SANDIA REPORT

SAND2010-2200
Unlimited Release
May 2010

Executive Summary for Assessing the Near-Term Risk of Climate Uncertainty: Interdependencies among the U.S. States

George Backus, Thomas Lowry, Drake Warren, Mark Ehlen, Geoffrey Klise, Verne Loose, Len Malczynski, Rhonda Reinert, Kevin Stamber, Vince Tidwell, Vanessa Vargas, and Aldo Zagonel

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin company, for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Sandia National Laboratories

NNSA
National Nuclear Security Administration

Issued by Sandia National Laboratories, operated for the U.S. Department of Energy by Sandia Corporation.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@adonis.osti.gov
Online ordering:	http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.fedworld.gov
Online order:	http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2010-2200
Unlimited Release
Printed May 2010

Executive Summary for Assessing the Near-Term Risk of Climate Uncertainty: Interdependencies among the U.S. States

George Backus,[*] Thomas Lowry,[†] Drake Warren,[‡] Mark Ehlen,[‡] Geoffrey Klise,[†] Verne Loose,[‡] Len Malczynski,[†] Rhonda Reinert,[⊥] Kevin Stamber,[ǂ] Vince Tidwell,[†] Vanessa Vargas,[‡] and Aldo Zagonel[ǁ]

[*]Exploratory Simulation Technologies Department, [†]Earth Systems Department, [‡]Infrastructure and Economic Systems Analysis Department, [⊥]Optimization and Uncertainty Estimation Department, [ǁ]Infrastructure Modeling and Analysis Department, [ǂ]Systems Research, Analysis, and Applications Department

Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-MS0370

Abstract

Policy makers will most likely need to make decisions about climate policy before climate scientists have resolved all relevant uncertainties about the impacts of climate change. This study demonstrates a risk-assessment methodology for evaluating uncertain future climatic conditions. We estimate the impacts from responses to climate change on U.S. state- and national-level economic activity from 2010 to 2050. To understand the implications of uncertainty on risk and to provide a near-term rationale for policy interventions to mitigate the course of climate change, we focus on precipitation, one of the most uncertain aspects of future climate change. We use results of the climate-model ensemble from the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) as a proxy for representing climate uncertainty over the next 40 years, map the simulated weather from the climate models hydrologically to the county level to determine the physical consequences on economic activity at the state level, and perform a detailed 70-industry analysis of economic impacts among the interacting lower-48 states. We determine the industry-level contribution to the gross domestic product and employment impacts at the state level, as well as interstate population migration, effects on personal income, and consequences for the U.S. trade balance. We show that the mean or average risk of damage to the U.S. economy from climate change, at the national level, is on the order of $1 trillion over the next 40 years, with losses in employment equivalent to nearly 7 million full-time jobs.

Acknowledgments

This study was performed under the Laboratory-Directed Research and Development (LDRD) program at Sandia National Laboratories (Project 138735), and we gratefully thank the Sandia LDRD program for its financial support of this study. We acknowledge the additional expert efforts of the following colleagues at Sandia: Tim Trucano, David Robinson, Arnie Baker, Brian Adams, Elizabeth Richards, John Siirola, Mark Boslough, Mark Taylor, Ray Finely, Lillian Snyder, Dan Horschel, Andjelka Kelic, Jesse Roach, Marissa Reno, William Stubblefield, Laura Swiler, Laura Cutler, Anna Weddington, William Fogelman, Jim Strickland, John Mitchiner, Howard Hirano, and James Peery. Contributions by Dr. James P. Smith with the Computer and Computational Sciences Group at Los Alamos National Laboratory (LANL), by Dr. David Higdon with the Statistical Sciences Group at LANL, and by Dr. Joe Galewsky from the Department of Earth & Planetary Sciences at the University of New Mexico are also greatly appreciated. In addition, we are grateful to the following reviewers for their insightful comments and suggestions: Dr. Terry Barker, Director, Cambridge Centre for Climate Change Mitigation Research, Department of Land Economy, Cambridge University; Dr. Chris Hope, Energy and Environment Research Group, Judge Business School, Cambridge University; Dr. Robert Harriss, President and CEO of the Houston Advanced Research Center and former Director of the Institute for the Study of Society and the Environment at the National Center for Atmospheric Research; Dr. Michael Mastrandrea in the Center for Environmental Science and Policy at Stanford University; Dr. Elizabeth Stanton at the Global Development and Environment Institute at Tufts University and the Stockholm Environment Institute; and Dr. Jonathan Overpeck, Co-Director in the Institute of the Environment and professor in the Geosciences and Atmospheric Sciences departments at the University of Arizona.

Contents

Figures

Tables

What we anticipate seldom occurs; what we least expect generally happens.
Benjamin Disraeli, British prime minister (Disraeli 1891)

We know we cannot wait for certainty. Failure to act because a warning isn't precise enough is unacceptable. . . . if we wait, we might wait too long.
General Gordon R. Sullivan, USA (Ret.)
Former Chief of Staff, U.S. Army (CNA 2007)

Overview

The uncertainty in climate change and in its impacts is of great concern to the international community. While the ever-growing body of scientific evidence substantiates present climate change, the driving concern about this issue lies in the consequences it poses to humanity. By the time the negative impacts of climate change significantly affect populations, it will be too late to prevent the escalating damage. The greenhouse gases that dominate the warming process, especially carbon dioxide (CO_2), will produce enduring impacts for over a millennium (Solomon et al. 2009). Should the extent of climate change cross a threshold where geophysical processes reinforce manmade climate change, the long-term consequences could be catastrophic (Keller et al. 2008). However, in this study we confine ourselves to the near-term risk of climate change through the year 2050, and we do not consider the long-term risk of catastrophic climate change.

In this study, we quantify the risk from uncertain climate change to each of the interacting U.S. states, noting the impact on the population and businesses as they respond to changing climatic conditions. Largely, it is the uncertainty associated with climate change and its impacts that presents the greatest problem for policy makers. If society knew how climate change would exactly unfold, it could readily determine what adaptation and mitigation responses should be undertaken. However, decades of climate science research indicate that it may not be possible to obtain a definitive reduction in the uncertainty, and certainly not possible within the time frame that is needed to counter the worst effects of climate change (Roe and Baker 2007). While current best estimates of global warming by the year 2100 forecast a rise in the global mean (average) temperature on the order of 2º to 4ºC, the uncertainty of these estimates is relatively large. Various studies have attempted to define this uncertainty, which has been characterized as the "long tail" (Hegerl et al. 2007) in statistical terms. Fundamentally, the long tail suggests that the future global temperature may be higher than projected best estimates.

The analyses by the Intergovernmental Panel on Climate Change (IPCC) and the ensemble of model results provided by these analyses are currently the generally recognized statement on the future of climate change. The variation or differences in results among the climate models used for the IPCC Fourth Assessment Report (AR4) embodies the uncertainty most associated with climate forecasts. In this study, we use the results of the AR4 ensemble of climate simulations as a proxy for representing climate uncertainty over the next 40 years. We apply this uncertainty to consider the risk of uncertain precipitation conditions as it applies to individual U.S. states as well as the nation. We select precipitation because it more directly affects economic activities and is more uncertain, which implies more risk, than the commonly used considerations related to temperature (Trenberth 2008; Allen and Ingram 2002; NAST 2001). In climate studies, temperature is the common attribute used to estimate the impacts of climate change.

Uncertainty and Risk

The impacts from climate change are largely negative (IPCC 2007a). From a policy perspective, the incentive to act comes by comparing the risk (cost) of inaction with the cost of action to successfully mitigate climate change. Risk is often characterized in terms of probability and consequence. There is a spectrum of conditions (or events) involved with climate change for assessing risk. At one end of the spectrum are those conditions that may occur frequently (high probability) and result in minimal damage (low consequence). An example of a high-probability, low-consequence type of event would be excessive rainfall that results in damage to the roof of your house. At the other end of the spectrum are conditions that do not occur frequently (low probability) but may be life changing or catastrophic (high consequence) if they do occur. Examples of low-probability, high-consequence types of risks would be a prolonged severe drought in an area and, at the very extreme, an asteroid collision with Earth.

The less we understand about climate change, the larger the tail on the uncertainty distribution for climate change becomes. Greater extremes in climatic conditions imply greater societal consequences should those extremes occur. Accordingly, the greater the uncertainty is, the greater is the risk. For example, taking a commercial flight on Virgin Galactic's SpaceShipTwo spacecraft is considered to have a relatively high risk because of a lack of information about its reliability. Risk derives and increases from "not knowing." The efforts of those skeptical of climate-change projections to demonstrate limitations in the accuracy of climate-change analyses may cause climate scientists to change the priorities of their research, but the real effect of emphasizing limitations is to accentuate the level of uncertainty in future climatic conditions. Rather than justifying a lack of response to climate change, the emphasis on the uncertainty enlarges the risk and reinforces the responsibility for pursuing successful long-term mitigation policy. If those skeptical of climate change want to halt government initiatives in climate policy, they must act to reduce the uncertainty and demonstrate that the future climatic conditions will remain below dangerous levels. See Mastrandrea and Schneider (2004) for a discussion on the potential for dangerous climate change.

The consequence of adverse conditions is often framed in economic terms, such as the monetary value of a loss or the number of jobs lost. And because human behavior is so complex, there is even greater uncertainty in the prediction of future economic conditions than there is in the prediction of climate change alone. Yet, despite uncertainty about the future, cost-benefit analyses are conducted on a daily basis as aids for policy makers on issues of critical importance to the nation such as health care, social security, and defense. Similarly, individuals weigh the costs and benefits of taking certain actions, like purchasing insurance, to minimize risk for themselves and their families.

We use computer models to predict the near-term impacts of climate change on state-level economies from 2010 through 2050 because, in the absence of quantifying the near-term cost, the need to address climate change seems more remote and has a diluted sense of urgency. The forecasts from the economic models we applied will almost certainly be highly inaccurate, but this approach is the only coherent option available to inform current decision making. An imprecise prediction can be useful for comparing options to address a significant problem if we assume that such a prediction adequately defines the future relative to the choices to be made and, more importantly, represents a mutually agreed upon basis from which stakeholders can debate alternatives on common ground. This same reasoning applies to climate change. While better science could reduce some of the uncertainty, this reduction will occur after the time frame for effective contemporary policy action. The IPCC climate projections (IPCC 2007b), along with any limitations and nuanced caveats associated with their usage, represent the best and the most visible climate-science reference for timely framing of the national and international assessment of climate-change risk.

Analysis Design and Process

All analyses in this study correspond to the IPCC Special Report on Emissions Scenarios (SRES) A1B scenario. The IPCC considers the A1B to be a “balanced” scenario of economic growth with expanding renewable energy use. We have not addressed variation in CO_2 emissions or mitigation efforts to reduce emissions. Figure 1 presents an overview of the three major steps in our analysis process. We start with the existing ensemble of the IPCC Program for Climate Model Diagnosis and Intercomparison (PCMDI) computer runs, as depicted in the left-hand box. Specifically, we use the PCMDI data set representing the A1B scenario and containing the precipitation data (Leroy et al. 2008) produced by 53 runs of 24 of the currently most accepted climate models. We use results from these runs to create a proxy probability distribution of potential climatic futures for precipitation and temperature conditions between 2010 and 2050. The interrelated volatility of both temperature and precipitation are included as part of the ensemble results and used in the analysis, but it is principally the uncertainty in precipitation that permeates the analysis. Next, using the Sandia hydrological model, we map the temperature and precipitation data to the county and state levels in the continental United States to determine the availability of water for selected industries within each state, as represented in the middle box. During the third step, noted in the right-hand box, we employ the Regional Economic Models Incorporated (REMI) macroeconomic model (REMI 2009) to determine the cost of adjusting water usage to match water availability and calculate the macroeconomic impacts resulting from revisions in the comparative economic advantage of each state.

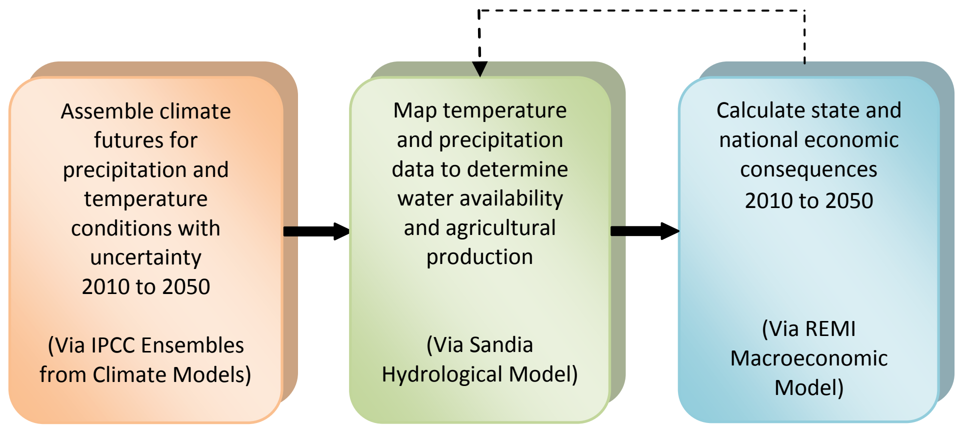

Figure 1. Analysis process.

We specifically analyze how consumers and industries respond (adjust) to the changing economic and physical conditions created by climate change. These responses attempt to lessen the economic impacts that would otherwise occur, and thus any integrated economic assessment needs to incorporate the actions that people take to compensate for negative events. The methodology underlying our analysis, which is implemented through the REMI model, is based on historical response patterns of industries and consumers—how real people in business and on a personal level have behaved in the past to changing economic conditions, policies, and events. We believe that using historical real-world behaviors is a more realistic approach than simulating the choices people make based on the commonly used economic assumptions of optimality and perfect knowledge of future conditions (Manne et al. 1995; Nordhaus and Yang 1996; Ackerman and Nadal 2004).

Economic studies often apply discount rates in their calculations of future costs either to (1) better accommodate adverse situations in the future based on the assumption that people will have greater access to resources in the future or (2) recognize that adversity in the present has a greater impact on human decision making than those threats that are still in a distant future. Essentially, a discount rate greater than zero percent (0%) places a lower value on money in the future than on money in the present. Because of the current controversy surrounding the use of different discount rates to assess the economic impacts of climate change, this study estimates the impacts using three discount rates: 0% per year, 1.5% per year, and 3.0% per year. The 1.5% rate roughly corresponds to the discount rate used in the Stern Review (Stern 2007). Other authors make a strong case for a 0% rate (Dasgupta et al. 1999; Posner 2004), whereas the 3% rate more closely conforms to historical orthodoxy (or conventional practice) in economic analyses (EPA 2000; OMB 2008). Because this study considers the costs to the economy from the perspective of those experiencing the impacts at a future time, and because there is no attempt to define mitigation or other policies in the present that would limit those impacts, we use the 0% discount rate as a point of neutrality. We thus are simply reporting the predicted future costs of climate change in the accounting sense. How the society determines the present values of those costs from a liability or preference perspective falls in the conventional realm of financial or social discounting—

appropriately using discount rates in excess of zero. Note that the values presented in some of the tables and figures reflect only the 0% discount rate. This approach has been taken to conserve space, and data on all three rates are generally available in our complete report.

We use precipitation, one of the most uncertain outputs from climate models, as the variable to characterize the primary uncertainty linking temperature and the frequency and intensity of future atmospheric conditions. Adjusting to the higher temperatures associated with climate change would not seem overwhelming if the United States had an inexhaustible supply of abundant clean energy and plenty of water. Air conditioning could, for example, be used within enclosed living spaces and work spaces for more months during the year than it is currently used, and the economic impacts would be manageable. At the other extreme, however, attempts to accommodate higher temperatures when there is no water available (for industry, people, or the energy sources that serve them) would produce severe economic impacts for the United States. We note that within the 40-year time frame addressed in this study, there is a diminishingly small probability that an impact on that scale would occur. However, to adequately assess the economic impacts of climate change, we need to consider the full range of possibilities of precipitation—from plenty of water to no water.

Analysis Results

Below we present some significant results from the analysis, including impacts on the U.S. GDP, employment, and industry. The analysis uses the concept of exceedance probabilities to describe the various levels of uncertainty. To generate the results, we simulate future conditions using the computer models and process noted in Figure 1 across the full range of exceedance probabilities. The range of exceedance probabilities extends from 100% (the maximum realizable precipitation) to 0% (the minimum realizable precipitation). An exceedance probability measures the likelihood (or chance) a particular consequence of climate change will exceed (be greater than) the value reported for that probability. For example, a 25% exceedance probability means there is an estimated 25% chance an impact will exceed the indicated value (for example, in dollars of lost GDP) associated with that percentage of impact. The body of the full report for this study (Backus et al. 2010) provides a detailed discussion of the analysis process and a thorough explanation of the results.

Figure 2 shows the estimated reduction in the U.S. GDP over the period 2010 to 2050 at various levels of uncertainty based on calculations for a 0% discount rate. The values on the solid red line represent the total cost over the 40-year period. These values are considered the “best estimates” in our analysis. The extreme risk is the possibility of losing most of the economy.

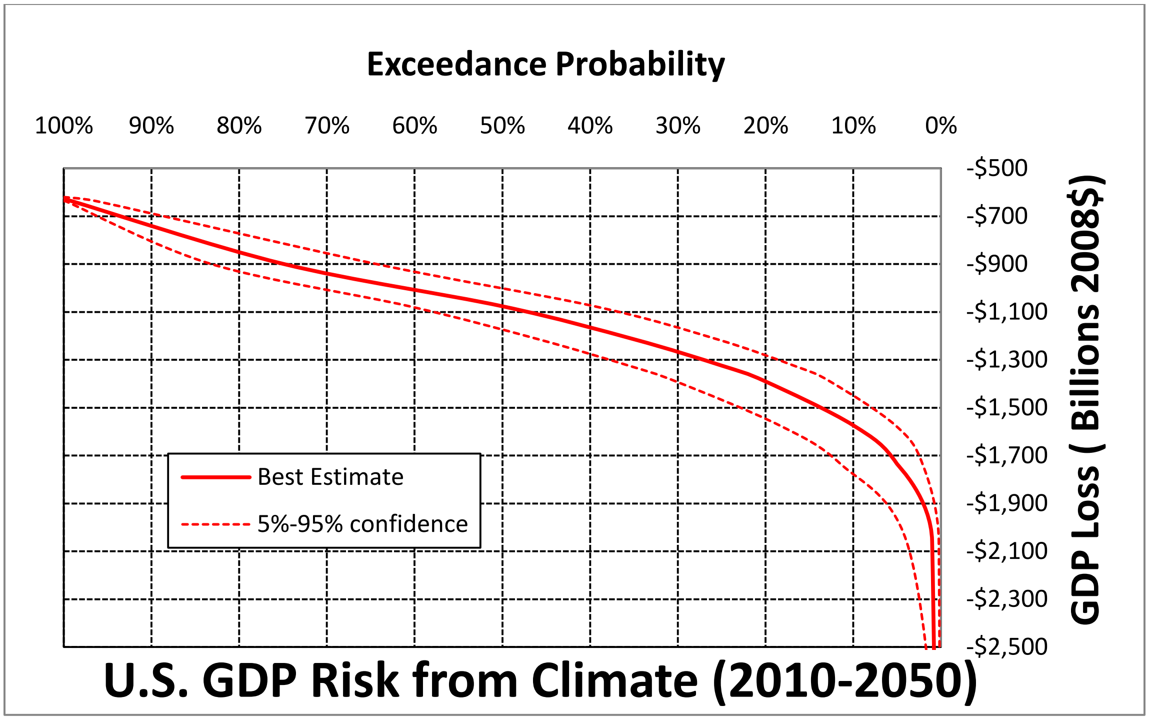

Figure 2. U.S. GDP impacts (2010–2050) for a 0% discount rate.

The dashed lines in Figure 2 are important because they characterize our knowledge of the uncertainty of the best-estimate values to within 90% confidence, reflecting a lower and an upper limit on the uncertainty, from 5% (lower dashed line) to 95% (upper dashed line). Effectively, the dashed lines represent the uncertainty of the best-estimate exceedance-probability values. In other words, for any given point on the best-estimate line, it is highly likely that the impact will lie somewhere between the corresponding values on the enveloping dashed lines.

Our study generates U.S. GDP impacts in 2050 that are comparable to the impacts determined in the Stern Review (Stern 2007) and in its associated studies (Ackerman et al. 2009). The Stern Review, however, includes noneconomic losses that are not contained in our study. Mendelsohn et al. (2000) considered global impacts that include the United States as a studied region, but these researchers derived a positive impact on the GDP within the 2050 time frame. Previous analyses, including the Stern Review, have relatively simple damage functions that primarily capture only the direct impacts. The use of combined industry-level econometric and input-output methods, as applied in our study, highlights the effects of economic multipliers that capture added indirect impacts as damages flow through the economy to suppliers and employees. Importantly, the indirect impacts are typically two to five times larger than the direct impacts.

Table 1 shows the values associated with the "best estimate" line in Figure 2 above at the three discount rates. Also included for each rate is the value for the summary (or total) risk. The total risk of climate change is approximately the sum of the consequence associated with each of the exceedance probabilities, from 100% to 0%, for all events considered in the study. These probabilities cover the full range of uncertainty. Note that the analysis only considers the impact of reduced precipitation. Even if there was abundant water on average, forecasts of climate change still have a trend toward reduced precipitation that includes both drought and flood conditions. We do not include the cost of flooding in the assessment. Flooding is easier to accommodate than drought, with lesser costs, and is the subject of other studies (McKinsey 2009).

Table 1. GDP Impacts and Summary Risk (2010–2050)

Change in National GDP (Billions of 2008$)										
Discount rate	Exceedance Probability									Summary Risk
	99%	75%	50%	35%	25%	20%	10%	5%	1%	
0.0%	-$638.5	-$899.4	-$1,076.8	-$1,214.5	-$1,324.6	-$1,390.8	-$1,573.9	-$1,735.4	-$2,058.5	-$1,204.8
1.5%	-$432.0	-$595.9	-$707.4	-$795.0	-$865.1	-$907.2	-$1,024.6	-$1,129.3	-$1,340.2	-$790.3
3.0%	-$301.9	-$407.4	-$479.4	-$536.6	-$582.4	-$610.0	-$687.2	-$756.8	-$898.2	-$534.5

The total estimated (average) loss to the GDP, the summary risk, due to climate change is approximately $1.2 trillion through 2050 at a 0% discount rate.[1] For the same discount rate, the forecast *annual* loss to the GDP by 2050 at the 50% exceedance probability could exceed $60 billion per year and could exceed $130 billion per year at the 1% exceedance probability. The summary loss is 0.2% of the cumulative GDP. Casting a $1.2 trillion impact, as we have calculated in this study for the loss in the GDP at a 0% discount rate, in the context of a relatively small percentage of total economic activity over the time period distorts the actual implications for those who locally experience the loss. Further, when taken in isolation, the value can give a false comfort in disregarding post-2050 impacts. The impacts increase rapidly in the end years of our analysis. If we had continued our analyses further into the future, the reported cost would be much larger than the 2050 cost we have estimated.

Figure 3 shows the impacts on employment measured in lost labor years from 2010 to 2050 at various levels of uncertainty for a 0% discount rate. A labor year is equivalent to having one full-time job for a year.

[1] All costs are presented in 2008 U.S. dollars.

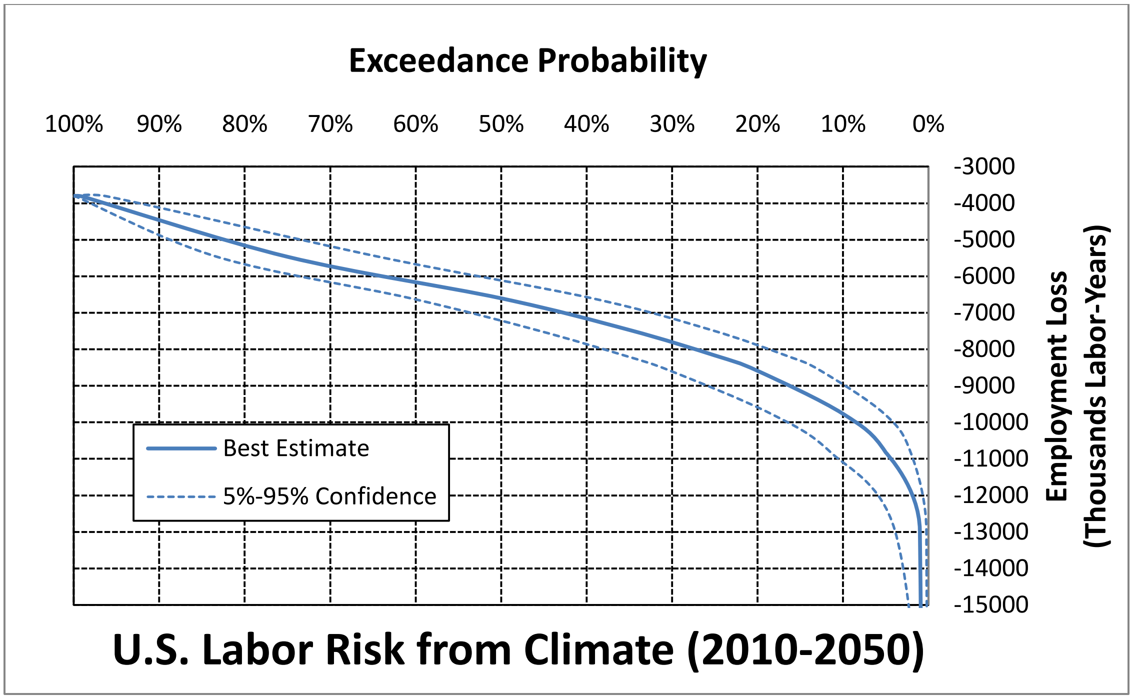

Figure 3. U.S. employment impacts (2010–2050) for a 0% discount rate.

Table 2 shows the employment-loss values associated with the best-estimate (solid blue) line in Figure 3 at a 0% discount rate. The total risk is nearly 7 million lost labor years due to climate change. The annual job loss by 2050 at the 50% exceedance probability is nearly 320,000 full-time jobs. At the 1% exceedance probability by 2050, the annual job loss rises to nearly 700,000 full-time jobs. Note that these latter job statistics have been taken from the data and are not included in Figure 3.

Table 2. Employment Impacts and Summary Risk (2010–2050)

Change in Employment (Thousands)									
Exceedance Probability									Summary Risk
99%	75%	50%	35%	25%	20%	10%	5%	1%	
-3,815	-5,463	-6,601	-7,468	-8,166	-8,587	-9,764	-10,819	-12,961	-6,863

When water availability limits economic production within the United States, one alternative is to import the lost commodities, especially food. Figure 4 shows the impact of climate change on the U.S. trade balance for the 40-year period. This study is U.S. centric and assumes that the rest of the world is unaffected by climate change and can accommodate additional U.S. demands for imports. Climate change may improve agriculture and the core industries of Canada and Russia, but a recent study by Nelson et al. (2009) indicates the costs of agricultural products will rise throughout the rest of the world. Figure 4 is assuredly inaccurate, but it does exemplify how climate change can affect trade balances.

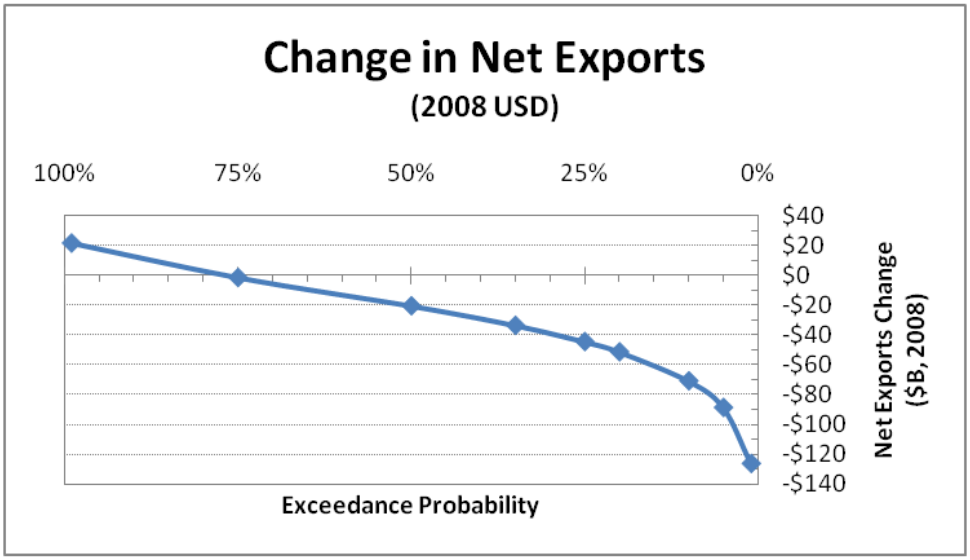

Figure 4. Trade-balance impacts (2010–2050).

The downward trend in Figure 4 indicates that the United States has to import increasing amounts of goods and services, most of which is food. For example, there is a 50% chance that the United States would need to import more than $20 billion in goods and services as a result of climate change over the 40-year period. Assuming that the rest of the world can accommodate increased U.S. demands, the annual trade balance by 2050 increases by an additional $0.5 billion per year at the 50% exceedance probability and by an additional $8 billion per year at the 1% exceedance probability.

Because climate change is predicted to increase the volatility of temperature and precipitation, the estimated impacts over time also show volatility. Figure 5 illustrates the annual impacts on the national GDP as a function of varying exceedance probabilities for reduced water availability, as stated in the legend of the graph. As shown, greater losses are evident in succeeding years, and the lower exceedance probabilities are associated with greater impacts on the GDP.

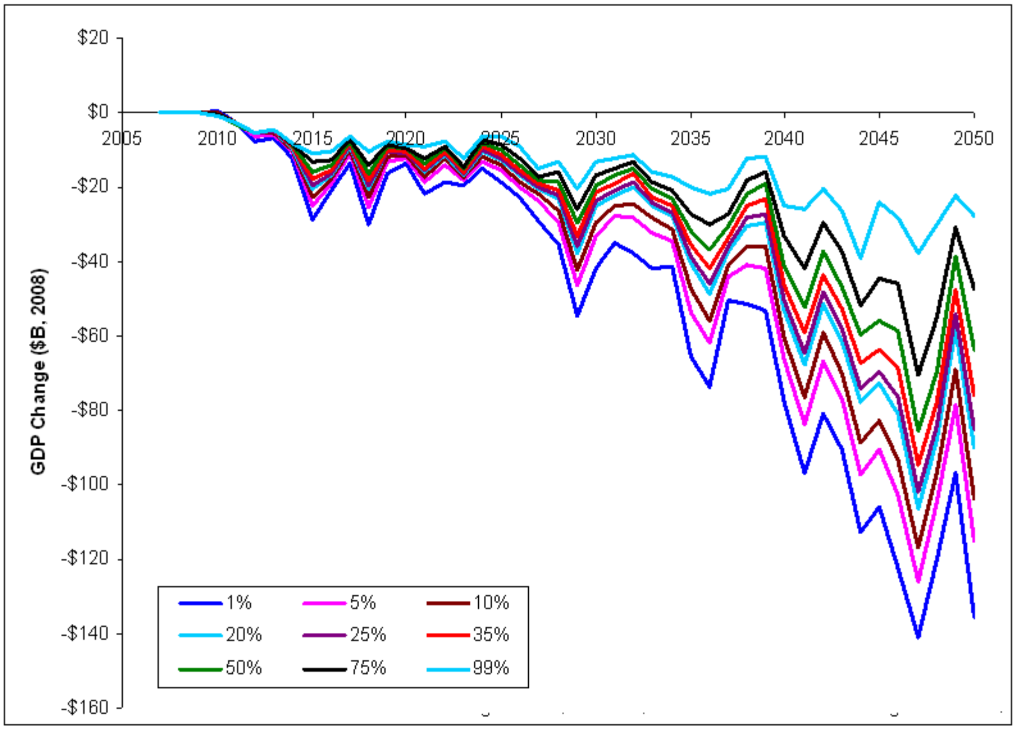

Figure 5. Annual U.S. GDP impacts from climate change.

Examining the estimated impacts for 2015 in Figure 5, the loss at the 99% exceedance probability is on the order of $10 billion, whereas at the 1% exceedance probability the loss is almost $30 billion. However, the same pattern of volatility represented by the climate is used in all the simulations run at the different exceedance probabilities to produce our results. Had a more challenging and increasingly volatile pattern of interannual climatic conditions been used, the economic impacts would be larger and more problematic (due to their more extreme volatility) than the summary monetary impacts of this study indicate.

The variation in employment depicted in Figure 6 shows a similar pattern to the variation in the GDP seen in Figure 5, though there are differences. These differences reflect diversity in the amount of employment demanded per unit of output across industries. Effectively, some industries are more labor intensive than others and experience a greater loss of jobs. For comparable years, say, 2015 and 2028, the losses (dips) portrayed across the two figures are deeper for employment than for the GDP. Certain labor-intensive industries are being affected more than others in these two particular years. In later years, such as in 2045, the patterns of employment and GDP are closer, meaning that more industries are experiencing similar losses in employment. This suggests that impacts of climate change are spreading throughout the entire economy by this time.

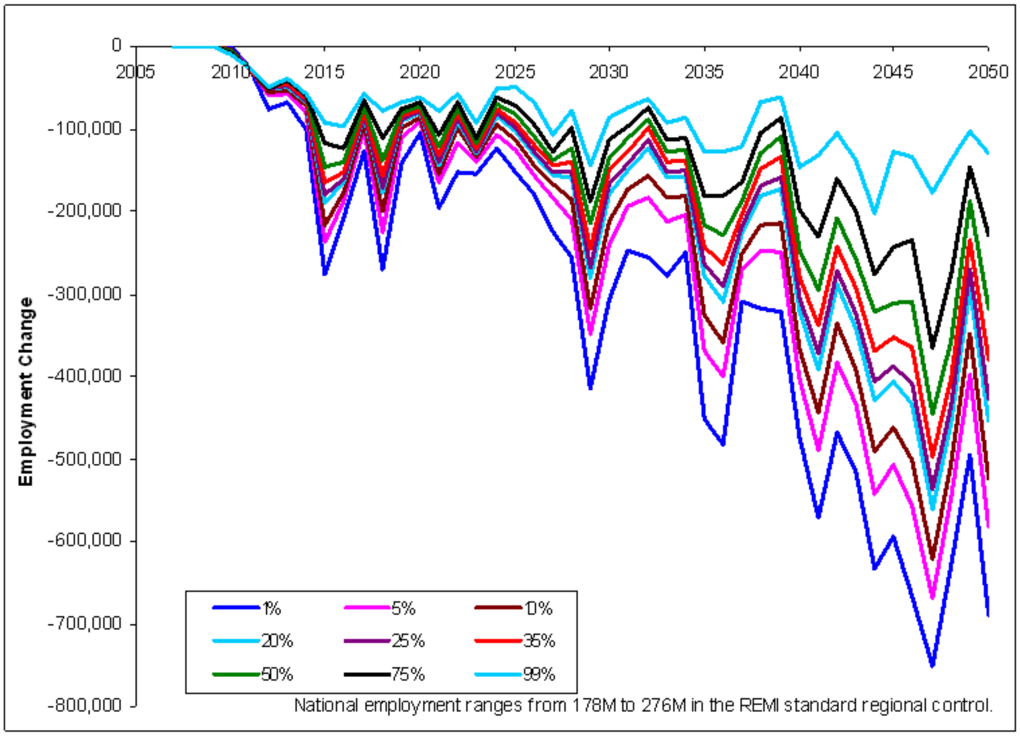

Figure 6. Annual U.S. employment impacts from climate change.

Figure 7 and Figure 8 present the summary-risk losses for the GDP and employment, respectively, as a geographic distribution over individual states. This information conveys the impacts of climate change with which state-level governments and business are likely to contend. The color-coded legend, consisting of ranges of percent impacts, explains how to interpret the figures. Note that it is the percentage of impact, not the amount of impact, that determines the color assigned to each state. Thus, the colors represent the relative nature of the impacts. In Figure 7, only six states, those colored green, experience gains in the GDP as a result of climate change. The GDP losses exhibited by all the other states indicate what it would be worth to avoid climate change even within short-term planning horizons, that is, if mitigation is possible. In Texas, for example, there is a risk of losing about $137 billion over the 40-year period, representing a negative impact to the state's economy of between 0.1% and 0.2%. The employment losses in Figure 8 indicate the pressures policy makers are likely to experience to minimize the impacts of climate change.

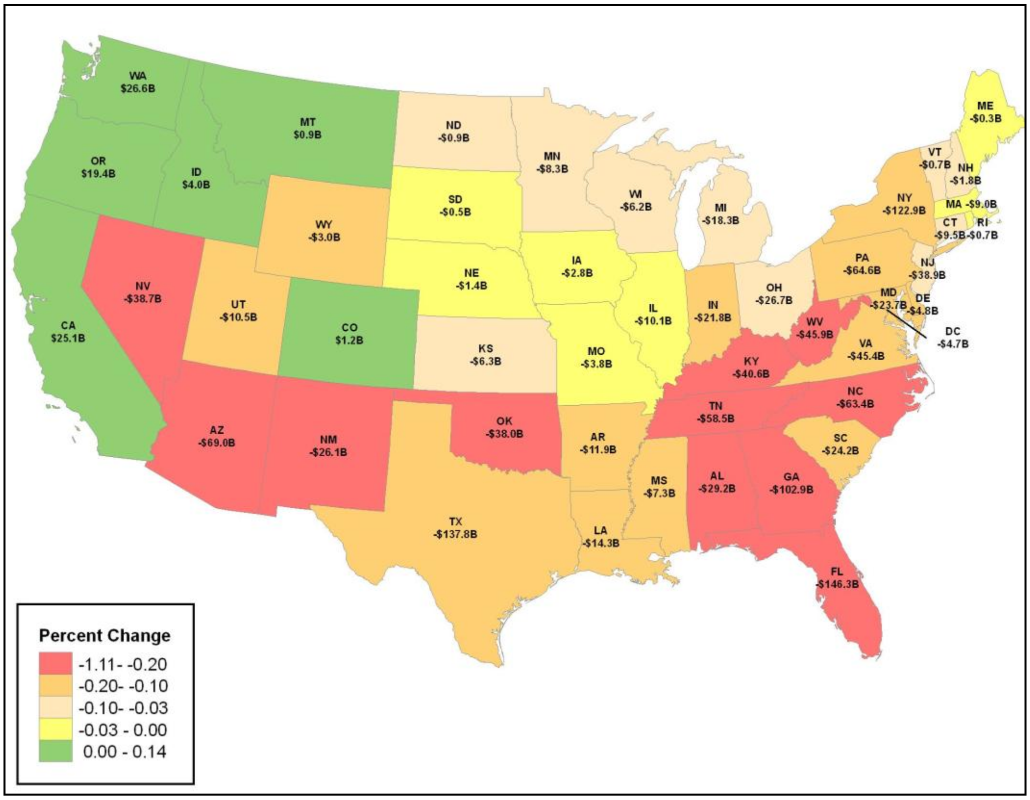

Figure 7. GDP risk (2010–2050) in billions of dollars at a 0% discount rate.

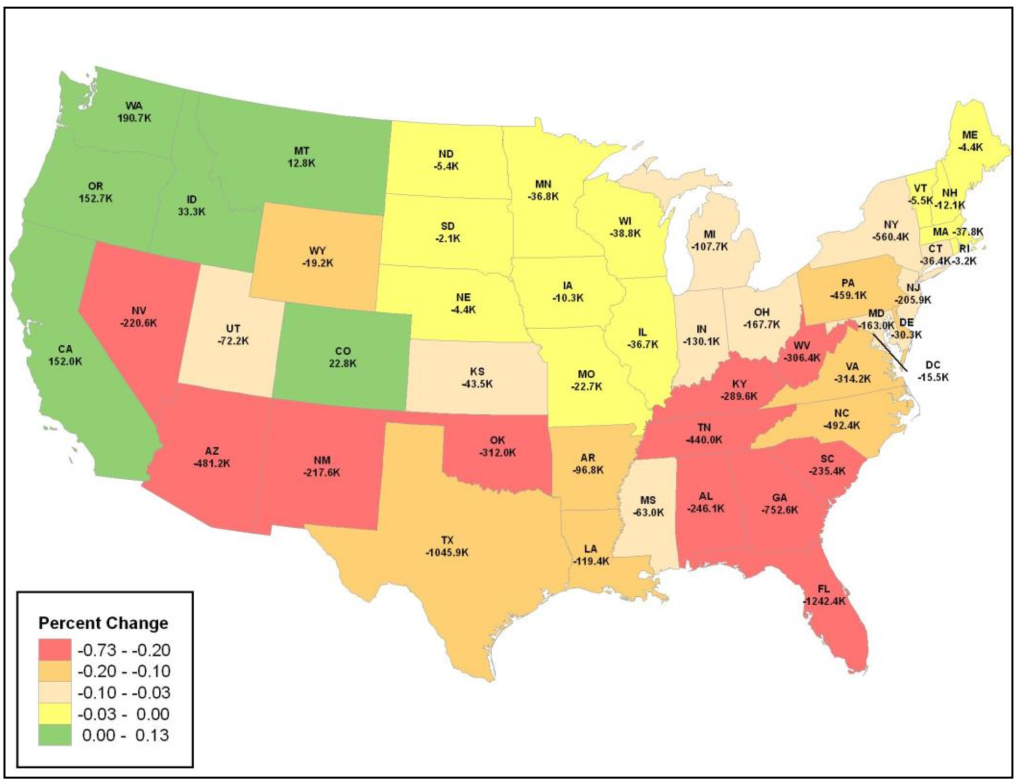

Figure 8. Employment risk (2010–2050) in thousands of labor years.

A more detailed example may help in understanding the analysis results. Despite suffering relatively greater drought conditions on average relative to the rest of the nation, California shows improvements by 2050 because its economic impacts are estimated to become relatively less than those of other states. Populations from other affected states migrate to California and stimulate its economy. This comparative advantage occurs because some states do not have much flexibility in dealing with water shortages, for example, because they have little agricultural irrigation from which water can be diverted. By and large, those states that already suffer water constraints (often due to irrigation loads combined with urban growth in arid regions) have processes in place to adjust to changes in water balances. Through the use of water purchases, irrigation water can act as a buffer against water shortages in other parts of the economy. Because the value added to the economy from certain types of industry is large compared with that for food production, growth in high-value-added industry can compensate for reduced agricultural production. In the near term and at higher exceedance probabilities, California does incur largely negative impacts. Note that the impacts for many states change sign over time, that is, many states alternately experience gains (positive sign) and losses (negative sign).

The Pacific Northwest states show improvement with climate change due to expected increased precipitation and population growth through migration. It is possible, however, that the damage to this region from climate change may be understated. Because this analysis is limited to the annual resolution of precipitation levels (other than capturing the monthly variation for agricultural assessments), we do not capture the impact of seasonal phenomena such as snow. In the Pacific Northwest, the dam system is not designed to accommodate significant changes in the timing of when and how fast snow melts. In the Pacific Northwest, the snow itself acts as a water-storage system and under conditions of warmer temperatures, the increased river flow from melting snow could not be effectively stored behind the dams nor could the additional water be efficiently used in producing electricity. Consequently, the positive impacts shown could be an artifact of our assumptions. On the other hand, migration to the Pacific Northwest may provide positive impacts even if hydropower declines.

Expected urban population growth and an expanding economy in the eastern United States will stress existing water supplies in the future even in the absence of climate change. Consequently, the Northeast and the Southeast experience negative impacts from climate change, even though reductions in long-term precipitation may be minimal. In general, a decreasing exceedance probability (from 50% to 1%) implies that reduced precipitation (i.e., drought) is moving north and east at a continental level, causing more-severe reductions in precipitation in areas that did not noticeably experience reduced precipitation at the larger exceedance probabilities (> 50%). Thus, areas such as Colorado go from having adequate water and benefits in high-exceedance-probability simulations to experiencing losses from reduced water availability in the low-exceedance-probability simulations. Other than in the Pacific Northwest, water availability decreases over time with climate change. Table 3 gives the numerical values of GDP impacts from 2010 to 2050 with all three discount rates. Also included in the table are the impacts on employment (2010–2050) and from population migration (shown only for the year 2050).

Employment changes and population migration represent changes in material conditions, as opposed to a change in monetary status for GDP impacts, and thus are not discounted.

Table 3. National and State-Level Risk (2010–2050)

Summary of Climate Impacts (2010-2050)

Region	Change in GDP (Billions of 2008$)			Change in Empl. (Thous. Labor-Years)	Change in Pop. (Thous. People)	Region	Change in GDP (Billions of 2008$)			Change in Empl. (Thous. Labor-Years)	Change in Pop. (Thous. People)
	Discount Rates						Discount Rates				
	0.0%	1.5%	3.0%				0.0%	1.5%	3.0%		
United States	**-$1,204.8**	**-$790.3**	**-$534.5**	**-6,862.7**	**0.0**	Montana	$0.9	$0.6	$0.4	12.8	2.9
Alabama	-$29.2	-$18.9	-$12.6	-246.1	-10.8	Nebraska	-$1.4	-$0.8	-$0.4	-4.4	2.5
Arizona	-$69.0	-$45.8	-$31.2	-481.2	-14.8	Nevada	-$38.7	-$26.2	-$18.1	-220.6	-2.8
Arkansas	-$11.9	-$7.6	-$5.0	-96.8	-2.4	New Hampshire	-$1.8	-$1.2	-$0.8	-12.1	2.6
California	$25.1	$16.6	$11.5	152.0	115.7	New Jersey	-$38.9	-$25.8	-$17.6	-205.9	3.6
Colorado	$1.2	$0.4	$0.0	22.8	15.3	New Mexico	-$26.1	-$17.9	-$12.7	-217.6	-8.3
Connecticut	-$9.5	-$6.3	-$4.3	-36.4	4.7	New York	-$122.9	-$80.5	-$54.4	-560.4	7.2
Delaware	-$4.8	-$3.1	-$2.1	-30.3	0.0	North Carolina	-$63.4	-$41.6	-$28.1	-492.4	-19.8
D.C.	-$4.7	-$3.1	-$2.1	-15.5	0.5	North Dakota	-$0.9	-$0.5	-$0.3	-5.4	0.8
Florida	-$146.3	-$97.5	-$66.9	-1,242.4	-55.5	Ohio	-$26.7	-$16.1	-$10.0	-167.7	1.7
Georgia	-$102.9	-$67.7	-$45.9	-752.6	-40.0	Oklahoma	-$38.0	-$25.2	-$17.2	-312.0	-15.3
Idaho	$4.0	$2.5	$1.6	33.3	6.9	Oregon	$19.4	$12.5	$8.3	152.7	20.5
Illinois	-$10.1	-$5.1	-$2.5	-36.7	15.7	Pennsylvania	-$64.6	-$42.4	-$28.7	-459.1	-7.7
Indiana	-$21.8	-$12.9	-$7.8	-130.1	-4.0	Rhode Island	-$0.7	-$0.5	-$0.3	-3.2	1.8
Iowa	-$2.8	-$1.4	-$0.6	-10.3	3.1	South Carolina	-$24.2	-$15.9	-$10.7	-235.4	-10.2
Kansas	-$6.3	-$4.1	-$2.7	-43.5	2.3	South Dakota	-$0.5	-$0.3	-$0.2	-2.1	1.3
Kentucky	-$40.6	-$24.9	-$15.6	-289.6	-21.6	Tennessee	-$58.5	-$37.3	-$24.4	-440.0	-23.0
Louisiana	-$14.3	-$9.4	-$6.3	-119.4	-0.9	Texas	-$137.8	-$91.0	-$61.9	-1,045.9	-28.5
Maine	-$0.3	-$0.2	-$0.2	-4.4	2.5	Utah	-$10.5	-$6.9	-$4.6	-72.2	2.2
Maryland	-$23.7	-$15.6	-$10.5	-163.0	0.1	Vermont	-$0.7	-$0.4	-$0.3	-5.5	1.0
Massachusetts	-$9.0	-$5.9	-$4.1	-37.8	12.9	Virginia	-$45.4	-$29.7	-$20.1	-314.2	-5.9
Michigan	-$18.3	-$11.2	-$7.1	-107.7	7.1	Washington	$26.6	$17.0	$11.2	190.7	29.5
Minnesota	-$8.3	-$4.9	-$2.9	-36.8	7.6	West Virginia	-$45.9	-$27.7	-$17.0	-306.4	-34.5
Mississippi	-$7.3	-$4.7	-$3.1	-63.0	-0.8	Wisconsin	-$6.2	-$3.7	-$2.2	-38.8	6.6
Missouri	-$3.8	-$2.2	-$1.3	-22.7	8.3	Wyoming	-$3.0	-$1.9	-$1.3	-19.2	-0.5

Migration across states is often based on comparative advantage. Even if a given state economy is having difficulties, it may be having less difficulty than other states. If we look at the state of New York, we see that the summary impact of climate change from 2010 to 2050 is a loss of $122 billion with a 0% discount rate. This loss is reduced to $81 billion with a 1.5% discount rate and to $54 billion with a 3% discount rate. The drop is dramatic because much of the impact occurs in the later years. Note that the reduced economic activity does reduce employment by 560,000 labor years by 2050 even though the population has risen by 7,200 people due to in-migration from the even-more-affected surrounding states. This means that the unemployment in New York is increasing even more than the drop in economic activity would indicate. If the other states were less affected by climate change, New York would have experienced large out-migration.

Table 4 presents our estimated risks to selected industries from climate-change uncertainty. The results shown are presented in terms of contribution to the GDP. The impact on sales and revenue would be larger, varying between less than 1.5 times larger for retail sales to more than 3.0 times larger for manufacturing. Due to construction, especially of power plants to augment lost hydroelectric capacity, positive effects in terms of economic value are experienced by utilities, electric equipment, and other manufacturing. Construction experiences a decline because of the overall national decline in economic growth. Transportation (not shown) sees a net zero economic impact, despite an overall reduction in economic activity, because of the added need for interstate trade, especially for food. Many professional services, including medical, suffer a decline because unemployment constrains additional spending. Agriculture-dependent industries, such as the chemical industry, encounter disproportional declines. Like agriculture, climate change strongly affects the mining industry because of the mining industry's relatively rigid dependence on water.

Table 4. Selected Industry Risks (2010–2050)

Selected National-Level Industry Impacts 2010–2050 (0% Discount Rate, Billions 2008$)				
Oil and gas extraction	-$9.4		Food manufacturing	-$82.3
Mining (except oil and gas)	-$86.3		Beverage and tobacco product manufacturing	-$29.4
Support activities for mining	-$7.3		Chemical manufacturing	-$18.2
Utilities	$13.6		Wholesale trade	-$45.3
Construction	-$30.8		Retail trade	-$127.2
Wood product manufacturing	-$1.1		Broadcasting, Telecommunications	-$28.1
Nonmetallic mineral product manufacturing	-$3.3		Monetary authorities, funds, trusts, financials	-$34.1
Primary metal manufacturing	-$2.4		Securities, commodity contracts, investments	-$39.9
Fabricated metal product manufacturing	-$3.7		Real estate	-$38.2
Machinery manufacturing	-$4.2		Professional and technical services	-$41.4
Computer and electronic product mfg.	-$10.3		Administrative and support services	-$21.2
Electrical equipment and appliance mfg.	$1.4		Ambulatory health care services	-$66.8
Motor vehicles, bodies & trailers, parts mfg.	-$8.8		Food services and drinking places	-$19.9

Conclusions

This study focuses on the uncertainty and volatility of climate change rather than on the development of a predictable and smooth transition to expected future conditions. The uncertainty associated with climate change, combined with the consequences it entails, defines the risk from climate change. Further, the volatility of conditions over time means the risk assessment needed to go beyond a static analysis and address the dynamics of the impacts and the response. The uncertainty within the results of the ensemble of IPCC data sets represents an accepted notion of climate uncertainty. These results do not, however, represent a formal quantification of uncertainty because they do not, for example, address threshold conditions where self-reinforcing phenomena lead to as-yet unrecognized threats, nor do they contain detail on phenomena, such as cloud formation, that could change our understanding of climate dynamics. The formal characterization of climate uncertainty for refining the risk assessment is one of the next steps in improving the analysis presented here.

The detailed, time-dependent approach used in the analysis shows the additional early consequences of the volatility in climate change. The impacts across 70 industries and 48 states demonstrate the interrelationships that produce consequences different from those consequences that would be indicated by the analysis of individual states or economic sectors in isolation. To date, this is the first study to address the interactive effects of climate change across the U.S. states and to deal explicitly with the problems of interstate population migration as a consequence of climate change.

Our risk assessment only considers the loss in the absence of mitigation or any other climate policy. The value of the loss, on the order of a trillion (2008) dollars for the United States at a 0% discount rate, can be interpreted as an upper limit on how much society could be willing to pay for a successful mitigation of climate change, even over the near term. We feel the risk-informed approach used in this work relates physical climate science to the societal consequences and thus directly helps inform policy debate. The integrated process of (1) recognizing uncertainty in climate-change forecasts, (2) transforming climate-change phenomena into physical impacts that affect economic and societal processes, and (3) converting those physical impacts to time-dependent changes in economic and societal conditions provides the end-to-end assessment capability recommended by the Obama Administration (Holdren 2009). By knowing what aspects of climate change have the most severe human consequences, this type of analysis can also guide and prioritize the scientific research to better quantify the most critical phenomena. We want to reemphasize that the methods of this study reveal how compelling risk derives from uncertainty, not certainty. The greater the uncertainty, the greater the risk. *It is the uncertainty associated with climate change that validates the need to act protectively and proactively.*

A fundamental shortcoming of this study is its focus on the United States. Although understanding the U.S. risks from climate change is a necessary foundation for informed policy debate (GAO 2009), climate change is global, and global turmoil affects the United States (CNA 2007). Our analysis assumes that the rest of the world fully accommodates climate change and that it can absorb a volatile U.S. export-and-import situation. The next phase of this work on the impact of climate change will include the characterized risks to the rest of the world and the implications of these risks on those for the United States. Those efforts must also recognize the pressures climate change can exert on geopolitical stability and on international socioeconomic relationships.

Appropriate to our purpose, we used the IPCC AR4 ensemble as the proxy for the uncertainty in climate change. As climate science advances and improved estimates of uncertainty become available, future risk assessments should include the then best understanding of the uncertainty. The methods for quantifying uncertainty in combined physical and societal simulations over time and across geographic regions require further development. Moreover, confidence in the results from physical and socioeconomic models can only occur through formal validation and verification (V&V) efforts. We are extending our long-standing research on infrastructure surety, systems reliability, probabilistic risk assessment, and V&V to improve statistically meaningful estimates of climate-change uncertainty.

In the conventional discourse on the impacts of climate change, mitigation denotes the (1) reduction in anthropogenic and natural greenhouse gas (GHG) emissions, (2) capture and storage of GHG from industrial processes such as geological sequestering or directly from the atmosphere such as by reforestation, or (3) alleviation of the effects of increased GHG concentrations through engineered efforts such as geoengineering.

Conventional adaptation denotes efforts to maintain the status quo socioeconomic conditions, to the extent possible, in the face of expected changes in environmental conditions such as through drought-resistant crops and seawalls. Because we devote our analysis to the impacts of climate change in the absence of policy initiatives, we did not consider the reliability or risk assessment of mitigation and adaptation policies. The methods developed in our study, however, are equally applicable to the risk assessment of policies. The larger challenge lies not in the technical difficulties of such an analysis but rather in the communication of the risk and uncertainty in a manner that connects to the vital concerns of the policy makers.

We have only systematically addressed the one dimension of precipitation uncertainty. For instance, we ignored disease vectors and extreme weather conditions like storms. We did not consider uncertainty in migration and trade dynamics. More generally, we did not confront the combined uncertainty across the many other dimensions of climate-change uncertainty that have consequences for society. Modern society depends on a complex network of infrastructure with its interdependencies, vulnerabilities, and potential for cascading failure modes. Through the National Infrastructure Simulation and Analysis Center (NISAC) program with the Department of Homeland Security, housed at Sandia National Laboratories and Los Alamos National Laboratory, many of the capabilities needed to extend this study for considering those added dimensions of risk already exist.

To sum up, despite the room for improvement, we feel the current study does establish a process for improved and more-meaningful risk assessments of climate change than is currently present in the literature. More importantly, the study offers a systematic foundation for policy debate. Uncertainty induces debate. In the presence of absolute certainty, there are no facts left to debate. This analysis used the current understanding of climate-change uncertainty to unambiguously quantify risk. The future evolution of policy on climate change will rest on refinements of the methods reported here and on continuing improvements in the quantification of uncertainty for both climate change and its consequences.

References

Ackerman, F., and A. Nadal. (2004). *The Flawed Foundations of General Equilibrium*: *Critical Essays on Economic Theory*. London: Routledge.

Ackerman, F., E. A. Stanton, C. Hope, and S. Alberth. (2009). “Did the Stern Review Underestimate US and Global Climate Damages?” *Energy Policy* 37, no. 7: 2717–2721.

Allen, M. R., and W. J. Ingram. (2002). “Constraints on Future Changes in Climate and the Hydrological Cycle.” *Nature* 419: 224–232.

Backus, G., T. Lowry, D. Warren, M. Ehlen, G. Klise, V. Loose, L. Malczynski, R. Reinert, K. Stamber, V. Tidwell, V. Vargas, and A. Zagonel. *Assessing the Near-Term Risk of Climate Uncertainty: Interdependencies among U.S. States*. (2010).

SAND 2010-2052. Albuquerque, NM: Sandia National Laboratories. https://cfwebprod.sandia.gov/cfdocs/CCIM/docs/Climate_Risk_Assessment.pdf.

CNA (2007). "Testimony Before the U.S. House of Representatives Subcommittee on Investigations and Oversight, Committee on Science and Technology." [To the CNA Corporation Report *National Security and the Threat of Climate Change*]. http://www.cna.org/nationalsecurity/climate/testimony/070927.aspx (accessed on February 2, 2010). [See the full report at http://securityandclimate.cna.org/report/SecurityandClimate_Final.pdf.]

Dasgupta, P., K. G. Mäler, and S. Barrett. (1999). "Intergenerational Equity, Social Discount Rates, and Global Warming." In *Discounting and Intergenerational Equity*, edited by P. R. Portney and J. P. Weyant. Washington, DC: Resources for the Future.

Disraeli, B. (1891). *Henrietta Temple: A Love Story*. New Edition. London: Longmans, Green, and Co (Book II, Chap. IV: 72). http://books.google.com/books?id=tWBLAAAAIAAJ&printsec=frontcover&dq=%22Henrietta+Temple%22&source=bl&ots=6UGsvdRsrJ&sig=5XaujDXMDDxv7NwKe3Jds6lbMhY&hl=en&ei=XihrS5PrFJO0sgOIqYCbAw&sa=X&oi=book_result&ct=result&resnum=3&ved=0CBAQ6AEwAg#v=onepage&q=seldom%20happens&f=false (accessed on April 6, 2010).

EPA (U. S. Environmental Protection Agency). (2000). *Guidelines for Preparing Economic Analysis*. EPA 240-R-00-003. Washington DC: U.S. Environmental Protection Agency.

GAO (U.S. Government Accountability Office). (2009). *Climate Change Adaptation: Strategic Federal Planning Could Help Government Officials Make More Informed Decisions*. GAO-10-113. Washington, DC: U.S. Government Accountability Office. http://www.gao.gov/new.items/d10113.pdf (accessed on February 2, 2010).

Hegerl, G. C., F. W. Zwiers, P. Braconnot, N. P. Gillett, Y. Luo, J. A. Marengo Orsini, N. Nicholls, J. E. Penner, and P.A. Stott. (2007). "Understanding and Attributing Climate Change." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. Cambridge, UK: Cambridge University Press.

Holdren, J. P. (2009). Testimony of John P. Holdren Assistant to the President for Science and Technology and Director of the Office of Science and Technology Policy, Executive Office of the President of the United States, before The Select Committee on Energy Independence and Global Warming U.S. House of Representatives on The Administration's View of the State of the Climate, December 2, 2009. http://globalwarming.house.gov/tools/3q08materials/files/holdren.pdf (accessed on February 2, 2010).

IPCC. (2007a). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson. Cambridge, UK: Cambridge University Press.

IPCC. (2007b). *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. Cambridge, UK: Cambridge University Press.

Keller K., G. Yohe, and M. Schlesinger. (2008). "Managing the Risks of Climate Thresholds: Uncertainties and Information Needs." *Climatic Change* 91, nos. 1–2: 5–10.

Leroy, S., J. A. Dykema, and J. G. Anderson. (2008). "Scalar Prediction in Climate Using Data and Model." Harvard School of Engineering and Applied Science. Harvard University. Submitted to *J. Climate*. https://wiki.ucar.edu/download/attachments/20382519/Leroyetal_JClimate2009a_submission.pdf (accessed on 12 March 2010).

Manne, A., R. Mendelsohn, and R. Richels. (1995). "MERGE : A Model for Evaluating Regional and Global Effects of GHG Reduction Policies." *Energy Policy* 23, no. 1: 17–34.

Mastrandrea, M. D., and S. H. Schneider. (2004). "Probabilistic Integrated Assessment of 'Dangerous' Climate Change." *Science* 304: 571–575.

McKinsey. (2009). *Shaping Climate-resilient Development. A Framework for Decision-making*. Report of the Economics of Adaptation Working Group. http://ec.europa.eu/development/icenter/repository/ECA_Shaping_Climate_Resilent_Development.pdf (accessed on February 4, 2010).

Mendelsohn, R. O., W. Morrison, M. E. Schlesinger, and N. G. Andronova. (2000). "Country-Specific Market Impacts of Climate Change." *Climatic Change* 45, nos. 3–4: 553–569.

NAST (National Assessment Synthesis Team). (2001). *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*. Cambridge, UK: Cambridge University Press. http://www.usgcrp.gov/usgcrp/Library/nationalassessment/ (accessed on November 4, 2009).

Nelson, G. C., M. W. Rosegrant, J. Koo, R. Robertson, T. Sulser, T. Zhu, C. Ringler, S. Msangi, A. Palazzo, M. Batka, M. Magalhaes, R. Valmonte-Santos, M. Ewing, and D. Lee. (2009). *Climate Change: Impact on Agriculture and Costs of Adaptation*. Washington, DC: International Food Policy Research Institute.

http://www.ifpri.org/publication/climate-change-impact-agriculture-and-costs-adaptation (accessed on November 13, 2009).

Nordhaus, W. D., and Z. Yang. (1996). "RICE: A Regional Dynamic General Equilibrium Model of Optimal Climate-Change Policy." *American Economic Review* 86, no. 4: 741–765.

OMB (Office of Management and Budget). (2008). *2009 Discount Rates for OMB Circular No. A-94*. Washington DC: Office of Management and Budget. http://www.whitehouse.gov/omb/assets/omb/memoranda/fy2009/m09-07.pdf (accessed on February 2, 2010).

Posner, R. (2004). *Risk and Response*. New York: Oxford University Press.

REMI. (2009). REMI PI+ v.1.1, REMI TranSight v3.1 Model Equations, Regional Economic Models, Inc., Amherst, MA.

Roe, G. H., and M. B. Baker. (2007). "Why Is Climate Sensitivity So Unpredictable?" *Science* 318, no. 5850: 629–632.

Solomon, S., G-K. Plattner, R. Knutti, and P. Friedlingstein. (2009). "Irreversible Climate Change due to Carbon Dioxide Emissions." *PNAS* 106, no. 6: 1704–1709, doi: 10.1073/pnas.0812721106.

Stern, N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge, UK: Cambridge University Press.

Trenberth, K. E. (2008). "The Impact of Climate Change and Variability on Heavy Precipitation, Floods and Droughts." In *Encyclopedia of Hydrological Sciences*, edited by M. H. Anderson. Chichester, UK: J. Wiley and Sons, Ltd.

For further information, contact:

John Mitchiner
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185
jlmitch@sandia.gov
505-844-7825

George Backus
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185
gabacku@sandia.gov
505-284-5787

Distribution

1	MS0899	Technical Library	9536 (electronic copy)
1	MS0123	D. Chavez, LDRD Office	1011