be too low. That is, a further revision to be consistent with our case studies would imply climate damages even greater than 3.6 percent of GDP by 2100.

Stern's innovations

There are two principal innovations in the Stern Review's economic modeling. First, the discount rate was set at an average of 1.4 percent per year, low enough to make future impacts important in today's decisions. At discount rates as high as 5 percent or more, favored by many other economists, the far future simply doesn't matter much today, as we saw in Chapter 4. That is, at a high discount rate it is not "worth" doing much to protect our descendants from climate change.

Stern's choice of a 1.4 percent discount rate is almost entirely based on the assumption of ongoing economic growth, presumed to be 1.3 percent annually: if future generations are going to be somewhat richer than we are, there is correspondingly less need to worry about their welfare today. The rate of "pure time preference," that is, the discount rate which would apply if all generations had the same per capita income, was set at only 0.1 percent per year. As Stern convincingly argued, pure time preference close to zero is required on ethical grounds – people are of equal importance regardless of when they are born – and it is essential for an economic analysis that values a sustainable future.

The second innovation is the explicit treatment of uncertainty. Many of the key parameters for an economic analysis of climate change are uncertain: for example, what is the best estimate of “climate sensitivity,” the long run temperature increase that will result from a doubling of carbon dioxide concentrations? How fast will economic damages increase as temperatures rise? What temperature is likely to trigger a catastrophe such as the complete collapse and melting of the Greenland ice sheet? For questions such as these, most economic models use a single “best guess” based on limited data. Because the data are limited, however, the answers to these questions are still subject to considerable uncertainty.

In order to reflect the effects of uncertainty, the Stern Review replaces this best guess methodology with a statistical technique called Monte Carlo analysis (see Chapter 4). For each of the uncertain parameters, a range of possible values is established, and one of these values is picked at random whenever the model is run. The model is run many times, and the results of all the runs are averaged.

Monte Carlo analysis generally leads to larger estimates of climate damages than a model restricted to best guesses. Roughly speaking, the reason is that the climate could potentially get much worse, but only moderately better, than the “most likely” estimate. So including both best and worst cases, as well as the central estimate, makes the average outcome worse. Replacing the Monte Carlo analysis with fixed, best guesses, as in most other models, would have the same bottom-line effect as doubling the discount rate.[38] Indeed, the combination of a low discount rate and the Monte Carlo analysis of uncertainty is the principal reason why the Stern Review finds immediate, vigorous climate policy to be cost-effective. This conclusion is at odds with, and has been criticized by, other economists who remain wedded to more traditional approaches (Nordhaus 2007b).

The use of Monte Carlo analysis, however, does not guarantee that uncertainty has been adequately incorporated. Indeed, we will see that plausible modifications to the Stern analysis lead to very different estimates.

U.S. damages in the Stern Review

The PAGE model reports estimates of damages for eight regions of the world, of which the United States is one. The model projects damages caused by climate change through 2200, expressing them as a percentage of U.S. GDP. In the terminology used in earlier chapters, PAGE estimates business-as-usual damages, but does not directly calculate the cost of inaction. Three categories of climate impacts are included in PAGE:

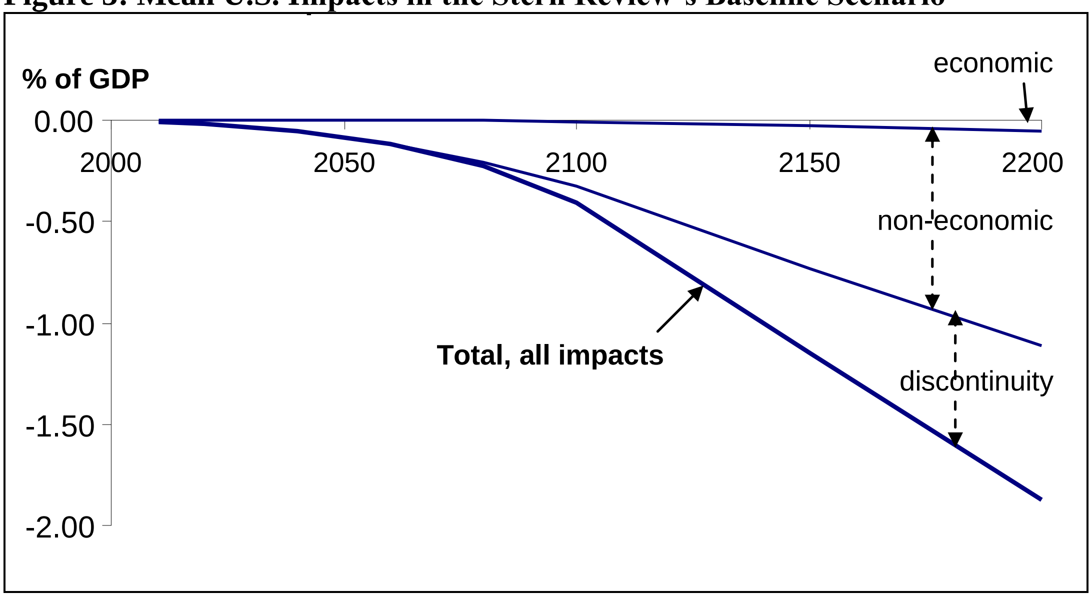
- economic impacts on sectors such as agriculture and energy use, which have market prices and are directly included in GDP;
- non-economic impacts, such as changes in human health, effects on wilderness areas and endangered species, etc., which are not directly included in GDP; and
- discontinuity impacts, which are increased risks of catastrophic events such as the melting of the Greenland and West Antarctic ice sheets.

Our case study estimates, in Chapters 2 and 3 of this report, are a subset of the first category; they are economic damages with market prices.

The PAGE model's underlying demographic, economic, and emissions data are taken from the A2 scenario of the IPCC's Third Assessment Report (2001). The global results of the PAGE model, as reported in the Stern Review, range from a 5 percent loss of GDP for economic impacts alone, up to a 20 percent loss of GDP for all three categories, economic, non-economic, and discontinuity impacts combined, using high (more damaging) assumptions about some remaining controversies in climate science.

Impacts as a fraction of GDP are, not surprisingly, much smaller for the United States than for the world. The worst impacts of climate change will be felt first in the hottest and poorest regions of the world, not in North America. Many parts of the United States enjoy a relatively cool climate, and the country has ample resources for adaptation to the early stages of climate change – although not always the foresight to use those resources wisely. Even compared to other rich countries, the United States is less vulnerable; for example, a much greater proportion of Europe's population and economic activity is concentrated along the coasts where it is vulnerable to sea-level rise and storm surges. The Stern Review assumes that low-cost adaptation eliminates 100 percent of U.S. and other developed country economic impacts up to 3.6°F of warming, and 90 percent of impacts at larger temperature increases. Adaptation is assumed to do much less for the other categories of impacts, reducing the non-economic impacts by only 25 percent, and catastrophic damages not at all.

Figure 3: Mean U.S. Impacts in the Stern Review's Baseline Scenario



Source: Hope and Alberth (2007)

Figure 3 shows the Stern Review's mean estimate of the three categories of impacts on the United States. (In the graph, the vertical distance between the lines represents the size of the impacts.) Stern's strong assumption about adaptation makes the economic impacts unimportant. The other impacts grow rapidly in the later years, with the combined total of all three categories amounting to only 0.1 percent of GDP in 2050, but rising to 0.4 percent by 2100 and 1.8 percent by 2200. The Stern Review reports PAGE model results through 2200; as the graph illustrates, the expected impacts become much larger in the next century.

Global impacts are about five times that large, roughly 10 percent of output in 2200. The United States emits about 20 percent of global emissions from now to 2200, but only suffers about 5 percent of global impacts.

The PAGE model also includes results for a high climate scenario described in detail in the accompanying technical paper.[39] The altered climate assumptions increase impacts by about 40 percent, for the United States and the world: by 2200, mean U.S. impacts reach about 2.8 percent of U.S. GDP, and mean global impacts reach about 14 percent of gross world product.

The results shown in Figure 3 are for mostly likely impact or 50th percentile result. The results that would be most comparable to the business-as-usual case presenting in this report, however, are the high end of the likely range, or the 83rd percentile. Table 17 shows the Stern Review's 83rd percentile for business-as-usual results for the United States: 1 percent of the U.S. GDP in 2100 for economic, non-economic and catastrophic damages combined. (The remainder of this chapter is based on 83rd percentile results from the PAGE model.)

Table 17: Business-As-Usual Case: U.S. Impacts in the Stern Review

as a percentage of GDP	2050	2100
Total U.S. damages	**0.19%**	**0.96%**

Source: Hope and Alberth (2007)

Revising Stern's PAGE model

Although the Stern Review represents a significant advance over conventional analyses, it is far from being the last word on the economics of climate change. In several respects, Stern appears to have chosen arbitrary, overly cautious assumptions that tend to lower the estimate of climate damages. In this section, we examine those assumptions and introduce the alternatives used in our analysis.

Damages without adaptation

The Stern Review damage estimates, particularly for the United States and other high-income countries, are understated by the treatment of adaptation: Stern never reports his actual estimate of total damages, but only the damages that would remain after an extremely extensive but low-cost adaptation effort. As noted above, Stern assumes that adaptation in developed countries eliminates all economic damages from the first 3.6°F of warming, 90 percent of economic damages above 3.6°F, and 25 percent of all noncatastrophic health and environmental damages.

In order to better understand the Stern estimates, we re-ran the same model assuming no adaptation. This change has the result of doubling the baseline Stern estimates, as presented above in Table 17. Damages in the no-adaptation scenario amount to 0.4 percent of U.S. GDP in 2050 and 1.7 percent in 2100, including economic, non-economic, and catastrophic impacts (see Table 18).

Table 18: Business-As-Usual Case: Stern's U.S. Impacts Revised to Exclude Adaptation

as a percentage of GDP	2050	2100
Total U.S. damages	**0.40%**	**1.73%**

Source: Hope and Alberth (2007)

Modeling the "no adaptation" scenario is not meant to imply that this is a likely outcome; there will undoubtedly be successful adaptation to many aspects of climate damages. It is useful as a starting point, however, to see how much damage there would be, if there were no adaptation or mitigation. That damage estimate can then be compared to the costs of adaptation and mitigation. Stern's results are only presented as the net effect after an assumed high level of low-cost adaptation; we have no way of knowing exactly how much adaptation will eventually take place at what cost.

Moreover, the Stern assumption of low-cost, successful adaptation to virtually all economic damages seems optimistic in the aftermath of Hurricane Katrina. The United States certainly had the resources to protect New Orleans and other affected communities; and, paralleling Stern's assumption, the cost of adaptation (such as bigger and better levees) would have been a small fraction of the cost of the damages caused by the storm. Yet it is not enough to have the resources for adaptation and, as in the case of Katrina, clear advance warning of potential harms. Unless we have the political will and foresight to listen to the warnings and actually build the levees, adaptation will not occur.

What percentage of the needed adaptation to climate impacts will actually occur in the future? The unfortunate lessons of the Katrina experience itself could lead to doing better next time – but the Stern assumption of 90 to 100 percent successful adaptation to non-catastrophic damages will not be achieved unless there is a substantial change in U.S. emergency preparedness and climate policy.

<u>High-temperature damages and risks of catastrophe</u>

How fast will damages increase as average temperatures rise? How soon will the world face real risks of an abrupt, catastrophic event such as the complete loss of the Greenland ice sheet (which would raise sea levels more than 20 feet, and destroy most coastal communities around the world)? These are among the most important questions in forecasting future climate damages. In both cases, the PAGE model analysis in the Stern Review makes surprisingly cautious projections, while the text of the Stern Review paints a more ominous picture of the future. Here we explore two changes to the model addressing these uncertainties.

One change involves the exponent of the damage function. PAGE, like many economic models, assumes climate damages are a function of temperature, using the equation discussed in Chapter 4:

(2) Damages = aT^N

Here, a is a constant, T is the temperature increase (usually relative to a recent base year), and N is the exponent governing how fast damages rise. Using this equation, if N = 1, then 4° is twice as bad as 2°; if N = 2, 4° is four times as bad; if N = 3, then 4° is eight times as bad, etc.

PAGE treats the exponent N as one of the uncertain parameters that is allowed to vary in the Monte Carlo analysis, with the minimum, most likely, and maximum values, respectively, set at [1, 1.3, 3]. There is essentially no evidence bearing directly on the value of this exponent, but the "most likely" value of 1.3 seems almost timid: it implies that 4° is only about 2.5 times as bad as 2°. In our variation, we set the minimum, most likely, and maximum values of the exponent at [1.5, 2.25, 3]. This alternative keeps the exponent within the same range used in the Stern Review, but weights the higher end of the range more heavily; it assumes that the exponent is most likely to be a little more than 2, the value used in many recent models.

A second change – actually a pair of related changes – involves the temperatures that trigger catastrophic damages. PAGE assumes that a threshold temperature (again measured in degrees above a recent base year) must be reached before catastrophic events become possible; once that threshold is crossed, the probability of catastrophe gradually rises along with the temperature. Two of the uncertain (Monte Carlo) parameters in PAGE are involved here. One is the threshold temperature, with minimum, most likely, and maximum values of [3.6, 9, 14.4] degrees Fahrenheit in the Stern analysis. Much of the discussion of potential catastrophes, such as the loss of the Greenland or West Antarctic ice sheets, has suggested that they become possible or even likely at temperatures well below the PAGE model's "most likely" threshold of 9°F of warming; even the narrative portions of the Stern Review make this suggestion. For this reason, the baseline assumption about threshold temperatures seems too conservative. We changed the threshold temperature to minimum, most likely, and maximum values of [3.6, 5.4, 7.2] degrees Fahrenheit.

A second parameter involved in this calculation is the rate at which the probability of catastrophe grows, as the temperature rises past the threshold. For Stern, the probability of catastrophe increases by minimum, most likely, and maximum rates of [1, 10, 20] percentage points per degree Celsius (i.e., per 1.8^oF) above the threshold. This also seems unduly conservative, minimizing the risk of catastrophe until warming is far advanced. In our changes to the model, the probability of catastrophe grows at minimum, most likely, and maximum rates of [10, 20, 30] percentage points per degree Celsius above the threshold.

Adding these changes to the no-adaptation scenario has very little effect by 2050 – even with the revised assumptions, a catastrophe remains quite unlikely in the first half of the century – but the increased risk of disaster more than doubles the projected damages by 2100 (compare Tables 18 and 19). Detailed analysis (see Hope and Alberth 2007) shows that the changes involving the threshold for catastrophic events are more important than the damage function exponent, although changes in both areas increase the damages.

Table 19: Business-As-Usual Case: Stern's U.S. Impacts Excluding Adaptation, Including Changes to Damage Function

as a percentage of GDP	2050	2100
Total U.S. damages	**0.46%**	**3.61%**

Source: Hope and Alberth (2007)

The PAGE model and our case studies

This exploration of alternatives within the PAGE model has suggested important ways in which Stern's estimates may understate the likely impacts of climate change on the U.S. economy, and has offered an alternative, noticeably higher estimate based on changing a few key assumptions. But even the best application of such models rests on many abstract assumptions, which are difficult to verify.

Our revised runs of the PAGE model provide aggregate damage estimates that look larger than the case study estimates in Chapters 2 and 3. Recall, however, that PAGE estimates combine economic damages, non-economic impacts, and catastrophic risks. Our case study estimates of the costs of business-as-usual, reaching 1.8 percent of U.S. GDP by 2100, should be compared to a subset of the PAGE economic damages. In fact, in our revised PAGE runs as well as in the Stern version, most of the PAGE damage estimates for the U.S. reflect the non-economic and catastrophic categories. Our case study results are considerably larger than the corresponding PAGE estimates for the economic cost category. This suggests that if the PAGE economic costs were adjusted to be comparable with the case studies, the result would be an even greater damage estimate. Even the best of the existing economic models of climate change cannot yet reflect the full extent of damages that would result from business as usual.

6. Conclusion

Estimates of future economic damages resulting from climate change have an important impact on policy decisions being made today. Reducing greenhouse gas emissions and protecting ourselves from those impacts that are now unavoidable will be costly, but a failure to act to address climate change would be even more expensive.

In this report, we have measured just a handful of potential damages from climate change to the U.S – hurricanes, residential real estate, energy and water. The likely damages from these four categories of costs could be as high as 1.8 percent of U.S. output in 2100 if business-as-usual emissions are allowed to continue, or as low as 0.3 percent if instead the whole world engages in an ambitious campaign of greenhouse gas reductions. The difference between these two estimates, what we call the cost of inaction, is 1.5 percent of U.S. output in 2100. This is a somber prediction, especially when one recalls all of the economic costs that we have not attempted to estimate – from damage to commercial real estate caused by sea-level rise to the changes in infrastructure that will be necessary as temperatures rise.

We compare these results to the Stern Review's PAGE model predictions for the U.S. in 2100 in the business-as-usual case: under a number of restrictive assumptions, just 1 percent of U.S. output would be lost, in an estimate that includes not only the kinds of economic costs that we have measured, but also non-economic and catastrophic damages. This report introduces a revised PAGE model, loosening the restrictive assumptions on future impacts, which produces an estimate of a loss of 3.6 percent of U.S. output in 2100 for economic, non-economic and catastrophic damages combined. The revisions bring the PAGE model much closer to a result consistent with our four case studies.

The bottom-line for the U.S. is more than 1.5 percent of GDP in 2100, nearly $1.6 trillion, in economic costs that could be avoided from hurricane damage, residential real estate losses, and increased energy and water sector costs alone. Today the United States is an obstacle to global climate policy. We could instead be a leader, pushing forward the effort to corral global greenhouse gas emissions, with a willingness to collaborate in international initiatives, a forward-thinking, ambitions set of progressive domestic programs, and generous assistance to those countries around the world that can least afford new technology. If we take the lead in acting now, our grandchildren will thank us for leaving them a more livable world.

Appendix A: Technical note on hurricane calculations

Our strategy in calculation is to base scenario damages on historical averages, adjusted by several economic, demographic, and climate-related factors. This appendix explains the derivation of those factors, and presents the equations used to estimate damages in each scenario. Variables with names beginning BAU and RS are specific to the business-as-usual and rapid stabilization scenarios, respectively. Variables with names ending in Factor are adjustment factors, which are applied to historical averages to create projections of future hurricane damages.

Scenario-independent calculations

The projected U.S. population level and GDP (in 2006 dollars) were calculated for each year from 2010 to 2100. The same population and GDP projections were used for both scenarios.

Following Pielke and Landsea (1998)) hurricane damages are treated as proportional to GDP; in addition, this logic is expanded upon to treat hurricane deaths as proportional to U.S. population. Since Texas and several other Atlantic and Gulf coast states have expected population increases much higher than the U.S. total, the choice of making hurricanes deaths proportional to the entire projected U.S. population, rather than just the coastal population, will tend to underestimate projected deaths (U.S. Census Bureau 2005). The resulting sets of population factors and development factors for each year were applied to the expected value of U.S. mainland hurricane deaths and damages, respectively:

$$(3)\ PopFactor_{yr} = \frac{Population_{yr}}{Population_{2000}}$$

$$(4)\ DevFactor_{yr} = \frac{Population_{yr} * PerCapitaGDP_{yr}}{Population_{2000} * PerCapitaGDP_{2000}}$$

Business-as-usual case

The predicted sea-level rise, above year 2000 levels, was calculated for the United States for each of the modeled years. In the business-as-usual case, sea-level rise reaches 45 inches by 2100. Nordhaus (2006) estimates that for every meter of sea-level rise, economic damages from hurricanes double, controlling for other kinds of impacts. In modeling mainland U.S. impacts, we have used Nordhaus' estimated impact both for economic damages, as he intended, and for hurricane deaths. Measuring sea-level rise (SLR) in meters, a doubling of damages for every meter of sea-level rise is expressed by:

$$(5)\ BAUSLRFactor_{yr} = 2^{BAUSLR_{yr}}$$

Nordhaus (2006) also estimates the impact of increasing atmospheric carbon dioxide levels and sea-surface temperatures on storm intensity and economic damages. He assumes that storm frequency will remain at the historical average, but maximum wind speeds will increase by 9 percent with a doubling of atmospheric carbon dioxide. Using a regression analysis of past hurricanes, Nordhaus finds that hurricane power rises as the cube of maximum wind speed (a result confirmed by existing literature) and that hurricane damages rise as the cube of hurricane power. According to his calculations, every doubling of atmospheric carbon dioxide results in a doubling of hurricane damages – independent of the effects of sea-level rise.[40] Again, Nordhaus estimated impacts are for economic damages, but are used here for deaths as well. Predicted carbon dioxide levels were calculated for the business-as-usual case for all modeled years (the rapid stabilization case assumes that hurricane intensity will remain constant). Business-as-usual storm intensity (SI) factors for each year are as follows:

(6) $BAUSIFactor_{yr} = \frac{BAUCO2Concentration_{yr}}{BAUCO2Concentration_{2000}}$

Future economic damages from mainland U.S. hurricanes are calculated by adjusting the expected value (EV) of hurricane damages upwards, using the development factor, the business-as-usual sea-level rise factor, and the storm intensity factor:

(7) $\text{BAU-Damage}_{yr} = \text{EVDamage}_{yr} * \text{DevFactor}_{yr} * \text{BAUSLRFactor}_{yr} * \text{BAUSIFactor}_{yr}$

Future deaths from U.S. hurricanes are calculated by adjusting the expected value of hurricane deaths using the population factor, the business-as-usual sea-level rise factor, and the storm intensity factor:

(8) $\text{BAU-Deaths}_{yr} = \text{EVDeaths}_{yr} * \text{PopFactor}_{yr} * \text{BAUSLRFactor}_{yr} * \text{BAUSIFactor}_{yr}$

Rapid stabilization case

The predicted sea-level rise, above year 2000 levels, was calculated for the United States for each of the modeled years. In the rapid stabilization case, sea-level rise reaches 7 inches in 2100. Paralleling the analysis in the business-as-usual case, as described in Chapter 2, sea-level rise (SLR) factors, by year, were constructed based on this estimate:

(9) $RSSLRFactor_{yr} = 2^{RSSLR_{yr}}$

Future economic damages from mainland U.S. hurricanes are calculated by adjusting the expected value (EV) of hurricane damages upwards, using the development factor and the rapid stabilization sea-level rise factor:

(10) $\text{RS-Damage}_{yr} = \text{EVDamage}_{yr} * \text{DevFactor}_{yr} * \text{RSSLRFactor}_{yr}$

Future deaths from U.S. hurricanes are calculated by adjusting the expected value of hurricane deaths using the population factor and the rapid stabilization factor:

(11) $RS\text{-}Deaths_{yr} = EVDeaths_{yr} * PopFactor_{yr} * RSSLRFactor_{yr}$

Damages net of economic and population growth

The final step is to take the difference between the damages for each scenario and the damages that would result in the baseline, no climate change scenario that holds today's climate constant but allows for the same amount economic and population growth modeled in the business-as-usual and rapid stabilization scenarios. The hurricane damage costs for each scenario are net costs that include only the additional damages due to changes in climate, not the additional damages that will result from a larger and richer population.

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Endnotes

[1] The IPCC does not make a single forecast, but rather offers multiple projections, including six major scenarios. As explained in Chapter 2, our business-as-usual scenario is based on the IPCC's A2 scenario – specifically, it uses the 83rd percentile outcomes, or upper end of the IPCC's "likely" range, for A2.
[2] For the IPCC, "likely" means a two-thirds probability of occurring, so the "likely" range extends from the 17th to the 83rd percentile of scenario results.
[3] The IPCC's (2007) "likely" range excludes the 17 percent of A2 predictions that showed the worst outcomes, and the 17 percent of predictions that showed the best outcomes. A2 is the IPCC scenario with the second highest atmospheric concentration of carbon dioxide.
[4] The IPCC provides predictions regarding changes in U.S. precipitation patterns based on the A1B scenario, which has a slightly lower atmospheric carbon dioxide concentration than the A2. A1B is the only scenario for which precipitation predictions were available.
[5] When the IPCC's little-published estimate of sea-level rise from melting is combined with other more predictable, and better publicized, effects – like thermal expansion – the total sea-level rise for the high end of the A2 likely range increases from 20 inches to 25 inches by 2100 (IPCC 2007b).
[6] For the purposes of these calculations, damages and deaths caused by each hurricane were scaled up to 2006 levels using U.S. GDP and population, respectively, as inflators.
[7] Note: Where discrepancies existed, the NHC (2007) data were used. NAIC (2007) data – used for two data points – are insured damages only; following the convention documented in NHC (2007), these insured damages were double to estimate total damages.
[8] We use the midpoint of the Titus *et al*. (1991) total damages from inundation at 100 cm sea-level rise for the calculations presented here.
[9] In terms of decreased efficiency, the important factor is not the reduction of water use, but the reduction of power output by switching over to dry cooling. Open loop cooling is much more efficient for power producing purposes than dry cooling when air temperatures are warm.
[10] Data from NERC (2007b); authors' calculations
[11] At West Point, GA. United States Geological Survey, November 29th, 2007. Real-time water data for USGS [stream gage] 02339500.
[12] Southern Company, October 24th 2007. Memorandum to Governors Crist, Perdue, and Riley. David Ratcliffe, Chairman, President, and CEO of Southern Company.
[13] The remainder of the nuclear plants primarily use ocean water and water from the great lakes for cooling purposes. Cooling is not as much of a problem for coastal plants; although a retrofit or the expansion of cooling ponds is expensive, it is a single time cost. The loss of a river used for cooling, however, is highly problematic for an inland plant.
[14] Note that this is a figure for water withdrawals from rivers and other sources; it differs in definition from the data on consumptive uses of water presented in the next section, where agriculture dominates the statistics. Most power plant cooling water is returned to its source and becomes available for other uses; consumptive (non-returned) use by power plants is a small fraction of their total withdrawals.
[15] "Southeastern" states combines South Atlantic and East South Central regions.
[16] Hourly air temperatures in 2005 from Phoenix, AZ; Los Angeles, CA; Dallas, TX; Miami, FL; Milwaukee, WI; Minneapolis, MN; Boston, MA; Seattle, WA; New York, NY; Philadelphia, PA; Detroit, MI; Chicago, IL; Denver, CO; Kansas City, MO; Oklahoma City, OK; Baton Rouge, LA; St. Louis, MO; Atlanta, GA; Memphis, TN; and Richmond, VA.
[17] With contemporary energy use preferences (influenced by building designs), the relationship between average annual temperature and the "ideal" temperature is quite consistent across the US: the ideal temperature increases by 0.7 ºF for every degree of average temperature. This suggests better insulation in cooler climates (hence, an ability to withstand cooler temperatures without heating) and adaptation or preference for warm temperatures in warmer climates.
[18] The Hadley CM3 Model is run with the IS92a scenario, doubling of CO_2 equivalently to the IPCC A2 scenario. In this case, we have linearly scaled the mid-range North American temperatures to be consistent with the 83rd percentile used elsewhere in this document (Hadley Centre 2007).
[19] Eighty-two percent of consumptive water use is for irrigation, and 3 percent for livestock (Jacobs *et al.* 2001 p. 418).

[20] That is, there was a sharp increase in the total amount of precipitation on the 5 percent of the days of the year with the heaviest precipitation, but little or no change in the amount of precipitation on most other days; data available only for 1939-99 (Jacobs *et al.* 2001).

[21] National Climatic Data Center's damage estimate of $61.6 billion in 2002 dollars was converted to 2006 dollars using the CPI.

[22] The original number in 1995 dollars was $462 billion for the scenario. We adjusted this to 2006 dollars using the CPI. Data from Frederick and Schwartz (2000) Tables 5.4 and 5.10; we used their Table 6.1 as a template for scenario cost calculation.

[23] Our temperature projection for 2100 is 12.5°F (average of U.S. east, central, and west), compared to 8.5°F in the Frederick and Schwartz analysis; we multiplied the Frederick and Schwartz cost by 12.5/8.5 = 1.47 to scale it up in proportion to final temperature. To calculate 2025 and 2100 values, we assumed straight-line growth from zero cost in 2005 to the adjusted Frederick and Schwartz estimate for 2095, and continuing at that rate through 2100. For 2050 and 2075 we interpolated between the 2025 and 2100 values, assuming costs grew at the same rate in each of the last three quarters of the century.

[24] The newer studies are the so-called "FACE" experiments (see IPCC 2007a Ch. 5)

[25] IPCC (2007a Ch. 5) reports a consensus that climate change is bad for agriculture everywhere once warming exceeds a threshold of 3°C (5.4°F).

[26] The 100th meridian is a north-south line which runs roughly through the middle of North Dakota, South Dakota, and Nebraska, and forms the eastern edge of the Texas Panhandle. It has long been recognized as a crucial boundary for rainfall, and hence for farming: most areas east of the 100th meridian have more than 20 inches of rain per year, and can support agriculture without irrigation; most areas west of the 100th meridian have less than 20 inches of rain per year, and require irrigation for most crops.

[27] Schlenker *et al.* (2006). Mean historical values of degree-days and precipitation are shown in Table 1, p. 117; optimal values from the statistical analysis are discussed on p.118. The optimal precipitation is two standard deviations above the mean historical precipitation.

[28] An increase in global mean temperature of 2.3ºF beyond year 2000 levels (or equivalently, 2°C beyond pre-industrial levels) is considered an important tipping point. At greater increases in temperature, the Greenland ice sheet is very likely to melt entirely and irreversibly, causing 20 feet of sea-level rise over several centuries. Remaining below 2.3ºF would require a stabilization of atmospheric carbon dioxide at 450ppm CO_2 (or 500ppm CO_2-equivalent including other greenhouse gases) (IPCC 2007b; UN Foundation and Sigma Xi 2007)

[29] We used the average of Stern's (2006) 450ppm and 550ppm CO_2-equivalent stabilization paths, as roughly equivalent to 450ppm CO_2. The low end of the likely temperature range – or the 17th percentile – is a linear interpolation of the 5th and 50th percentiles. We assume 1.1ºF in temperature increase from preindustrial to year 2000. Stern's estimates are for global mean temperatures. We estimated regional U.S. temperatures using the same ratios of regional to global as the low end of the likely range of the IPCC's B1 scenario.

[30] Seven inches by 2100 is the low end of the likely range for the IPCC's (2007b) B1 scenario.

[31] Conservatively estimated at 0.5% growth in per-capita electricity use per year as Americans increasingly use power for multiple televisions, computers, and other electronic devices. The Energy Information Administration's Annual Energy Outlook (2007a) projects increases in residential electricity consumption at 1.3% per year from 2005 to 2030 and population-corrected increases in delivered energy of 0.8% per year for various regions. We optimistically assume that, over time, this demand will decrease as technology continues to improve on existing appliances.

[32] This assumes annual discounting, as in a spreadsheet model. The continuous-time approach to discounting favored in economic theory would yield different numbers, but would support all the same qualitative conclusions about the role of high versus low discount rates.

[33] In the latest version of the Nordhaus model, benefits from warming are still calculated on the same basis, and reduce, but no longer completely outweigh, climate damages (Nordhaus 2006).

[34] For a critique of Lomborg's latest attack on climate policy see Ackerman (2008).

[35] The estimated 1.98 percent of gross world output is the sum of the output-weighted average across all regions for each category.

[36] Formally, it is the PAGE2002 model; the name is abbreviated to PAGE to simplify the narrative in this report.

[37] We approximate the business-as-usual case, as described earlier in this report, as the 83rd percentile of the Stern Review's baseline scenario.

[38] See the sensitivity analyses in Dietz *et al.* (2007) (the Stern team's response to critics). Using the modal value for each Monte Carlo parameter has about the same effect as adding 1.4 percentage points to the pure rate of time preference (i.e. raising the average discount rate from 1.4 percent to 2.8 percent).

[39] See the accompanying report by Chris Hope and Stephan Alberth for explanation of this and other technical details of the model (Hope and Alberth 2007).

[40] This is because a doubling of carbon dioxide leads to an increase in wind speed by a factor of 1.09; damages are proportional to the ninth power of wind speed; and $1.09^9 = 2.18$, i.e. slightly more than doubling.