SANDIA REPORT
SAND2010-0692
Unlimited Release
Printed January 2010

Estimates of the Long-Term U.S. Economic Impacts of Global Climate Change-Induced Drought

Drake E. Warren, Mark A. Ehlen, Verne W. Loose, and Vanessa N. Vargas

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

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of Energy's
National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States 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

SAND2010-0692
Unlimited Release
Printed January 2010

Estimates of the Long-Term U.S. Economic Impacts of Global Climate Change-Induced Drought

Drake E. Warren, Ph.D.
Mark A. Ehlen, Ph.D.
Verne W. Loose, Ph.D.
Vanessa N. Vargas

Computational Economics Group
Org. 06321 Infrastructure and Economic Systems Analysis Department
Sandia National Laboratories
Albuquerque, NM

October 2, 2009

While climate-change models have done a reasonable job of forecasting changes in global climate conditions over the past decades, recent data indicate that actual climate change may be much more severe. To better understand some of the potential economic impacts of these severe climate changes, Sandia economists estimated the impacts to the U.S. economy of climate change-induced impacts to U.S. precipitation over the 2010 to 2050 time period. The economists developed an impact methodology that converts changes in precipitation and water availability to changes in economic activity, and conducted simulations of economic impacts using a large-scale macroeconomic model of the U.S. economy.

This page intentionally blank

Table of Contents

1 Introduction ... 7

1.1 Extreme Global Climate Change ... 7
1.2 Dimensions to Climate Change ... 8
1.3 Estimating U.S. Climate Change and Its Economic Impacts ... 8
1.3.1 Uncertainty in Climate Change and Economic Impacts ... 9
1.4 Purpose and Scope of this Report ... 10

2 Economic Impact Methodology ... 11

2.1 Overall Impact-Analysis Process ... 11
2.2 Economic Impact Methodology ... 12
2.2.1 Climate-to-Economy Modeling Assumptions that Address Uncertainties ... 12
2.2.2 Modeling Agricultural Impacts ... 13
2.2.3 Modeling Impacts to Municipal Water Use ... 19
2.2.4 Modeling Impacts to Power Production ... 20
2.2.5 Modeling Impacts to Industry and Mining ... 26
2.3 Specific Modeling Procedures ... 34
2.3.1 Agriculture ... 34
2.3.2 Electricity Production ... 36
2.3.3 Industry and Mining ... 37
2.4 The REMI PI+ Macroeconomic Model ... 38

3 Estimates of Climate Impacts on the U.S. Economy ... 41

3.1 Macroeconomic Simulations ... 41
3.2 Factor Analysis ... 41
3.3 Detailed Estimates of Impact ... 50

4 Summary ... 63

References ... 65

List of Figures

Figure 1. Modeled versus Actual Arctic Ice Levels: 1990 - 2100 ... 7
Figure 2. Climate Change Domains ... 8
Figure 3: Data Flows between Hydrology, Direct Economic Impact, and Macroeconomic Modeling ... 12
Figure 4. Major REMI Economic Variable Categories and Relationships ... 39
Figure 5. Calculating Economic Impacts In REMI ... 40
Figure 6: National Employment Impacts of Farm, Thermoelectric, and Hydroelectric Changes: 2010-2050. ... 43
Figure 7: National Employment Impacts of Farm Industry, Mining, and Industry Changes: 2010-2050 ... 44

Figure 8: Change in National GDP (2008 USD) due to Farm, Thermoelectric, and Hydroelectric Changes: 2010-2050. 45
Figure 9: Change in National GDP due to Farm Industry, Mining, and Industry Changes: 2010-2050.......... 45
Figure 10: Change in National Real Disposable Personal Income due to Farm, Farm Industry, Thermoelectric, Hydroelectric, and Mining and Industry Changes: 2010-2050 46
Figure 11: Change in National Employment based on Simulated Thermoelectric Sector Water Availability Data: 2010-2050. 48
Figure 12: Change in National GDP based on Simulated Thermoelectric Sector Water Availability Data: 2010-2050. 49
Figure 13: Change in National Real Disposable Income based on Simulated Thermoelectric Sector Water Availability Data: 2010-2050. 50
Figure 14: Range of Drought Severities Analyzed using the Sandia Hydrology Model 51
Figure 15: Change in National GDP 52
Figure 16: Change in National Employment, by Climate Change Probability: 2010-2050 54
Figure 17: Change in National GDP 54
Figure 18: Change in Corn and Soy Production, by Climate Change Probability: 2010-2050 55
Figure 19: Change in National Real Disposable Personal Income, by Climate Change Probability: 2010-2050 55
Figure 20: Changes in National GDP, by Private, Non-Farm Sectors (2010-2050): 1% Simulation 56
Figure 21: Percent Change in Employment-Years (2010-2050), by State: 1% Simulation 58
Figure 22: Percent Change in GDP (2010-2050), by State: 1% Simulation 59
Figure 23: Percent Change in Real Disposable Personal Income (2010-2050), by State: 1% Simulation 60
Figure 24: Percent Change in Population (2010-2050), by State: 1% Simulation 61
Figure 25: Percent Change in Corn and Soy Production (2010-2050), by State: 1% Simulation 62

List of Tables

Table 1: Measures of Hydrological Impact. 12
Table 2: Industries with Requirements from Farms of at least $0.05 / $1 Output. 18
Table 3: Average Cost to Ship Grain by Rail. 18
Table 4: Industrial use of Water in Canada. 30
Table 5: Non-Cooling Consumption Rates Compared to Industry Output. 31
Table 6: Total Consumption, by Industry 31
Table 7: Change in Employment-Years, GDP, and Real Disposable Personal Income: 2010-2050 46
Table 8: Modeled States with Largest Percentage Changes in Population and Income: 2050..... 47
Table 9: Change in Employment-Years, GDP, and Real Disposable Personal Income: 2010 - 2050.......... 53

1 Introduction

1.1 Extreme Global Climate Change

There is considerable recent concern about global climate change, such as global warming, global atmospheric change, and global and regional precipitation. As a result, significant research is being performed to predict the potential impacts of these changes, over the next 50 to 100 years.[1] While most of this research focuses on forecasting "best estimates" of future impacts, the complexity of the real earth climate creates tremendous uncertainty in these estimates; not only can they be very biased, but there is a real probability that actual global climate changes and ensuing economic impacts could be substantially greater.

As an example of these model biases, Figure 1 plots current-model estimates of arctic ice levels against actual ice levels, over the 1900 to 2100 time period.

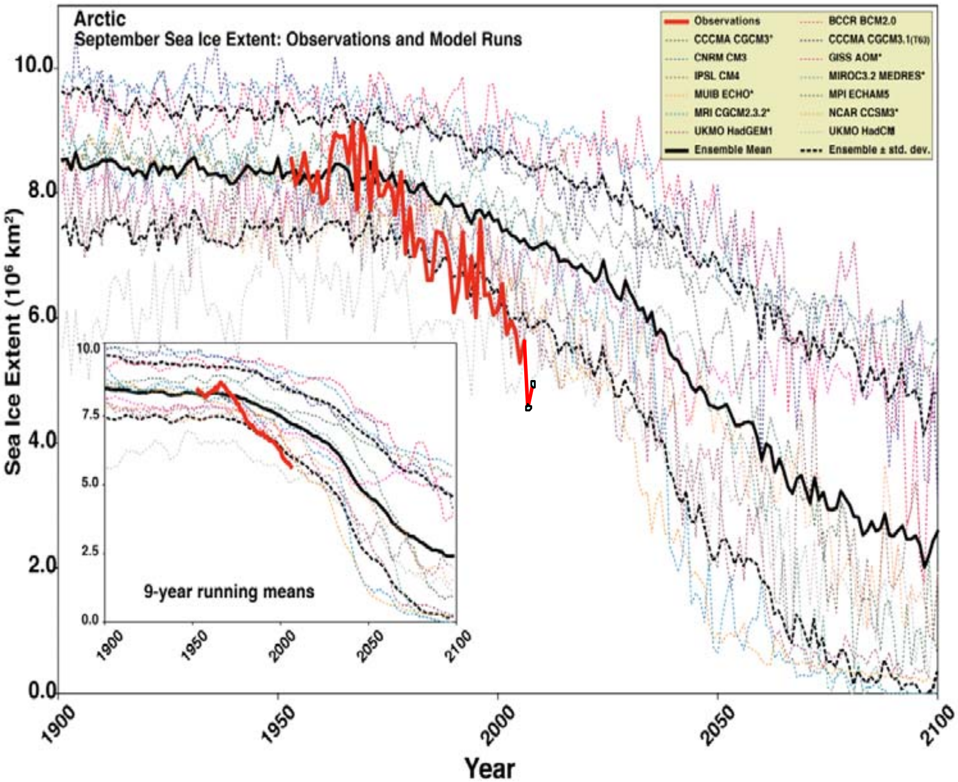


Figure 1. Modeled versus Actual Arctic Ice Levels: 1990 - 2100[2]

---

[1] For a review of research about the possible impacts of climate change in natural and social systems, see Field, C.B., L.D. Mortsch, M. Brklacich, D.L. Forbes, P. Kovacs, J.A. Patz, S.W. Running and M.J. Scott, "North America," *Climate Change 2007: Impacts, Adaptation and Vulnerability*, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, pp. 617-652.

[2] Adapted from: Stroeve, J., M. M. Holland, W. Meier, T. Scambos, and M. Serreze, "Arctic sea ice decline: Faster than forecast," *Geophysical Research Letters*, 34, L09501, 2007.

The solid black line in the figure represents the average forecast for arctic ice from a set of eleven arctic ice models, the two dotted black lines represent the upper and lower bounds of these models' estimates (one standard deviation), and the solid red line represents the actual levels of arctic ice. As illustrated by the figure, recent actual ice levels are much less than even the models' lower bound. If models of other climate conditions are similarly biased in their forecasts, such as for declining U.S. agricultural crop productivity and declining water availability, the real future consequences of global climate change are likely much worse.

1.2 Dimensions to Climate Change

There are at least four dimensions to climate change that are important in terms of their impact on the economy (Figure 2): first, different types of severe climate change could occur (the figure lists in red the types discussed in this report), including increased heat, increased severe weather, significant reductions in water levels in navigable waterways, and increased carbon dioxide. Second, these global climate changes affect different economic sectors (the figure lists the sectors covered in detail by the latest publication of the U.S. Global Climate Change Research Program[3]). This report examines some of the consequences to water resources, energy supply and use, and agriculture. Third, the location, spatial extent, and resolution of the consequences of climate change can vary widely. Finally, the time period of climate change and impacts can be very different (this report examines the years 2010 to 2050). In total, the potential combinations of these physical consequences, sectors, locations, and time are large and ultimately warrant significant scientific research and consequence analyses.

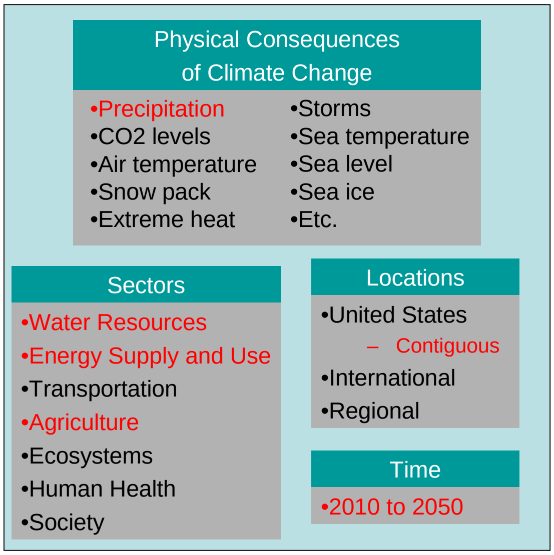


Figure 2. Climate Change Domains

1.3 Estimating U.S. Climate Change and Its Economic Impacts

To better understand the economic impacts of extreme global climate change, research teams at Sandia National Laboratories analyzed a set of climate change scenarios of different severities that induce drought in United States, thereby reducing agricultural productivity and water

---

[3] Source: U.S. Global Climate Change Research Program, 2009, *Global Climate Change Impacts in the United States*, Cambridge University Press, 2009.

available for consumption. Using detailed water-system models, hydrologists in the Earth Systems Department[4] estimated how a set of realizable changes in precipitation could impact the availability of fresh water for industrial and household consumption and for U.S. agricultural production, all over the 2010 to 2050 period. Using a detailed macroeconomic model of the U.S., economists from the Infrastructure and Economic Systems Analysis Department[5] then estimated the potential direct and indirect impacts to the U.S. economy of these changes in water availability and agricultural productivity, over the same forecast period.

The economists developed and applied an economic impact methodology that translates the results of the physical drought consequences of climate change from the Sandia hydrology models into economic changes that can be input into macroeconomic models. Specifically, changes in agricultural crop productivity/yield were translated into changes in national agricultural production of key U.S. crops (corn and soybeans), changes in water availability for industrial uses were translated into changes in the production costs and output of industries, and changes in hydroelectric power production were translated into changes in demand for alternate sources of power. The economic analysis used the REMI PI+ model,[6] a commercial macroeconomic model of the U.S. economy, to forecast national macroeconomic impacts over the 2010 to 2050 time period.

1.3.1 Uncertainty in Climate Change and Economic Impacts

When estimating the economic impacts of climate change, the primary source of parametric uncertainty is the actual level of climate change itself (as exemplified by Figure 1). Of all the models that estimate the physical consequences of climate change, a limited number of them, such as Sandia’s hydrology models, do quantify the uncertainty in the climate change consequences (e.g., see Figure 14 and the discussion on p. 51). This report, then, quantifies the uncertainties in economic impacts of climate change by estimating the economic impacts of physical changes in climate across a range of drought severities, where the Sandia hydrology models estimate the probabilities of climate change.

Another important source of uncertainty is how the economy and broader United States will respond to extreme climate change. Specifically, there is significant structural and parametric uncertainty in

- the future structure, technologies, and growth of the U.S. economy;
- the full range of effects that climate change can have on the economy;
- how changes in crop yield and water availability will affect economic business-sector activities;
- the indirect economic effects on sectors of the economy that are relatively isolated from direct climate effects;
- how regional impacts will propagate to other regions and their sectors; and

---

[4] Org. 06733 Earth Systems Department, Sandia National Laboratories, Albuquerque, NM. Contact: Tom Lowry, Staff Member.

[5] Org. 06321 Infrastructure and Economic Systems Analysis Department, Sandia National Laboratories, Albuquerque, NM. Contact: Lillian A. Snyder, Manager.

[6] Regional Economic Models, Inc, “The REMI PI+ Model, United States, 51-Region, 70-Sector, Version 1.1.6, Last History Year 2007, Build 1944, Date September 21 2008,” 433 West Street, Amherst, MA, 01002, 2009.

- how populations and society as a whole will respond to the changing economic and climate conditions.

As an initial, example step, then, the economists focused their analysis on impacts caused only by changes in drought conditions, specifically changes in:

- agricultural productivity;
- water available for consumption to municipal water utilities;
- water available for thermoelectric power generation;
- water available to industries that consume large amounts of water, including mining; and
- hydroelectric power production,

over the years 2010 to 2050. Structural uncertainties about how the economy will react to climate change were managed by making strong, conservative economic-modeling assumptions designed to establish an upper bound for the magnitude of economic impacts.

1.4 Purpose and Scope of this Report

This report describes first estimates of the economic impacts on the future U.S. economy of significant changes in water precipitation, agricultural productivity, and the availability of water for power generation and economic uses. It details the economic method used to translate changes to climate into structural changes to the economy, including how uncertainty in the hydrology models creates uncertainty in the economic models. It then gives detailed data on economic impacts and their interpretation. Section 2 describes the climate-to-economic-impact methodology, Section 3 describes the estimates of economic impact, and Section 4 summarizes.

2 Economic Impact Methodology

2.1 Overall Impact-Analysis Process

The Sandia hydrologists and economists followed a four-step process to estimate the economic impacts of global climate change:

1. **Estimate hydrology impacts.** First, Sandia's hydrology models produced forecasts of agricultural productivity and water allocations available to be consumed by various water-consuming sectors. These models also quantified the uncertainty of regional drought levels by generating probability distributions of various levels of rainfall. Several scenarios are generated for different probability levels (1, 5, 10, 15, 25, 35, 50, 75, and 99 percent) in the lower tail of the probability distribution.

2. **Estimate direct economic impacts of hydrological changes resulting from climate-induced drought.** Sandia economists them developed an economic impact methodology that addresses two questions: (1) What does a physical climate change mean economically, and (2) how can this change be modeled in a macroeconomic model? To answer these questions, the economists created a climate-to-economic impact model that can translate hydrology impacts to direct macroeconomic impacts, i.e., impacts directly experienced from climate change. The economic methodology developed in this step must deal with a substantial array of uncertainties discussed in the previous subsection by making strong, conservative, bounding assumptions that simplify the economic methodology. When the economic methodology was applied to the hydrology impacts, it resulted in a large number of variables (6,985 variables for each year of the simulation). Calculating these variables and putting them into a format that can be read by REMI required the creation of a set of spreadsheets that can be imported into the REMI user interface. Once this spreadsheet tool was created, updates to the hydrology impacts were quickly translated into new REMI model inputs.

3. **Estimate national macroeconomic impacts.** The economists then input the set of direct impacts into the REMI model and conducted a large number of preliminary, final, factor analysis, and sensitivity analysis simulations.

4. **Interpret results.** Finally, the economists interpret the economic-impact results. Sensitivity analysis using hydrology data from a variety of drought severities was used to estimate the probability distribution of economic impacts, and factor analyses of different categories of economic change was used to determine which aspects of climate change were the most significant drivers of overall economic impact.

Figure 3 illustrates the data that flows from the Sandia hydrology models (forecast in an effort separate from that of this report) to the direct economic impact modeling (described in Section 2), and then to the macroeconomic modeling conducted using the REMI PI+ model.

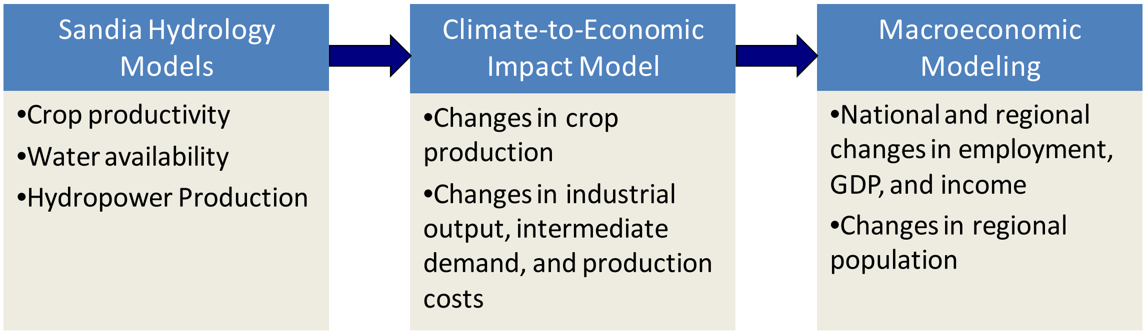


Figure 3: Data Flows between Hydrology, Direct Economic Impact, and Macroeconomic Modeling

2.2 Economic Impact Methodology

The economic impact methodology developed by Sandia economists is designed to answer two methodological questions:

1. What does a physical climate change mean to the U.S. economy?
2. How can this change be modeled in a macroeconomic model?

To answer the first question, Sandia economists used forecasts of hydrological change reported by the Sandia hydrology models. Table 1 lists the types of hydrological change forecast by these models, by state and over the 2010 to 2050 period.

Table 1: Measures of Hydrological Impact.

Variable	Description
$\alpha^{i}_{x,t}$	Relative production (compared to a base year) for crop *x* (both irrigated and non-irrigated crop production, combined)
H^{i}_{t}	Fraction of normal water availability for municipal consumption
E^{i}_{t}	Fraction of normal water availability for thermoelectric generation consumption
HP^{i}_{t}	Fraction of normal hydroelectric power production
I^{i}_{t}	Fraction of normal water availability for industrial consumption
M^{i}_{t}	Fraction of normal water availability for mining consumption

As described below, the economists then translated these hydrology impacts to direct economic impacts, by developing a set of assumptions about the direct economic impacts of each, modeling these impacts, and then quantifying the actual direct economic effects. These direct effects were then input into the REMI model to estimate the total (direct plus indirect) economic impacts over the 2010 to 2050 period.

2.2.1 Climate-to-Economy Modeling Assumptions that Address Uncertainties

During the methodology development stage, a large number of informed assumptions were made to address the substantial uncertainties in modeling the economic impacts of climate changes. A significant constraint to our the methodology was that the REMI macroeconomic model requires specific, single-point values as inputs rather than ranges of values with probabilities; the climate-to-economic methodology had to therefore develop calculations that produce single-point values of economic impact. To address this constraint preventing direct assessment of economic uncertainties, the economists conducted factor analyses to assess how reasonable changes to these single-point values affected the overall estimates of national and regional economic impacts.

Furthermore, in line with the overall task of assessing the economic impacts of extreme climate events, the economists focused on making strong, upper bound assumptions and estimates of economic impact. As an example, in the event of higher energy costs caused by lack of water, new energy technologies and policies would likely be developed in the future U.S. economy, but since the economists could not make informed estimates of the types and extents of these technology changes, they assumed that this technological change would not occur. As a result, the impact estimates herein are biased toward higher impacts than might actually occur.

Finally, to translate each hydrological change into a direct economic impact, a set of economic assumptions, models, and calculations were made, by type of change and the sectors in which they occur. Each is described now, in turn, beginning first with two assumptions that apply across all non-farming sectors.

To simplify the economic methodology and to reduce uncertainties, two assumptions apply to the non-farming sectors:

1. States that are adjacent to oceans are assumed to have access to desalinated water. Desalinated water capacity will be built quickly enough so that supplies of desalinated water will be plentiful. Construction of desalination facilities might be too slow to supply demand, which could lead to shutdowns in the non-farming sectors. In a sector such as electric power, such shutdowns could have large, short-term effects. However, modeling the timing of capital investments and short-term shutdowns is beyond the scope of this analysis, so the economists chose to make this first assumption.

2. Retrofits (i.e., modifications to existing physical capital, such changes made to production facilities after they are first constructed) to conserve water are made instantly. In reality, there may be some delays in producing machinery for the retrofits, which could lead to short term shutdowns of facilities in the various sectors. These shutdowns will likely be relatively minor, so they are ignored.

2.2.2 Modeling Agricultural Impacts

To model the effects of changes in agricultural productivity on the U.S. economy, separate strategies were developed estimate the impacts to (1) farm industries and their suppliers and (2) non-farm industries that use farm outputs as inputs to their own production.

Impacts to Farming Industry

As with all of the climate-to-economy modeling, the estimates of direct economic impact need to be variables that can be input directly in to the REMI model. This is problematic with agriculture in particular, since REMI treats all agriculture production as being exogenous to the overall economy, that is, it neither users nor provides commodities to the larger economy.[7] To address this assumption when modeling impacts of the farming sector, REMI includes a Translator Module that allows users to model impacts to sectors not explicitly captured in the model. For each state and year in the simulation period, the module takes as an input the change in the total value of production for that industry and 'translates' it into impacts to a broader set of industries. For farm industries, the module calculates estimates of the changes in government spending, farm employment, farm compensation, and intermediate demand to 65 other industries within the state. These translated variables are then used as the inputs to the REMI model.

Modeling Assumptions

Given that the farming industry is complex and that behaviors of individual farmers depend on a wide range of factors that are hard to capture with the REMI Translator Module, a number of simplifying assumptions were made.

- The climate-based changes in hydrology only impact agricultural production to the combined irrigated and non-irrigated crops as forecast by the Sandia hydrology models. The economists do not, for example, incorporate price-based decisions by farmers to produce or not produce crops. The hydrology models ignore many physical factors and human factors (e.g., differences in fertilizer applications due to fertilizer prices), although they implicitly incorporate some factors like soil productivity and, to some extent, farmers' decisions about when to apply fertilizer and how much to apply based upon changes in rainfall.

- Only corn and soybean production are impacted (since corn and soybean farming have the greatest shares of production). According to the National Agricultural Statistics Service, in 2008 the production of corn for grain was $47.4 billion and the production of soybeans was $27.4 billion. By comparison, the production of all "field and miscellaneous crops" was $134 billion, the production of "34 major vegetables" was $10.4 billion, and fruit production was $16.5 billion.[8] The third largest crop is hay ($18.8 billion), whose productivity is not modeled within the Sandia hydrology models. It is assumed that crops other than corn and soybeans remain at the same level of production.

- Absolute and relative crop prices are constant over time. Agricultural commodity prices actually fluctuate on a day-to-day basis based upon events in world commodity markets. By affecting agricultural productivity, global climate change will affect global commodity prices. It is uncertain whether agricultural commodities will be more or less

---

[7] This is an assumption inherent in the REMI model. It may be justified economically because a principal factor in agricultural production is land, which—unlike capital or labor—is immobile. Furthermore, agricultural markets are international in scope, thus much of the supply and demand and agricultural markets is largely exogenous to the United States.

[8] Source: U.S. Department of Agriculture, National Agriculture Statistics Service, *Crop Values 2008 Summary*, February 2009, http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.pdf , http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.zip, accessed May 27, 2009.

expensive due to global climate change;[9] therefore, the economists assumed that relative global prices do not change.

- The only agricultural and water-use substitutions made are those predicted by the hydrology regression models. There are no additional substitutions on the economics portion of the modeling. In reality, there are a wide range of substitutions that individual farmers make: for example, crops are often rotated; farmers may change the mix of crops in response to price changes or expectations in productivity, may install irrigation systems or choose not to use existing irrigation systems, may bring land in and out of cultivation, and may alter the timing of plantings and fertilizer applications. By holding these fixed, a conservative bound is being imposed; this is consistent with conservative estimate process described above.[10]

- Agriculture production technologies follow the exogenous growth pattern estimated by REMI through annual changes in its Translator Module. Overall output in corn and soybeans is assumed to grow at the same rate as REMI's (exogenous) forecast of increases in farm GDP. This assumption implicitly assumes that the ratio of GDP to production remains constant over time. Although technological change will likely occur in the real future economy, the economists had no means for estimating this change.

- Climate change does not affect livestock farming directly. In reality, livestock farming may be impacted by changes in the price of feed, changes in the productivity of forage eaten by grazing livestock, and water used in livestock farming and manufacturing.[11] Industrial livestock production may be affected indirectly through impacts to the food manufacturing industry (see next section).

- Climate change will not affect forestry. While it is likely that climate change will impact forest productivity, it is not modeled in the Sandia hydrology models, hence it is ignored in these economic models.

Modeling Procedures

Since the output of the REMI translator is proportional to the magnitude of the inputs, a standard set of impacts were developed by calculating the translator outputs per $1 million change in the input, and then scaling appropriately for each impact. This linear, first approximation allowed the economists to automate the calculation of REMI inputs; otherwise, inputs would have had to be entered manually for each of the regions.

---

[9] A global model of agricultural productivity response to climate change may provide a better idea of whether agricultural commodities will become more or less expensive. Even with such a model, there will remain many factors that will lead to substantial uncertainty about the overall effect of climate change on commodity prices.

[10] This logic cannot be applied to changes in price because price changes will benefit some people but harm some others.

[11] Water use is less than one percent of all U.S. water use. Source: Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A. (2004) "Estimated Use of Water in the United States in 2000," USGS Cicular 1268, Revised Feb. 2005, http://pubs.usgs.gov/circ/2004/circ1268/, accessed May 27, 2009.

Estimates of corn productivity from the Sandia hydrology models were used to estimate changes in REMI's grain farming industry and changes in soybean productivity in REMI's oilseed farming industry. Changes in production values (measured in aggregate dollars across the state) for each crop, *x*, (which were be entered into the REMI model via the Translator) were calculated as

$$\Delta Y_{x,t}^{i} = Y_{x,t}^{i} - Y_{x,b}^{i} = (\alpha_{x,t}^{i} - 1) Y_{x,b}^{i} \frac{GDP_{t}^{farm}}{GDP_{b}^{farm}},$$

where

$\Delta Y_{x,t}^{i}$ = the change in production for crop *x* in state *i*,[12]

$Y_{x,t}^{i}$ = the value of production in year *t*,

$Y_{x,b}^{i}$ = the average production in the baseline period (an average of 2006 to 2008 data[13]),

$\alpha_{x,t}^{i}$ = the relative production of crop *x* in year *t* in state *i* to the baseline production (an output of the hydrology models),

GDP_{t}^{farm} = REMI's (exogenous) forecast of national farm GDP in year *t*, and

GDP_{b}^{farm} = REMI's (exogenous) forecast of national farm GDP in the baseline period (an average of 2006 to 2008).

To create variables that can be used to model in REMI, $\Delta Y_{x,t}^{i}$ was converted to millions of dollars and multiplied by the 68 variables produced by the REMI translator, for each state and year in the forecast period.

Impacts to Industries that use Farm Output

In addition to directly impacting agriculture, changes in agricultural productivity will impact the downstream users of agricultural farm output. These users are modeled directly within REMI except for the intermediate inputs they purchase from the exogenous farm industry.

Modeling Assumptions

Modeling the effects to these downstream users requires a number of assumptions in addition to those listed above. First, the actual amount that the users of the commodity pay to obtain the commodity includes the cost of transportation. Although this "economic geography" process is modeled in most industries in REMI, again it does not apply to the exogenous farm industry. In this case, the net price of these food commodities is assumed to include transportation costs. If production in a state decreases, then net prices are assumed to increase due to the higher costs necessary to transport the commodities.

---

[12] Taken as the average of 2006 through 2008 data (Source: United States Department of Agriculture, National Statistics Service, "Crop Values 2008 Summary," February, 2009, http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.pdf, http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.zip , accessed May 27, 2009.

[13] *Ibid.*

The degree to which an industry is affected by net price changes of farm production is proportional to the total requirements of that industry that originate from the farm industry. Table 2 shows BEA industries that have total requirements of $0.05 or more for each dollar of production, which has been chosen as the cutoff for industries that are modeled. Changes in net price will change the production costs for the industries shown in the right column of Table 2. The economists assumed that changes in productivity of corn and soy production, when averaged together using a weighted average based upon baseline production of the two crops, serve as proxies for changes in productivity for all farm inputs within a state.

To estimate the direct GDP contribution of crop production, the economists estimated the ratio of GDP directly due to crop production to production of corn and soybeans. Between 2006 and 2008, national corn and soybean production averaged $58.1 billion (2000 USD) and crop production averaged $126.0 billion.[14] During the same time, the average estimated (exogenous) farm GDP in REMI was $87.9 billion. In 2006, the measured output in livestock was $112.1 billion).[15] Therefore, the estimated ratio is [$126.0 / ($112.1 + $126.0) x $87.9] / $58.1 = 0.801.

REMI's projected changes in technology in industries that use farm products as inputs account for REMI's forecast changes in food production technologies. Therefore, only the changes in productivity measured by the hydrology models (i.e., not REMI's forecast increases in farm GDP) are used to calculate changes in production costs.

Final demand for farm output is small (personal consumption expenditures are $52.9 billion compared to industry output of $294.8 billion). Most consumer demand for farm production comes by way of demand for the production of the industries shown in Table 2 (e.g., personal consumption expenditures for Food and Beverage and Tobacco Products are $482.5 billion compared to industry output of $722.2 billion and personal consumption from Food Services and Drinking Places is $497.8 billion compared to industry output of $614.1 billion[16]). Therefore, the economists did not model changes in the net prices of farm production that directly affect consumers, while they recognized that REMI will endogenously model impacts to consumers via these other industries.

---

[14] *Ibid.*

[15] Source: Bureau of Labor Statistics, "Industry output and employment projections to 2016", *Monthly Labor Review*, November 2007, pp. 53-85, http://www.bls.gov/opub/mlr/2007/11/art4full.pdf, accessed August 10, 2009.

[16] Source: U.S. Census Bureau, Bureau of Economic Analysis, "The Use of Commodities by Industries after Redefinitions" for 2007, summary level, (http://www.bea.gov/industry/iotables/table_list.cfm?anon=82430), accessed May 27, 2009.

Table 2: Industries with Requirements from Farms of at least \$0.05 / \$1 Output.[17]

IO Code	BEA Industry Name	Requirement for \$1 Output (R_x)	REMI Industry/Industries
111CA	Farms	\$1.18	N/A
311FT	Food and beverage and tobacco products	\$0.31	#19: Food manufacturing, #20: Beverage and tobacco product mfg.
113FF	Forestry, fishing, and related activities	\$0.10	#2: Agriculture and forestry support activities; Other
722	Food services and drinking places	\$0.07	#62:Food services and drinking places

Modeling Procedures

Because farm production is a basic input for most of the production in the industries in Table 2, it is difficult to substitute to other inputs. An increase in the net costs of farm production will look like an exogenous increase in production costs in these industries (because the farm industry is not modeled endogenously in REMI). Therefore, increased net costs to these industries were modeled by increasing the Production Cost variable in REMI, which is "used when a specific policy will affect the cost of doing business in a region without directly changing the relative costs of factor inputs."[18] Farm input is not included as a factor input in REMI.

It was assumed that if farm production within a state changes, the changes are compensated by imports or exports via rail transportation. Table 3 shows some average costs of shipping grain by rail, as well as the price of each crop. The "% Rail" column indicates the cost of the rail transportation relative to the price and can be thought of as the increase in net price if a firm had to obtain these grains via rail instead of on-site. With this data as a guide, it was assumed that production costs will increase or decrease by 20 percent of the decrease or increase of agricultural production in the state.

Table 3: Average Cost to Ship Grain by Rail.[19]

Grain	Avg. Rail Cost Per Bushel	July 2010 Price Per Bushel	% Rail
Corn	\$0.99	\$4.75	21%
Soybeans	\$1.04	\$9.87	11%

The change in production costs caused by changes in agricultural production in state *i* was estimated with the following equation:[20]

---

[17] Source: U.S. Census Bureau, Bureau of Economic Analysis, "BEA Industry-by-Industry Total Requirements after Redefinitions," 2007 summary-level table, accessed May 27, 2009.

[18] Source: Regional Economic Models, Inc. Variable description for "Production Cost," "REMI PI+," v. 1.0.114, March 24, 2009 build, 51-region, 70-sector model, Amherst, MA.

[19] Sources: USDA "Grain Transportation Report", May 14, 2009, www.ams.usda.gov/GTR), July 2010; futures price (closing price on 5/19/2009 on Chicago Mercantile Exchange, http://www.cmegroup.com/); and calculation of the rail costs as a percentage of the futures price.

[20] In states without either corn or soybean production, this term is assumed to be zero.

$$\Delta PC\%^{i}_{x,t} = -20\% \times R_x \times \left(\frac{(\alpha^{i}_{corn,t} - 1) \times Y^{i}_{corn,b} + (\alpha^{i}_{soy,t} - 1) \times Y^{i}_{soy,b}}{Y^{i}_{corn,b} + Y^{i}_{soy,b}} \right),$$

where

$\Delta PC\%^{i}_{x,t}$ = the percentage change in production costs for industry *x* (of those in Table 2),

R_x = the total requirements of industry *x* for farm products to produce a dollar of outputs (listed in Table 2),

$\alpha^{i}_{x,t}$ = the relative production of crop *x* in year *t* in state *i* to the baseline production (an output of the hydrology models), and

$Y^{i}_{x,b}$ = the average production in the baseline period (an average of 2006 to 2008 data[21]).

The term $\Delta PC\%^{i}_{x,t}$ was entered into REMI as the change in the “Production Cost (share)” variable for the appropriate industry.

2.2.3 Modeling Impacts to Municipal Water Use

Municipal water use is one output from the Sandia hydrology model that is not modeled directly in the economics model, for the following reasons: first, the allocation of water by the hydrology team prioritizes municipal use above all other uses, thus municipal use is unlikely to be substantially affected. Second, as this section shows, there are many opportunities for substantial municipal water conservation that will be inexpensive and have little effect on the livability of a region. Finally, modeling municipal water in REMI is relatively difficult: while there is a Utilities sector within REMI, municipal water utilities are not modeled explicitly. Therefore, a number of assumptions need to be made to model the effects of water shortages to municipal water utilities.

Modeling Assumptions

Drought-induced water conservation is relatively easy to conduct. For example, the EPA estimates that 30 percent of household water is used for outdoor watering (and this is higher in arid regions),[22] suggesting that a significant fraction of water consumption would be eliminated in time of drought. Also, the American Water Works Association estimates that 30 percent of household water could be saved if all homes installed common water-saving features.[23] Finally, 60 percent (or more) of household water use could be cut fairly painlessly with current, affordable technology.

---

[21] Source: U.S. Department of Agriculture, National Agriculture Statistics Service, *Crop Values 2008 Summary*, February 2009, http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.pdf, http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.zip.

[22] Environmental Protection Agency, “Outdoor Water Use in the United States”, *WaterSense*, http://www.epa.gov/watersense/pubs/outdoor.htm, accessed May 27, 2009.

[23] American Water Works Association, “Water Use Statistics”, http://www.drinktap.org/consumerdnn/Default.aspx?tabid=85, accessed May 27, 2009.

Municipal water losses of greater than 60 percent would have to be made up with more extreme conservation measures, such as developing new no- or low-water technologies, increased conservation measures (e.g., shorter showers, less frequent clothes washing, disposable dishware, eliminating car washes, closing golf courses, or population migration).[24]

Many technologies exist that may help provide long-term sources of municipal water. For example, rain harvesting technology, water treatment, desalination, and water pipelines could be used to increase supply. The economists assumed that the use of technology remains the same as today, except that desalination may be increased near the. Because the use of these technologies will mitigate the effects of reduced water supplies, this assumption provides a conservative bound to the simulation.

2.2.4 Modeling Impacts to Power Production

Although water consumption in agricultural irrigation is highest, thermoelectric power production is the sector with the largest U.S. water withdrawals.[25] As a result, water shortages could be expected to have significant impacts on electricity supplies. Technology exists that eliminates water consumption in thermoelectric generation, thereby making it a "backstop technology" in the event of water shortages. In states adjacent to oceans, desalinated water used in evaporative cooling systems and ocean water used in once-through cooling systems provide an even cheaper alternative. To capture these effects, the economists modeled in REMI the effect of water shortages on electricity production by increasing the costs of generating electricity, to reflect the increased costs of the backstop technology.

Additional impacts to power production result from changes in water volumes in rivers and streams that change available hydroelectric power production. The economists modeled these changes by changing demand for alternate sources of electricity production in REMI.

Thermoelectric Power in States not Adjacent to an Ocean

Modeling Assumptions

Thermoelectric power was responsible for 48 percent of water withdrawals in 2000.[26] However, much of that water (91 percent) is used in once-through cooling, where most water is returned to the source where it originated, at a higher temperature, and therefore the water supply is not lost. The remainder of water is used in closed-loop cooling systems where most of the water is evaporated, hence lost.

Due to climate change, it is possible that some freshwater sources for once-through cooling will no longer have sufficient volume. Hydroelectric power may be similarly affected by volume

---

[24] As for minimum water requirements, the USAID recommends 20 to 40 liters per person per day, while a separate study recommends a Basic Water Requirement right of 50 l/p/d (17% of average U.S. household use and 9% of average California household use). Source: Gleick, P.H., "Basic Water Requirements for Human Activities: Meeting Basic Needs," *Water International*, v. 21, pp. 83-92.

[25] Source: Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., "Estimated Use of Water in the United States in 2000," USGS Cicular 1268, Revised Feb. 2005. http://pubs.usgs.gov/circ/2004/circ1268/, accessed May 27, 2009. Consumption is higher in agriculture because 91 percent of thermoelectric withdrawals are used in once-through cooling, which consumes very little water.

[26] *Ibid.*

reductions, which may necessitate additional supplies of power from alternate sources such as thermoelectric power.

Climate change may also increase the temperature of water and air, which may decrease the cooling efficiency of thermoelectric power plants. Additionally, warmer water discharged from power plants can alter species composition in aquatic ecosystems.[27] Temperature changes in water are not considered by the Sandia hydrology models, and thus the economic effects of these changes were not modeled by the economists.

A third type of cooling is air-based (dry) cooling. This technology is a backstop because it consumes little water, but instead works similarly to air refrigeration by removing heat from steam and transferring it to the ambient air with fans. The economists assumed that only when faced with water shortages, electricity producers would retrofit to dry cooling. A large portion of thermoelectric power generation is converting to combined-cycle,[28] much of which will be using dry cooling (and in the event of water shortages, an even greater share will be dry cooling) due to the reduced cooling needs these plants. Therefore, our assumption that dry cooling will only be used during water shortages is a very conservative assumption — dry cooling will likely grow even without water shortages.

The economists used an estimate of the additional cost of dry cooling through calculations made by Powers Engineering for retrofitting generation in California.[29] They perform calculations for a hypothetical plant that find the increased cost of generation of converting from once-through cooling to a wet tower will be between $0.0013 to $0.0039/kilowatt hour (kWh) (against a wholesale price of $0.07/kWh) depending on the capacity utilization of the plant. They also cite projections that dry cooling retrofits would cost 25% more than wet tower retrofits, which means that the range would be $0.0016 to $0.0049/kWh. These calculations assume a 7-percent interest rate and 100-percent debt financing. A more realistic mix at 55-percent debt financing (taxed at 12 percent) and 45-percent equity financing (taxed at 50 percent) triples the cost[30] to $0.0048 to $0.0147/kWh.

Retrofits have the additional effect of making power production less efficient. Power Engineering estimates that cooling will reduce the efficiency of the plant and cost an additional 1-2 percent for retrofitting to wet, closed-loop cooling, but they do not recommend a value for dry cooling, which is more energy intensive. A power consultant[31] identifies increases of 1.9 percent for production costs when retrofitting wet, closed-loop cooling and 4.9 percent for dry cooling. Assuming that wholesale prices of $0.07/kWh can be used as costs and multiplying those prices by 4.9 percent increases the cost by $0.00343/kWh.

---

[27] Source: U.S. Global Climate Change Research Program, *Global Climate Change Impacts in the United States*, Cambridge University Press, 2009, p. 56.

[28] Source: Powers Engineering, "Once-Through Cooling and Energy", http://www.cacoastkeeper.com/assets/pdf/Energy_OTC_Fact_Sheet.pdf, accessed on May 27.

[29] *Ibid.*

[30] Source: Communication with George Backus on May 30, 2009.

[31] Source: John S. Maulbetsch, Maulbetsch Consulting, "Water Conserving Cooling Status and Needs", July 25, 2006, accessed at http://www.sandia.gov/energy-water/West/Maulbetsch.pdf , accessed on May 27, 2009.

Adding the increased capital costs increases the cost of retrofits to results in a range of $0.00823 to $0.01813/kWh. The economists assumed the high end of the range is correct and assume that retrofits to dry cooling will cost an additional $18.13/megawatt hour (MWh).

An alternative backstop technology is gas turbines. However, they tend to be relatively expensive to use due to high natural gas prices and have low capacity utilization rates because they are used mainly to serve peak demand. Therefore, the economists assumed that power producers would not switch to gas turbines for the purpose of mitigating water shortages.

The economists assumed that once retrofits have been implemented, the electric power in the state would be able to fully operate with the reduced level of water consumption, at the increased costs in future years.

Different states have different mixes of once-through cooling, so they will be impacted differently by water shortages. For example, all cooling in many arid states is wet, closed-loop due to a lack of water volume necessary for once-through cooling.[32] However, the economists assumed that water shortages would affect power generation of generation technologies that commonly consume water (i.e., fueled by coal, natural gas, nuclear, other, other biomass, other gases, petroleum, and wood and derived fuels) in proportion to the state's water shortage. This is a conservative estimate, for four reasons: first, wet, closed-loop cooling consumes a much greater amount of water than does once-through cooling for the same power production. It is likely that wet, closed-loop cooling would be converted first to dry cooling, which would reduce a large fraction of water consumption but impact relatively little power production. For example, the economists estimated that in Texas wet, closed-loop cooling consumes 97 percent of all water consumed for cooling, but is used to produce only 62 percent of power.[33] Our conservative assumption assumes that a 97-percent reduction in available water will necessitate that 97 percent of generation be retrofitted, likely an overestimate. Second, some portion of power production in each state, especially power produced with natural gas, already uses dry cooling, thus less power generation within the state needs to have its cooling retrofitted. Third, retrofits would first occur for plants that operate at a high capacity utilization rate, thus the average capital costs of the retrofit will be lower than these estimates for mild water shortages. Fourth, plants that use ocean water as their source are unlikely to need to be retrofitted because they are consuming salt water from a source that is expected to increase in volume.

Modeling Procedures

The additional production cost of electric power in each state, *i*, and each year, *t*, is calculated as[34]

$$\Delta Y_t^i = \$18.13 \times (1 - E_t^i) \times X^i ,$$

where

---

[32] Calculated from U.S. Department of Energy, EIA, "Annual Steam-Electric Plant Operation and Design Data (EIA-767)," http://www.eia.doe.gov/cneaf/electricity/page/eia767.html, accessed May 27, 2009, using data from 2005.

[33] *Ibid.*

[34] Source: U.S. Department of Energy, EIA, "2007 Net Generation by State by Type of Producer by Energy Source (EIA-906)," http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html, accessed May 27, 2009.

E_t^i = the fraction of normal demand for water by electric power producers that is satisfied, and

X^i = the total power production, in MWh, of production in the state in 2007 for power fueled by coal, natural gas, nuclear, other, other biomass, other gases, petroleum, and wood and derived fuels.

Because producers can permanently operate with a reduced supply of water following retrofits, $E_{t+1}^i \le E_t^i$. (If this identity does not hold in the input data, it will be adjusted so that any year has, at most, as much water availability as the previous year.) In years where the electric power available for electricity production decreases (i.e. $E_t^i < E_{t-1}^i$) investment in cooling retrofits will be measured by[35]

$$\Delta IN^i = \$71.35 \times (E_{t-1}^i - E_t^i) \times X^i ,$$

which assumes that all investments are made immediately.

REMI contains a "Cap and Trade Scenario" that provides guidance in modeling the economic impacts of cap-and-trade policies. Because cap and trade is likely to impact the electric power generation sector, the scenario suggests manipulating utility costs. An increase in production costs due to retrofitting equipment in order to reduce water use is a similar cost increase.

Utility costs are changed by increasing the production costs for the utilities sector. Specifically, the economists increased the "Production Cost (amount)" of the utilities sector by the amount (ΔY_t^i) determined by the above equation. During years where producers must invest in retrofitting technologies, this additional demand (ΔIN_t^i from the above equation) was invested. This amount was entered into REMI using "Investment Spending (amount)" in "Producer's Durable Equipment." However, this allocates demand generically in a way that overly favors production in industries like "Computer and Electronic Product Manufacturing." REMI's Translator Module was used to adjust these numbers for different types of equipment such as "Industrial Equipment." However, like the translator for agriculture, the equipment translator produces many variables (up to 65) that are slightly different for each region. The economists calculated that on net, around 60 percent of additional demand goes to "Machinery manufacturing" and 33 percent goes to "Electrical equipment and appliance manufacturing." To simplify calculations, the economists assumed that two-thirds of ΔIN_t^i goes to "Machinery manufacturing" and one-third goes to "Electrical equipment and appliance manufacturing" via the "Exogenous Final Demand (amount)" variable.

---

[35] Powers Engineering's calculations for a retrofit from once-through to wet-tower cooling are $100,000/MW of capacity. Using their estimate that dry cooling costs 25 percent more, this becomes $125,000/MW. Using the low-end capacity of 20 percent (8,760 hours × 0.20 = 1,752 kWh/year), this averages to $71.35/MWh. Source: Powers Engineering, "Once-Through Cooling and Energy," http://www.cacoastkeeper.com/assets/pdf/Energy_OTC_Fact_Sheet.pdf, accessed on May 27, 2009.

Thermoelectric Power in States Adjacent to an Ocean

Modeling Assumptions

In states that adjacent to oceans, water shortages to electric power were assumed to be mitigated by using once-through cooling with saline ocean water or desalinating water and using it in wet-tower cooling. The economists assumed that thermoelectric generation plants in a state would conserve water by switching wet-tower cooling systems to desalinated water during water shortages.

Desalination is a proven technology. Therefore, the economists assumed that any state on a coast has access to desalinated water as a backstop before water shortages become too severe. (In addition, states not on the coast may have access to desalinated brackish water, but the economists ignored this possibility because it will affect a relatively small population.) In these states, the main consideration for modeling is the increased cost of the desalination.

Desalinating saline water is more expensive than surface or ground water. A National Academies study[36] cites the current price of water in San Diego as $\$0.24/\text{m}^3$ but the cost of desalination as between $0.64 and $\$1.04/\text{m}^3$. A review of cost estimates for various technologies conducted at SNL[37] found estimates from 23 studies. For seawater these estimates range from $0.27 to $\$6.56/\text{m}^3$; however, the high range is an outlier. Removing one study puts the upper estimate at $\$1.86/\text{m}^3$. The economists assumed that upper estimate is correct and using desalinated water will increase cost by $\$1.62/\text{m}^3$.

A study of water use by thermoelectric plants finds that the mean withdrawals per kWh of electricity for evaporative cooling is between 4.54 and 4.95 cubic decimeters for kWh, depending on the technology used.[38] Taking the larger value, the economists assumed a value of $4.95\text{m}^3/\text{MWh}$. Thus the additional cost of using desalinated water in wet-tower cooling is $9.21/MWh. Because the cost of using desalinated water is about half the cost of converting to dry cooling ($9.21/MWh vs. $18.13/MWh) conservation of water will likely occur by substituting to desalinated water.

Modeling Procedures

The additional production cost of electric power in each state, *i*, and each year, *t*, is calculated by

$$\Delta Y^i = \$9.31 \times (1 - E_t^i) \times X^i,$$

where

E_t^i = the fraction of normal demand for water by electric power producers that is satisfied, and

---

[36] Source: National Research Council Committee on Advancing Desalination Technology, *Desalination: A National Perspective*, The National Academies Press, Washington, D.C., http://www.nap.edu/catalog.php?record_id=12184 , accessed May 17, 2009.

[37] Source: Miller, J.E., “Review of Water Resources and Desalination Technologies,” Sandia National Laboratories SAND Report #2003-0800, http://www.prod.sandia.gov/cgi-bin/techlib/access-control.pl/2003/030800.pdf , accessed May 17, 2009.

[38] Source: Yang, X. and Dziegielewski, B., “Water Use by Thermoelectric Power Plants in the United States,” *Journal of the American Water Resources Association*, v 43(1), 2007, pp. 160-169.

X^i = the total power production, in MWh, of production in the state in 2007 for power fueled by coal, natural gas, nuclear, other, other biomass, other gases, petroleum, and wood and derived fuels.[39]

In states where cooling retrofits were necessary to conserve water, electricity production could permanently operate with less water. However, in the case of states adjacent to oceans, electricity producers may use desalinated water in one year and return to fresh water in following years when the shortages are less severe.

As before, the economists increased the "Production Cost (amount)" of the utilities sector by the amount (ΔY_t^i) determined by the above equation. In addition, "Industry Sales/Exogenous Production (amount)" for the Utilities industry is increased by ΔY_t^i to account for the increased water production that the power generators require from water utilities that provide desalinated water. Increases in production in REMI automatically trigger investment in the industry, thus REMI will automatically account for investments that are made to build desalination capacity.

Hydroelectric Power

Modeling Assumptions

Drought conditions will change rainfall, thus changing volumes of water flowing through rivers and streams. Hydroelectric power creates electricity from the potential energy in water, so lesser/greater volumes of water reduce/increase the amount of power that a hydroelectric plant can generate.

The economists assumed that the marginal cost of producing hydroelectric power is zero because the major costs of producing hydroelectric power are about the same regardless of how much power the plant actually produces. Capital costs to build hydroelectric power generation are sunk costs, thus the cost is the same no matter how much power is produced. Labor costs are relatively small, and the same amount of labor will be required from workers such as guards and operators, no matter the level of power production. Hydroelectric power does not use a costly fuel source as thermoelectric power does. Therefore, changes to hydroelectric power, alone, were assumed not have any aggregate macroeconomic impact.

Changes to hydroelectric power production will have a macroeconomic impact through substitutions away from or to other forms of production with a greater marginal cost. The economists assumed that reductions in hydroelectric power lead to an equally large increase in demand for thermoelectric power, while decreases in hydroelectric power lead to an equally large decrease in demand for thermoelectric power within the state where the hydroelectric power is produced. These changing demands will change production levels, but not necessarily within the same state—power can be imported or exported outside the region.

The economists assumed a monetary value for changes in demand of \$138.13/MWh, which is equal to the cost of new coal power generation (\$120/MWh)[40] plus the costs of retrofits to dry

---

[39] Source: US. Department of Energy, EIA, "2007 Net Generation by State by Type of Producer by Energy Source (EIA-906)," http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html, accessed May 28, 2009.

cooling towers ($18.13/MWh—a conservative assumption since cooling "retrofits" will likely be cheaper to implement when designed into new construction.)

The economists did not calculate any changes to demand for other sectors. In reality, an increase in demand for Utilities, for example, could reduce demand for other sectors due to price and income effects. However, modeling at this detailed level is beyond the scope of this report. By assuming that there are no changes to demand in other sectors due to changes in demand for Utilities, the economists are making a bounding assumption about the maximum possible impact.

Modeling Procedures

Changes in the demand for alternate sources of power due to changes in hydroelectric production is modeled in the REMI model as a change in the "Exogenous Final Demand (amount)" variable to the Utilities sector. To satisfy changes in demand, REMI will change production and investment in capital stock (e.g., increasing capital stock if thermoelectric power plants are needed) in a state and its neighbors.

The change in "Exogenous Final Demand (amount)" for the Utilities sector in state *i* and year *t* is calculated as

$$\Delta D^i = \$138.13 \times (HP_t^i - 1) \times X_{HP}^i \ ,$$

where

HP_t^i = the fraction of normal hydroelectric power production in state *i* and year *t* and,

X_{HP}^i = the total hydroelectric power production, in MWh, in the state in 2007.[41]

2.2.5 Modeling Impacts to Industry and Mining

Of all the major sectors of water withdrawal (5 percent of U.S. water withdrawals or greater), industry is the smallest (5 percent of all water withdrawals), after thermoelectric power (48 percent), irrigation of agriculture (34 percent), and public water supplies (11 percent).[42] Mining, whose water availability will be modeled separately from the aggregate of other industries, uses less than 1 percent of all water.

Modeling Assumptions

A USGS report[43] provides information about aggregate withdrawals of water for all industries and mining, but does not break down the numbers by industry or provide data on how much water is consumed (e.g., evaporated or incorporated into a product) or returned to its source, such

---

[40] Sources: Communication from George Backus on June 24, 2009, citing a cost of coal power plants of $100/MWh (source: LAZARD, *Levelized Cost of Energy Analysis—Version 2.0*, June, 2008, http://www.narucmeetings.org/Presentations/2008%20EMP%20Levelized%20Cost%20of%20Energy%20-%20Master%20June%202008%20(2).pdf, 2007, accessed June 24, 2009) and a transmission and distribution cost of $20/MWh (Northwest Power and Conservation Council, 2009, "Appendix B: Draft Economic Forecast," February 13, 2009, http://www.nwppc.org/library/2009/2009-03.pdf, accessed June 24, 2009).

[41] Source: U.S. Department of Energy, EIA, "2007 Net Generation by State by Type of Producer by Energy Source (EIA-906)," http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html, accessed May 28, 2009.

[42] Source: Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., "Estimated Use of Water in the United States in 2000," USGS Cicular 1268, Revised Feb. 2005. http://pubs.usgs.gov/circ/2004/circ1268/ , accessed May 27, 2009.

[43] *Ibid.*

as with once-through cooling. Statistics Canada provides a large number of tables with a large breadth of data based on surveys of industrial and mining users of water.[44] The economists assumed that the water use of Canadian industries mirrors that of U.S. industries, proportionally. This assumption is reasonable because the two countries user similar technologies and the industries are both classified using the North American Industry Classification System (NAICS). (Because temperatures in the United States are generally warmer than in Canada, it is possible that more U.S. industrial water is used for cooling. In the bullets below, a greater amount of cooling means that there are more opportunities for conservation by converting to dry cooling, thus assuming that the United States and Canada use the same proportions for cooling is a conservative assumption.)

The USGS report says that food, paper, chemicals, refined petroleum, and primary metals are the largest industrial users of water, and they provide separate data for the mining industry. The Statistics Canada survey reports similar findings, but also includes Beverage and Tobacco manufacturing as a significant consumer of water. These six industries account for 87 percent of all industrial (non-mining) consumption of water. The economists focused on these industries.

The data from the hydrologists' models provide the percentage of normal consumption that can be provided by water supplies. Therefore, the economists assumed that there is plenty of water to withdraw, but only a limited amount of this water can be consumed. The remainder of the water must be treated and returned to water supplies where it can be withdrawn, and ultimately consumed, by other users.

A summary of pertinent statistics for the Statistics Canada survey is provided in Table 4. Only 13.5 percent of water intake is actually consumed. The remainder of the water is for:

- **Food.** It is likely that a large portion of the food industry's water consumption is used for "Sanitary Service," most likely in the animal processing industries. This water is probably relatively difficult to conserve, but it can be treated or transferred to irrigation use. Surface discharge is very small, probably because it is difficult to treat. It is likely that most of the discharge becomes irrigation water. (The italics indicate undisclosed data that the economists have imputed by assuming that 29 percent of water intake is used for cooling, as it is in the beverage and tobacco industry.)

- **Beverage and Tobacco.** This industry's consumption rate is the highest of all at 51 percent. The high percentage is likely due to the fact that water comprises the majority of most beverages.

- **Paper.** This industry's consumption rate is only 5 percent, it discharges 89 percent of its intake to the surface, and it spends a lot of money doing this. There is very little it can do to conserve because it consumes so little and is already spending a lot to treat water.

- **Petroleum and Coal.** This industry is based on the transformation of petroleum and coal into usable products (i.e., it does not include extraction). It has a consumption rate of 12

---

[44] Source: Statistics Canada, 2008, "Industrial Water Use 2005," Catalogue no. 16-401-X, March 2008, http://www.statcan.gc.ca/pub/16-401-x/16-401-x2008001-eng.pdf , accessed May 28, 2009.

percent. Much of this is likely due to evaporation as 87 percent of the water is used for cooling, condensing, and steam. This 12 percent could be conserved using similar technologies as in electricity generation.

- **Chemicals.** Chemicals consume a relatively high amount of water, probably because the water is used in chemical reactions or as a solute. There is no conservation opportunity with this use of water. A large portion of water is used for cooling, condensing, and steam (80 percent) so there are opportunities to conserve water here by using similar technologies as in electricity generation.

- **Primary Metals.** Primary metals manufacturing uses a moderate amount of water in cooling, condensing, and steam (hence there are moderate conservation opportunities) and returns a relatively large percentage of water (80 percent) in surface discharge.

- **Mining.** Statistics Canada surveys only "Mining (Except Oil and Gas)." Surface discharge is 98 percent of withdrawals. Consumption is 37 percent because mining often "generates" water when mines are below the water table. If the intake is adjusted by adding "Mine Water," the total intake is 674.9 million cubic meters and consumption is 7 percent. The recycling rate is 448 percent, meaning that the same water is used over and over again. Since mining consumes so little water and it already has a high recycling rate, there are few conservation opportunities.

The USGS study of water use in the United States includes oil and gas in its mining data. This data is much more limited than the Canadian data and covers only a subset of states. The data reports that mining uses 2,250 thousand acre-feet per year of fresh water and 1,660 thousand acre-feet of saline water. Of this saline water, 1,260 thousand acre-feet per year is ground water.

Information about the output of Canadian industries is included in Table 5. The economists assumed that U.S. industries use water at the same rate, per amount of output, as Canadian industries (i.e., the right column of Table 5 is representative of U.S. industries). Due to a lack of information about water use in Oil and Gas Extraction, the economists assumed that the industry has the same water-use characteristics as Mining (Except Oil and Gas).

To calculate the costs of retrofitting cooling systems to dry cooling systems, the economists assumed that the costs per amount of water consumption saved are the same as in the electric power industry. The economists assumed that the maximum percentage of water that can be conserved by retrofitting cooling systems in each industry is equal to the amount of water used in cooling divided by the total intake. This ranges from 6 percent for mining to 87 percent for petrochemicals and coal. As before, the economists assumed a value of the aforementioned 4.95 cubic meters (m^3)/MWh for the amount of water used by thermoelectric plants for evaporative cooling.[45] The economists used the previous value of retrofitting power generation plants of

---

[45] Source: Yang, X. and Dziegielewski, B., "Water Use by Thermoelectric Power Plants in the United States," *Journal of the American Water Resources Association*, v 43(1), 2007, pp. 160-169.

\$18.13/MWh. Dividing by the value from the previous bullet equals an additional cost of \$3.66/m^3 for water saved by retrofitting to dry cooling.[46]

The economists used the previous value of investment necessary to retrofit power generation plants of \$71.35/MWh. Dividing by 4.95m^3/MWh equals an investment cost of \$14.41/m^3 for water conserved by retrofitting to dry cooling. As with electric power, any cooling retrofits that occur will reduce industrial requirements for water in future years.

The economists assumed that once the maximum amount of water has been conserved by retrofitting to dry cooling, additional water is not easily conserved because it often goes into production or is otherwise lost in the production process. Water will have to be obtained through desalination or otherwise firms will have to shut down production to conserve any remaining water. Desalination is available to firms in states that are adjacent to an ocean at an increased cost of \$1.62/m$^{3.}$ Because the increased cost of using desalinated water is much cheaper than the increased cost of retrofitting to dry cooling, the economists assumed that firms will use desalinated water to adjust to the shortfall in water. Firms in all industries will conserve water in the same proportion (e.g., if the available water is a fraction I_t^i of normal demand, all firms will have access to that fraction.)

In states not adjacent to an ocean, the economists assumed that all industries would initially retrofit cooling systems to conserve water. For simplification purposes, industries will retrofit according to a linear function that is proportional to the industry's consumption of water for cooling purposes multiplied by the water shortfall.[47] Once all retrofits have been performed, if the retrofits have not conserved enough water, industries will shut down in equal proportions. This is a conservative assumption because industries are likely to shut down according to how intensively they use water for non-cooling purposes (based upon water consumption per dollar of output), with the most intensive industries shutting down first. Calculations of these intensities are shown in Table 6.

---

[46] This is slightly more expensive than the \$1.62/m^3 increase for desalinated water used earlier. Thus, it may be slightly cheaper for a wet, closed-loop cooling system to use desalinated water rather than retrofitting. However, the cooling in these data is an aggregate of wet, closed-loop and once-through.

[47] The implication of this assumption is that different industries will conserve water at different rates depending upon the intensity at which they consume water for cooling.

Table 4: Industrial use of Water in Canada.[48]

	Food	Beverage/ Tobacco	Paper	Petroleum and Coal	Chemicals	Primary Metals	Mining	Mining (adjusted)
Intake (mil m3)	1366.8	160.6	2598.3	364.8	532.5	1606.2	458.9	674.9
Consumption (mil m3)	272.7	81.3	134.3	42.3	149.9	238.4	-171.7	44.3
Consumption Rate	20%	51%	5%	12%	28%	15%	-37%	7%
Process Water	869.4	-	1800.4	42.5	92	518.8	376.7	376.7
% Intake	64%	-	69%	12%	17%	32%	82%	56%
% Cons.	319%	-	1341%	100%	61%	218%	-219%	850%
Cooling, Condensing, Steam	*394.0*	46.3	731.9	317.5	423.4	839.6	37.7	37.7
% Intake	*29%*	29%	28%	87%	80%	52%	8%	6%
% Cons.	*144%*	57%	545%	751%	282%	352%	-22%	85%

---

[48] Source: Statistics Canada, “Industrial Water Use 2005”, Catalogue no. 16-401-X, March 2008, http://www.statcan.gc.ca/pub/16-401-x/16-401-x2008001-eng.pdf , accessed May 28, 2009.

Table 5: Non-Cooling Consumption Rates Compared to Industry Output.

	Non-cooling Consumption (M m^3) [49]	2005 Output $CAN mil (2002) [50]	Output in $USD M (2008) [51]	Non-cooling Consumption m^3/$M USD Output
Food Manufacturing	194.1	$71,028	$102,330	1,897
Beverage and Tobacco Product Manufacturing	57.9	$13,901	$20,027	2,889
Paper Manufacturing	96.5	$33,546	$48,330	1,996
Petroleum and Coal Product Manufacturing	5.5	$59,228	$85,330	64
Chemical Manufacturing	30.7	$54,659	$78,747	390
Primary Metal Manufacturing	113.8	$49,790	$71,733	1,586

Table 6: Total Consumption, by Industry

	Cooling % Intake	Consumption (M m^3)	2005 Output $CAN M (2002)	Output in $USD M (2008)	Consumption m^3/$M USD Output
Food Manufacturing	29%	272.7	$71,028	$102,330	2,665
Beverage and Tobacco Product Manufacturing	29%	81.3	$13,901	$20,027	4,059
Paper Manufacturing	28%	134.3	$33,546	$48,330	2,779
Petroleum and Coal Product Manufacturing	87%	42.3	$59,228	$85,330	496
Chemical Manufacturing	80%	149.9	$54,659	$78,747	1,904
Primary Metal Manufacturing	52%	238.4	$49,790	$71,733	3,323
Mining (adjusted)	6%	44.3	$24,351	$35,083	1,263

---

[49] *Ibid.*

[50] Source: Statistics Canada, "National economic accounts: Input-output," "Input and output, by industry and commodity, M-level aggregation," "2005 total outputs per industry," http://www.statcan.gc.ca/nea-cen/list-liste/io-es-eng.htm, accessed May 28, 2009.

[51] Converted to 2005 Canadian dollars by multiplying by 1.099 (112.27/102.13) (Source: NationalMaster, "Time Series > Economy > GDP deflator > Canada", http://www.nationmaster.com/time.php?stat=eco_gdp_def-economy-gdp-deflator&country=ca-canada, accessed May 28, 2009), converted to 2005 USD by multiplying by 1.21 (2005 exchange rate and PPP equivalence, source: World Bank, International Comparison Project, "Tables of Results," Washington, D.C., http://siteresources.worldbank.org/ICPINT/Resources/icp-final-tables.pdf, 2005, accessed May 28, 2008), and converted by 2008 USD by multiplying by 1.08 (122.422/113.026, Source: EconStats, "Implicit Price Deflator, BEA release: 04/29/2009," http://www.econstats.com/gdp/gdp__a4.htm, accessed May 28, 2009).

Modeling Procedures

The following outline the equations that will be used to determine impacts from water shortages in industry, using the assumptions generated in the previous sections.

States not Adjacent to an Ocean

These states will first retrofit industrial cooling systems to conserve water. If additional water conservation is necessary, industries will need to halt some production. For each state *i* and year *t*, a fraction of water consumption that can be saved through dry-cooling retrofits is calculated by weighting each industry's cooling water intake as follows, using data from Table 6 and REMI's standard regional control outputs:

$$\overline{\%c}^{\,i}_{t} = \frac{\%c_f WI_f Y^i_{f,t} + \%c_b WI_b Y^i_{b,t} + \%c_p WI_p Y^i_{p,t} + \%c_e WI_e Y^i_{e,t} + \%c_c WI_c Y^i_{c,t} + \%c_m WI_m Y^i_{m,t}}{WI_f Y^i_{f,t} + WI_b Y^i_{b,t} + WI_p Y^i_{p,t} + WI_e Y^i_{e,t} + WI_c Y^i_{c,t} + WI_m Y^i_{m,t}}$$

where

f, b, p, e, c, and *m* represent the six non-mining industries,

$\%c_x$ = the percentage of consumption assumed to be used in cooling (the second column of Table 6),

WI_x = the water intensity of each industry (the right-most column in Table 6), and

$Y^i_{x,t}$ = the output of industry *x* (in millions of 2008 USD, from REMI's standard regional control).

Because mining is disaggregated from the Sandia hydrology model data, its value is simply 6 percent. Production costs in each industry will increase by:

$$\Delta PC^i_{x,t} = \left\{ \begin{array}{l|l} (1 - I^i_t)/\overline{\%c}^{\,i}_{t} \times \$3.66 \times \%c_x WI_x Y^i_{x,t} & (1 - I^i_t) < \overline{\%c}^{\,i}_{t} \\ \$3.66 \times \%c_x WI_x Y^i_{x,t} & (1 - I^i_t) \geq \overline{\%c}^{\,i}_{t} \end{array} \right.$$

where

I^i_t = the fraction of usual water demanded that is available to all industries.

For mining, which includes both Mining (Except Oil and Gas) and Oil and Gas Extraction, this equation simplifies to:

$$\Delta PC^i_{m,t} = \left\{ \begin{array}{l|l} (1 - M^i_t)/0.06 \times \$3.66 \times 0.06 \times 1263 Y^i_{m,t} & (1 - M^i_t) < 0.06 \\ \$3.66 \times 0.06 \times 1263 Y^i_{m,t} & (1 - M^i_t) \geq 0.06 \end{array} \right.$$

where

M^i_t = the fraction of usual water demanded that is available to mining.

Increases in production costs, $\Delta PC^i_{x,t}$, are entered into REMI as increases in "Production Cost (amount)" for the appropriate industry. Investment in cooling-system retrofits will be made until all industrial cooling systems have been retrofitted (i.e., $\overline{\%c}_t^i$ has been conserved). Investment is based upon previous retrofits in the following equations:

$$\Delta IN_{x,t}^i = \left\{ \begin{array}{l|l} (I_{t-1}^i - I_t^i) \times \$14.41 \times \%c_x WI_x Y_{x,t}^i & (1 - I_{t-1}^i) \le (1 - I_t^i) < \overline{\%c}_t^i \\ {[I_{t-1}^i - (1 - \overline{\%c}_t^i)]} \times \$14.41 \times \%c_x WI_x Y_{x,t}^i & (1 - I_{t-1}^i) < \overline{\%c}_t^i < (1 - I_t^i) \\ 0 & otherwise \end{array} \right.$$

and for mining:

$$\Delta IN_{m,t}^i = \left\{ \begin{array}{l|l} (M_{t-1}^i - M_t^i) \times \$14.41 \times 0.06 \times 1263 Y_{x,t}^i & (1 - M_{t-1}^i) \le (1 - M_t^i) < 0.06 \\ {[M_{t-1}^i - (1 - 0.06)]} \times \$14.41 \times 0.06 \times 1263 Y_{x,t}^i & (1 - M_{t-1}^i) < 0.06 < (1 - M_t^i) \\ 0 & otherwise \end{array} \right.$$

The first case occurs when water availability is lower than the previous year but still higher than the maximum amount that can be conserved with cooling retrofits. The second case occurs when water availability is lower than the previous year and lower than the maximum that can be conserved with cooling system retrofits. The third case occurs when water availability increases or decreases further below the maximum retrofitting conservation amount. Because the industry can operate with less water every year to the point where all possible retrofits have been made,

$$I_t^i \le \max(I_{t-1}^i, (1 - \overline{\%c}_t^i))$$

and

$$M_t^i \le \max(M_{t-1}^i, (1 - 0.06)) .$$

(Input data may need to be adjusted for this identity to hold).

As with investments for dry-cooling retrofits for electric power generation, the economists assumed that two-thirds of $\Delta IN_{x,t}^i$ goes to “Machinery manufacturing” and one-third goes to “Electrical equipment and appliance manufacturing” via the “Exogenous Final Demand (amount)” variable.

When water availability is below the level that can satisfy industry needs through cooling-system retrofits (e.g. $(1 - I_t^i) > \overline{\%c}_t^i$) firms will need to shut down some portion of production to conserve water. The economists assumed that firms will reduce their output in proportion to the amount that the water shortage exceeds the level that can be conserved with cooling system conservation. This can be represented as:

$$\Delta Y_{x,t}^i = -(1 - I_t^i - \overline{\%c}_t^i) / (1 - \overline{\%c}_t^i) Y_{x,t}^i \Big| (1 - I_t^i) > \overline{\%c}_t^i$$

for mining, this simplifies to:

$$\Delta Y^{i}_{m,t} = -(1 - M^{i}_{t} - 0.06)/(1 - 0.06)Y^{i}_{m,t} \Big| (1 - M^{i}_{t}) > 0.06$$

This change in output will be modeled in REMI as a change to "Industry Behavior" through reduced "Industry Sales/Exogenous Production (amount)" of $\Delta Y^{i}_{x,t}$. An alternative strategy is to target Firm Sales through "Firm Behavior", which allows "displacement due to competition in the local and nearby markets and the national market", whereas "Industry Behavior" leads to an exogenous change that will not be compensated for by other firms increasing their production levels. Although it is likely that firms in regions of the country with abundant water would increase production to take up the slack created by water shortages, REMI does not include water availability as a variable; many of the firms picking up the slack in a REMI simulation would be within the same region, which is unrealistic if production is reduced due to water shortages. Thus choosing "Industry Behavior" is the more conservative assumption.

States Adjacent to an Ocean

These states will conserve water by purchasing desalinated water with a cost of $\$1.62/\text{m}^3$ for water conserved. The increase in production costs for each industry will be based upon the industry's water intensity for water consumption (the right-most column in Table 6) and the industry output. This can be represented as $\Delta PC^{i}_{x,t} = \$1.62 \times (1 - I^{i}_{t}) \times WI_{x} Y^{i}_{x,t}$. This equation assumes that each industry loses the same fraction $(1 - I^{i}_{t})$ of its normal water demanded. The whole amount of the change in production costs will be applied as increased production costs for industry *x* and a fraction of the amount, $\overline{\%c}^{i}_{t}$, will be applied to increased production in the utility industry to correspond to increased production of desalinated water.

2.3 Specific Modeling Procedures

This section provides highlights about the calculations used to create inputs for the REMI model and the procedure for putting those inputs into REMI. Detailed information about the assumptions and modeling that were used to develop this procedure is located in Section 2.2.

2.3.1 Agriculture

Impacts to Farms

Calculations: For each crop *i* (corn, soybeans, or other), the change in production value is calculated by

$$\Delta Y^{i}_{x,t} = Y^{i}_{x,t} - Y^{i}_{x,b} = (\alpha^{i}_{x,t} - 1)Y^{i}_{x,b} \frac{GDP^{farm}_{t}}{GDP^{farm}_{b}}$$

where

$\Delta Y^i_{x,t}$ = the change in production for crop *x* in state *i* between the baseline period (an average of 2006 to 2008 data[52]),
$Y^i_{x,t}$ = the value of production in year *t*,
$Y^i_{x,b}$ = the average production in the baseline period,
$\alpha^i_{x,t}$ = the relative production of crop *x* in year *t* in state *i* to the baseline production (an output of the hydrology models),
GDP^{farm}_t = REMI's (exogenous) forecast of national farm GDP in year *t*, and
GDP^{farm}_b = REMI's (exogenous) forecast of national farm GDP in the baseline period (an average of 2006 to 2008).

REMI Input: The change in production $\Delta Y^i_{x,t}$ of each crop is multiplied by standardized impacts from the REMI translator module that map changes in crop production to 68 variables for each state.

Impacts to Industries that use Farm Output

Calculations: The percentage change in production costs are calculated by

$$\Delta PC\%^i_{x,t} = -20\% \times R_x \times \left(\frac{(\alpha^i_{corn,t} - 1) \times Y^i_{corn,b} + (\alpha^i_{soy,t} - 1) \times Y^i_{soy,b}}{Y^i_{corn,b} + Y^i_{soy,b}} \right),$$ [53]

where

$\Delta PC\%^i_{x,t}$ = the percentage change in production costs for industry *x* (of those in Table 6),
R_x = the total requirements of industry *x* for farm products to produce a dollar of outputs (listed in Table 6),
$\alpha^i_{x,t}$ = the relative production of crop *x* in year *t* in state *i* to the baseline production (an output of the hydrology models), and
$Y^i_{x,b}$ = the average production in the baseline period (an average of 2006 to 2008 data[54]).

REMI Input: The percentage increase in production costs for each industry is entered into REMI as a percentage change in the "Production Cost (share)" variable.

---

[52] Source: U.S. Department of Agriculture, National Agriculture Statistics Service, *Crop Values 2008 Summary*, February 2009, http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.pdf , http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.zip , accessed October 2, 2009.

[53] In states without either corn or soybean production, this term is assumed to be zero.

[54] Source: U.S. Department of Agriculture, National Agriculture Statistics Service, *Crop Values 2008 Summary*, February 2009, http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.pdf , http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.zip , accessed October 2, 2009.

2.3.2 Electricity Production

Thermoelectric Power in States Not Adjacent to Ocean

Calculations: The additional production cost of electric power in each state, *i*, and each year, *t*, is calculated by

$$\Delta Y_t^i = \$18.13 \times (1 - E_t^i) \times X^i ,$$

where

E_t^i = the fraction of normal demand for water by electric power producers that is satisfied (The hydrology input should be adjusted, if necessary, so that $E_{t+1}^i \leq E_t^i$) and

X^i = the total power production, in MWh, of production in the state in 2007 for power fueled by coal, natural gas, nuclear, other, other biomass, other gases, petroleum, and wood and derived fuels.[55]

When $E_t^i < E_{t-1}^i$, the change in investment for cooling retrofits is calculated as $\Delta IN_t^i = \$71.35 \times (E_{t-1}^i - E_t^i) \times X^i$.

REMI Input: To enter the change in annual costs into REMI, increase the "Production Cost (amount)" of the utilities sector by ΔY_t^i. During years where producers must invest in retrofitting technologies, increase "Exogenous Final Demand (amount)" by allocating one-third of ΔIN_t^i to "Electrical equipment and appliance manufacturing" and two-thirds to "Machinery manufacturing".

Thermoelectric Power in States Adjacent to Ocean

Calculations: The additional production cost of electric power in each state, *i*, and each year, *t*, is calculated by $\Delta Y_t^i = \$9.21 \times (1 - E_t^i) \times X^i$.

REMI Input: As before, the economists increased the "Production Cost (amount)" of the utilities sector by the amount (ΔY_t^i) determined by the above equation. In addition, they increased "Industry Sales/Exogenous Production (amount)" by ΔY_t^i for the Utilities industry.

Hydroelectric Power

Calculations: The change in demand for alternate sources of power is calculated as

$$\Delta D_t^i = \$138.13 \times (HP_t^i - 1) \times X_{HP}^i$$

where

HP_t^i = the fraction of normal hydroelectric power production in state *i* and year *t* and

X_{HP}^i = the total hydroelectric power production, in MWh, in the state in 2007.[56]

REMI Input: The economists changed the "Exogenous Final Demand (amount)" variable to the Utilities sector by ΔD_t^i.

---

[55] Source: U.S. Department of Energy, EIA, "2007 Net Generation by State by Type of Producer by Energy Source (EIA-906)," http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html, accessed May 27, 2009.

[56] Ibid.

2.3.3 Industry and Mining

States Not Adjacent to Ocean

Calculations: For each state *i* and year *t*, a fraction of water consumption that can be saved is calculated by weighting each industry's cooling water intake as follows, using data from Table 6 and REMI's standard regional control outputs:

$$\overline{\%c}_t^i = \frac{\%c_f WI_f Y_{f,t}^i + \%c_b WI_b Y_{b,t}^i + \%c_p WI_p Y_{p,t}^i + \%c_e WI_e Y_{e,t}^i + \%c_c WI_c Y_{c,t}^i + \%c_m WI_m Y_{m,t}^i}{WI_f Y_{f,t}^i + WI_b Y_{b,t}^i + WI_p Y_{p,t}^i + WI_e Y_{e,t}^i + WI_c Y_{c,t}^i + WI_m Y_{m,t}^i}$$

where

f, b, p, e, c, and *m* represent the six non-mining industries,

$\%c_x$ = the percentage of consumption assumed to be used in cooling (the second column of Table 6),

WI_x = the water intensity of each industry (the right-most column in Table 6), and

$Y_{x,t}^i$ = the output of industry *x* (in millions of 2008 USD, from REMI's standard regional control).

Because mining is disaggregated from the Sandia hydrology model forecasts, its value is simply 6 percent.

Production costs in each industry will increase by:

$$\Delta PC_{x,t}^i = \begin{cases} (1 - I_t^i) / \overline{\%c}_t^i \times \$3.66 \times \%c_x WI_x Y_{x,t}^i & \left| (1 - I_t^i) < \overline{\%c}_t^i \right. \\ \$3.66 \times \%c_x WI_x Y_{x,t}^i & \left| (1 - I_t^i) \geq \overline{\%c}_t^i \right. \end{cases}$$

where

I_t^i = the fraction of usual water demanded that is available to all industries (if necessary, input data should be adjusted so that $I_t^i \leq \max(I_{t-1}^i, (1 - \overline{\%c}_t^i))$ and $M_t^i \leq \max(M_{t-1}^i, (1 - 0.06))$).

For mining, which includes both Mining (Except Oil and Gas) and Oil and Gas Extraction this equation simplifies to:

$$\Delta PC_{m,t}^i = \begin{cases} (1 - M_t^i) / 0.06 \times \$3.66 \times 0.06 \times 1263 Y_{m,t}^i & \left| (1 - M_t^i) < 0.06 \right. \\ \$3.66 \times 0.06 \times 1263 Y_{m,t}^i & \left| (1 - M_t^i) \geq 0.06 \right. \end{cases}$$

where

M_t^i = the fraction of usual water demanded that is available to mining.

Investment in cooling retrofits is calculated using the following equations:

$$\Delta IN^{i}_{x,t} = \begin{cases} (I^{i}_{t-1} - I^{i}_{t}) \times \$14.41 \times \%c_{x} WI_{x} Y^{i}_{x,t} & (1 - I^{i}_{t-1}) \leq (1 - I^{i}_{t}) < \overline{\%c}^{i}_{t} \\ [I^{i}_{t-1} - (1 - \overline{\%c}^{i}_{t})] \times \$14.41 \times \%c_{x} WI_{x} Y^{i}_{x,t} & (1 - I^{i}_{t-1}) < \overline{\%c}^{i}_{t} < (1 - I^{i}_{t}) \\ 0 & otherwise \end{cases}$$

and for mining:

$$\Delta IN^{i}_{m,t} = \begin{cases} (M^{i}_{t-1} - M^{i}_{t}) \times \$14.41 \times 0.06 \times 1263 Y^{i}_{x,t} & (1 - M^{i}_{t-1}) \leq (1 - M^{i}_{t}) < 0.06 \\ [M^{i}_{t-1} - (1 - 0.06)] \times \$14.41 \times 0.06 \times 1263 Y^{i}_{x,t} & (1 - M^{i}_{t-1}) < 0.06 < (1 - M^{i}_{t}) \\ 0 & otherwise \end{cases}$$

When water availability is low (e.g., $(1 - I^{i}_{t}) > \overline{\%c}^{i}_{t}$) firms will reduce their output in proportion to the amount that the water shortage exceeds the level that can be conserved with cooling system conservation. This can be represented as:

$$\Delta Y^{i}_{x,t} = -(1 - I^{i}_{t} - \overline{\%c}^{i}_{t}) / (1 - \overline{\%c}^{i}_{t}) Y^{i}_{x,t} \Big| (1 - I^{i}_{t}) > \overline{\%c}^{i}_{t}$$

for mining, this simplifies to:

$$\Delta Y^{i}_{m,t} = -(1 - M^{i}_{t} - 0.06) / (1 - 0.06) Y^{i}_{m,t} \Big| (1 - M^{i}_{t}) > 0.06$$

REMI Input: Increases in production costs, $\Delta PC^{i}_{x,t}$, will be entered into REMI as increases in "Production Cost (amount)" for the appropriate industry. Increases in investment, $\Delta IN^{i}_{x,t}$ are allocated so that two-thirds goes to "Machinery manufacturing" and one-third goes to "Electrical equipment and appliance manufacturing" via the "Exogenous Final Demand (amount)" variable. Any changes in industrial output will be modeled in REMI as a change to "Industry Behavior" through reduced "Industry Sales / Exogenous Production (amount)" of $\Delta Y^{i}_{x,t}$.

States Adjacent to Ocean

Calculations: The increase in production costs for each industry will be based upon the industry's water intensity for water consumption (the right-most column in Table 6) and the industry output. This can be represented as $\Delta PC^{i}_{x,t} = \$1.62 \times (1 - I^{i}_{t}) \times WI_{x} Y^{i}_{x,t}$.

REMI Input: Increases in production costs, $\Delta PC^{i}_{x,t}$, will be entered into REMI as increases in "Production Cost (amount)" for the appropriate industry.

2.4 The REMI PI+ Macroeconomic Model

Sandia economists used the REMI PI+ macroeconomic model[57] to forecast economic impacts over the period 2010 to 2050. REMI is a dynamic econometric input-output model of the entire United States that simulates a wide variety of economic and demographic effects on an annual

---

[57] Regional Economic Models, Inc. "REMI PI+", v. 1.0.114, March 24, 2009 build, 51-region, 70-sector model, Amherst, MA.

basis.[58] The particular REMI model used contains 51 regions (one for each state and the District of Columbia) and 70 economic sectors, and can estimate impacts through the year 2050.

Figure 4 illustrates the major categories of REMI economic variables and relationships that capture economic and demographic activity (such as population levels and movements) across the nation, between states, and within states. These relationships are based on data collected by the federal government (e.g., input-output accounts that describe the flow of goods to make commodities in different industries) and on econometric estimation of key relationships (e.g., the price elasticity of consumer demand) using historical data.

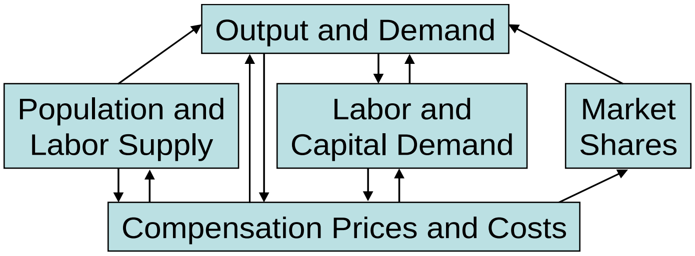


Figure 4. Major REMI Economic Variable Categories and Relationships.

A REMI analysis is carried out in two steps. In the first step, the REMI model simulates the baseline behavior of the U.S. economy using hundreds of detailed regional and sectoral variables and relationship within the aforementioned broad categories of variables. Each version of REMI contains a built-in baseline model (termed, the “standard control”) that reflects publicly available macroeconomic forecasts as well as forecasts developed by Regional Economic Models, Inc. Alternatively, Sandia economists can make adjustments to the baseline forecasts. In the second step, changes in this baseline behavior, e.g., caused by climate change, can be made by specifying exogenous changes in the economic variables, for specific regions and forecast years. REMI incorporates those changes into the simulation, and the impacts of these exogenous changes are measured by comparing the impacts in the baseline forecast with the impacts from the simulation that incorporates the exogenous changes. For example, in the figure below, the solid line shows the baseline forecast of GDP between 2007 and 2020, while the dashed line shows an alternate forecast due to a hypothetical impact in 2009. The difference between the two lines is the forecast economic impact.

---

[58] For a more detailed description of the REMI model, see the resources available at REMI’s website (www.remi.com), including: Treyz, G.I., Rickman, D.S., and Shao, G., “The REMI Economic-Demographic Forecasting and Simulation Model,” *International Regional Science Review*, 14(3), 1991, pp. 221-253.

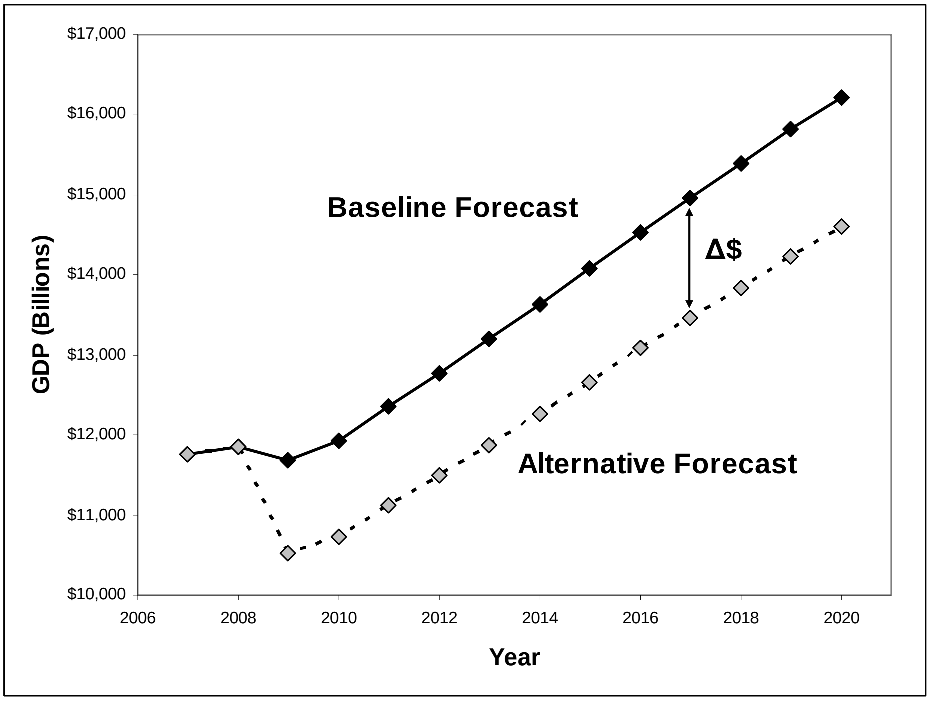


Figure 5. Calculating Economic Impacts In REMI

As with any macroeconomic model, the REMI model has limitations that bias its estimates of the impacts of climate change: first, it models actual U.S. firms as a aggregation of a large number of firms, thereby masking the true relationships between firms and their individual actions within markets. Second, the behavior in REMI is driven by observed, historic data on goods and services and the technologies that make them. Considering the magnitude of technological change that has occurred over the past forty years, it is very difficult for any economic model to forecast the pace and consequences of technological and economic change over the next forty years. Third, significant pre-modeling must be done to convert the hydrological impacts into a form that can be input into the REMI model, and this pre-modeling has inherent biases. Finally, as mentioned above, there are significant uncertainties regarding the sources, types, and levels of climate change, and of their direct and indirect effects on the U.S. economy. These and other factors influence the confidence intervals of our economic impact estimates.

3 Estimates of Climate Impacts on the U.S. Economy

3.1 Macroeconomic Simulations

The economic methodology was carried out in REMI by creating set of spreadsheets that takes the forecasted results of the Sandia hydrology models, applies the economic methodology, and creates outputs that are imported into the REMI user interface. The REMI model is run on an annual basis for the years 2007 to 2050, which is the maximum year in the model.[59]

A set of simulations was run for the factor analysis, which explores the contributions of subcategories of economic impacts. The factor analysis was conducted using results from the Sandia hydrology models for the scenario with the most extreme climate change. Simulations were also run for the aggregate results using results of the hydrology models across a range of drought severities, which runs simulations when all direct economic impact variables are included.

3.2 Factor Analysis

Comparison of All Sectors

To explore the relative contributions of subcategories of inputs, a factor analysis was conducted by separately running five categories of inputs variables into REMI:

1. Impacts to Farms,
2. Impacts to Industries that Use Farm Output,
3. Thermoelectric Production,
4. Hydroelectric Power, and
5. Industry and Mining.

These five were run in separate REMI simulations. Additionally, the Industry and Mining category was run for a subcategory of variables without shutdowns for mining. All factor analysis simulations used the most extreme global climate change scenario that forecasts droughts that have a one percent chance of being exceeded in magnitude.

The goal of the factor analysis was to understand the relative contributions of different sets of input variables to aggregate results. This factor analysis was conducted using results from the Sandia hydrology models, which allocate water so that each sector absorbs a percentage of the deficit that is equal to that sector's water demand in relation to the total demand.

REMI produces hundreds of output variables. This analysis concentrates on three of those variables: employment, gross domestic product (GDP—a measure of total value added), and real

---

[59] Runs of the model assume that Keynesian closure rules are followed, which "[does] not use an interest rate mechanism to correct changes in U.S. employment that have been caused by an exogenous policy shock" (Source: Regional Economic Models, Inc. Description for "Closure Options", "REMI PI+", v. 1.0.114, March 24, 2009 build, 51-region, 70-sector model, Amherst, MA). The other options, which assume "coordination between fiscal and monetary policy makers resulting in interest rate adjustments that would immediately adapt to new policies, so that employment would be maintained at a constant rate" are too unrealistic, especially when the changes to the model will be caused by unpredictable changes in weather and climate.

disposable personal income (income adjusted for taxes and changes in price levels). For each variable, two charts are presented. The first includes the first four (Farms, Farm Industry, Thermoelectric, and Hydroelectric) categories of input variables while the second includes two variants of the fourth (Industry and Mining) category: the full scenario and the scenario without shutdowns in the mining industry. This split was chosen because the industry variables produce much larger economic consequences than the other categories, and the mining shutdown variables (i.e., reductions in "Industry Sales / Exogenous Production (amount)") have especially large effects.

Graphs of these output variables are presented in Figure 6 to Figure 10. In addition, a table with the total changes between 2010 and 2050 is presented in Table 7 and a table with the biggest percentage changes to states is in Table 8. These figures and table show that the economic impacts of the farm variables are generally positive, but have the smallest magnitude. The farm industry variables have a larger magnitude and are noisy with a decreasing trend.

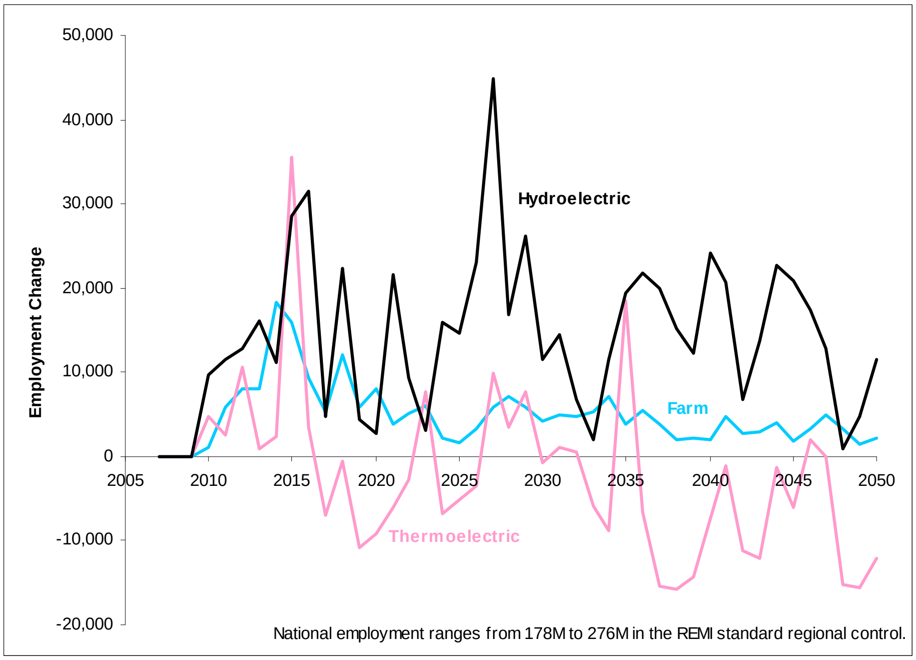
The thermoelectric variables produce economic consequences of greater magnitude than the Farm variables and slightly smaller magnitude than the Hydroelectric variables. Positive spikes in GDP and employment occasionally occur, especially in the early years when investments in retrofits first begin, but these increases are often overwhelmed by the negative effects of increasing production costs in later years. The increases in production costs increase the price index throughout time, which results in a steadily decreasing level of Real Disposable Personal Income, reaching an annual loss of over $8B by 2050. Despite the net decrease of Real Disposable Personal Income of -$155B during this period, there is a slight net increase in GDP of $2B. However, that difference is due to investments in cooling retrofits that mitigate water shortages. If those retrofits were unnecessary, economic resources would be freed to be used more productively.

The only economic impacts that are generally positive are due to reductions in hydroelectric power production; reductions to hydroelectric power increase the demand for alternate sources of power from the Utilities sector. This increased demand causes increases to the economic variables as power plants are built, workers are hired to work in those plants, and fuel is purchased to power the plants, while the hydroelectric plants continue to operate with the same labor and costs. The increases in economic activity highlight a problem—most familiar to economists who analyze disasters—with using aggregate measures of economic flows for consequence analysis: the lost service of hydroelectric power production is not measured in these economic flows, but the increased economic activity necessary to compensate for these losses is measured. If hydroelectric power production did not decrease, the economic resources utilized to create power from alternate sources could be used for other means (such as building luxury items) that would make consumers better off.

The Farm Industry input variables have the second highest magnitude to Employment and GDP, and the greatest impact to Real Disposable Personal Income. The annual loss in GDP reaches hovers around -$30B in the later years of the simulation, while the annual loss in Real Disposable Personal Income reaches -$40B.

The Mining and Industry variables are generally of a much greater magnitude than the other categories of variables, except the magnitude of the losses to Real Disposable Personal Income is slightly less than it is for Farm Industry input variables. The maximum loss in annual GDP is about -$103B, while the maximum annual loss in any of the other three categories is about -$35B (for the Farm Industry). Shutdowns of mining and industry have a substantial negative effect on the output variables and are largely responsible for the substantial variability of the output variables—when no shutdowns are included in the REMI inputs, all of the output variables decrease relatively smoothly. Water availability to Industry never reaches low enough levels to cause industry shutdowns—even in this most severe scenario—thus shutdowns only affect mining.

Reductions in water availability to mining cause relatively severe economic consequences because mining consumes very little of its water through cooling (6 percent—see Table 4), so there are few opportunities for conservation without shutting down mining activity in states that are not adjacent to the ocean. All of the industries use a much greater share of their water for cooling, so they can conserve much greater portions of their consumption. Additionally, the industries are aggregated, so no industry begins shutting down production until all industries have made all possible cooling retrofits, thus raising the fraction of water that can be conserved through cooling retrofits.[60]



National employment ranges from 178M to 276M in the REMI standard regional control.

Figure 6: National Employment Impacts of Farm, Thermoelectric, and Hydroelectric Changes: 2010-2050.

---

[60] The smallest value of $\overline{\%c_t^i}$, which is the percentage of industrial consumption that can be conserved by retrofitting cooling in states not adjacent to an ocean is 32.4 percent. The median is 41.0%. For mining, on the other hand, this percentage is always 6 percent.

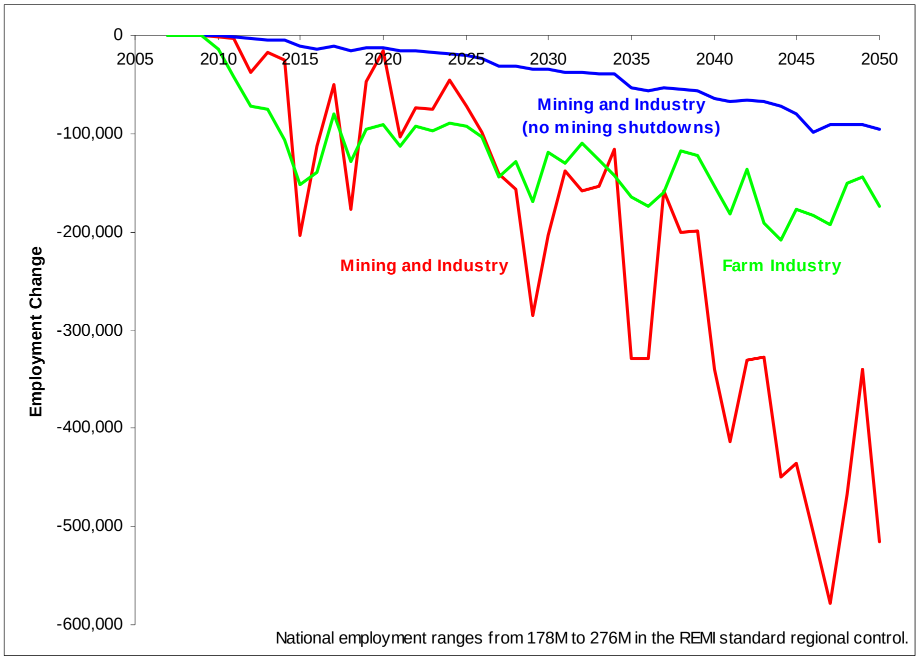


Figure 7: National Employment Impacts of Farm Industry, Mining, and Industry Changes: 2010-2050.

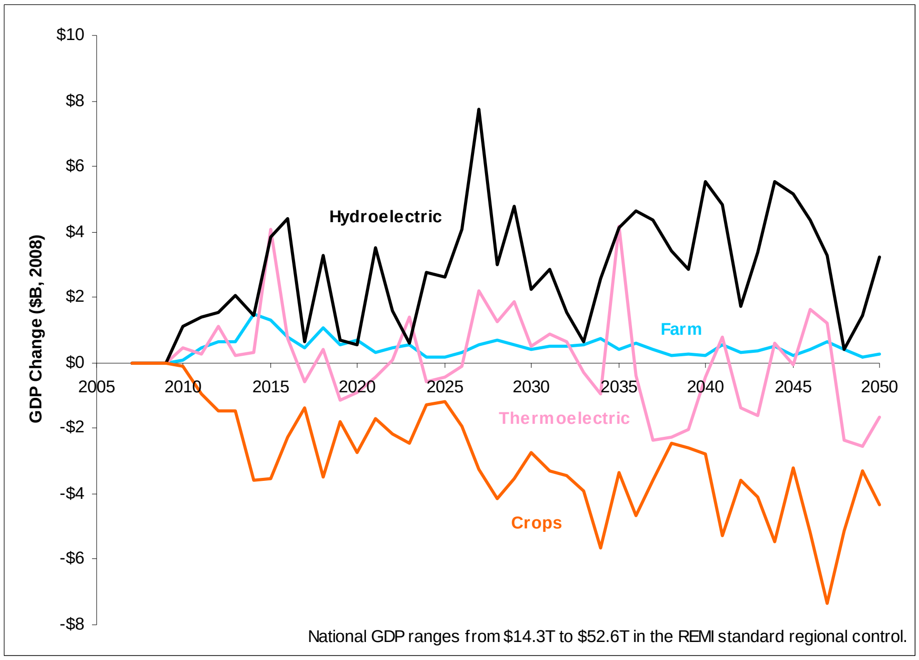


Figure 8: Change in National GDP (2008 USD) due to Farm, Thermoelectric, and Hydroelectric Changes: 2010-2050.

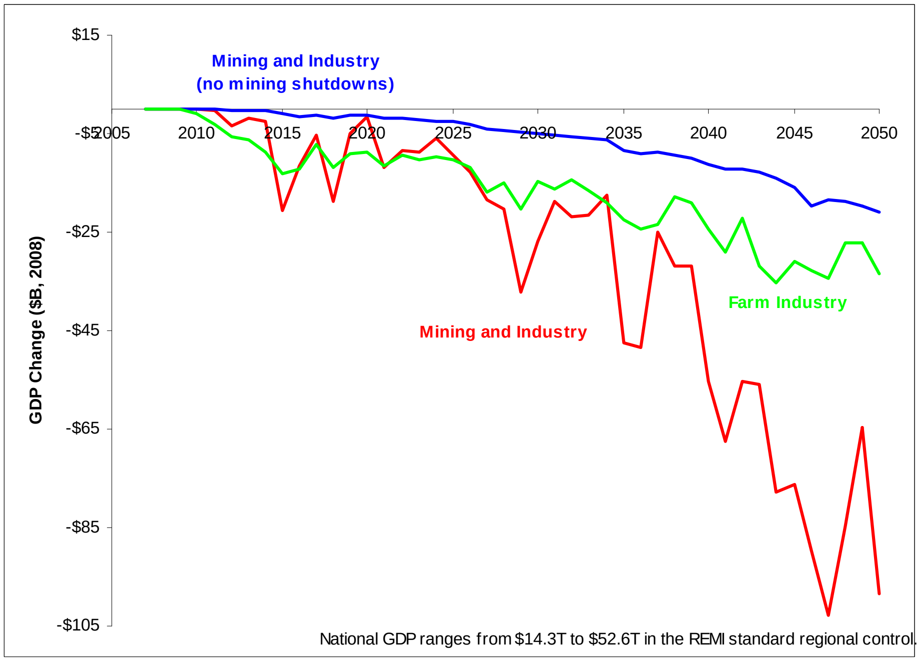
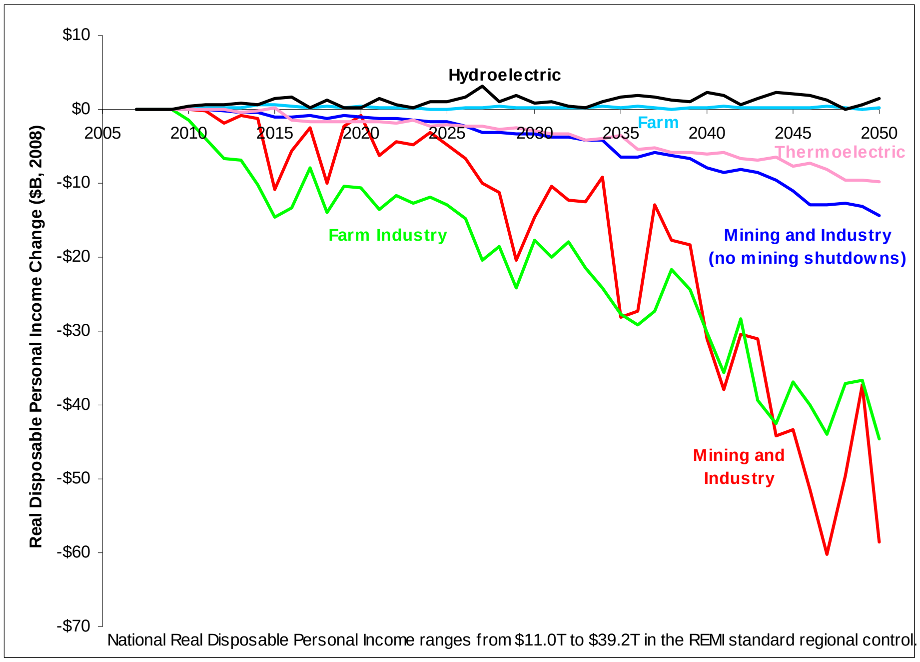


Figure 9: Change in National GDP due to Farm Industry, Mining, and Industry Changes: 2010-2050



National Real Disposable Personal Income ranges from $11.0T to $39.2T in the REMI standard regional control.

Figure 10: Change in National Real Disposable Personal Income due to Farm, Farm Industry, Thermoelectric, Hydroelectric, and Mining and Industry Changes: 2010-2050

Table 7: Change in Employment-Years, GDP, and Real Disposable Personal Income: 2010-2050[61]

Category	Employment Years (k)		U.S. GDP		Real Disposable Personal Income	
1. Farm	216	0.0024%	$21B	0.0017%	$11B	0.0012%
2. Farm-Demanding Industries	-5,286	-0.0594%	-$719B	-0.0598%	-$887B	-0.0976%
3. Thermoelectric	-91	-0.0010%	$2B	0.0002%	-$155B	-0.0170%
4. Hydroelectric	622	0.0070%	$120B	0.0100%	$47B	0.0052%
5. Industry and Mining	-8,428	-0.0946%	-$1,324B	-0.1101%	-$746B	-0.0820%
-Not including mining shutdowns	-1,641	-0.0184%	-$285B	-0.0237%	-$197B	-0.0217%

Because the REMI model used for these simulations is a state-level model, regional economic consequences can be measured. Table 8 lists the states with the largest percentage gains and losses in 2050 of population and real disposable personal income (both variables chosen because they change relatively smoothly and are measures of socio-economic dislocation). The relative magnitudes of the largest state-level changes in the different simulations are similar to the magnitudes of the national-level variables.

---

[61] A higher discount rate will decrease the magnitude of these changes because future changes would be discounted. A discount rate of zero is a conservative assumption, and it may be justified by the uncertainty and potentially catastrophic effects of climate change. (Source: Weitzman, M., "On Modeling and Interpreting the Economics of Catastrophic Climate Change," *The Review of Economics and Statistics,* XCI(1), February 2009.)

Table 8: Modeled States with Largest Percentage Changes in Population and Income: 2050

Category	Population		Real Disposable Personal Income	
Largest Loss (Smallest Gain)				
1. Farm	0.00%	WY	0.00%	WY
2. Farm-Demanding Industries	-0.24%	GA	-0.38%	GA
3. Thermoelectric	-0.10%	WV	-0.15%	WV
4. Hydroelectric	-0.01%	MD	0.00%	IL
5. Industry and Mining	-3.41%	WV	-4.11%	WV
-Not including mining shutdowns	-0.05%	IA	-0.09%	IA
Largest Gain (Smallest Loss)				
1. Farm	0.02%	NE	0.02%	NE
2. Farm-Demanding Industries	0.26%	OR	0.16%	OR
3. Thermoelectric	0.02%	DE	0.00%	DE
4. Hydroelectric	0.02%	AZ	0.03%	AZ
5. Industry and Mining	0.13%	OR	0.01%	OR
-Not including mining shutdowns	0.02%	OR	-0.01%	OR

The largest losses are to West Virginia in the simulation that includes shutdowns of the mining industry. In this simulation, West Virginia loses 3.41 percent of its projected population and 4.11 percent of its projected real disposable personal income by 2050. This result is expected because a large fraction (8 percent of output[62]) of the West Virginia economy is mining, and mining is hit severely within these models.

For many of the categories of input variables, the largest gains and losses for Population and Real Disposable Personal Income are in states with large populations. For example, for the Industry and mining category, California gains over 58,200 residents by 2050, which is over twice as great as the second greatest increase (Florida, with a gain of about 27,500 residents). Based on the percentage gain compared to the baseline, however, California has the eighth largest gain (an increase of 0.10 percent). These gains in population come despite large losses in GDP (-$3.9B) and Real Disposable Personal Income (-$1.2B). Other states fare relatively worse and their residents choose to relocate. California, as the most populous state in the nation, is a likely destination of those emigrants.

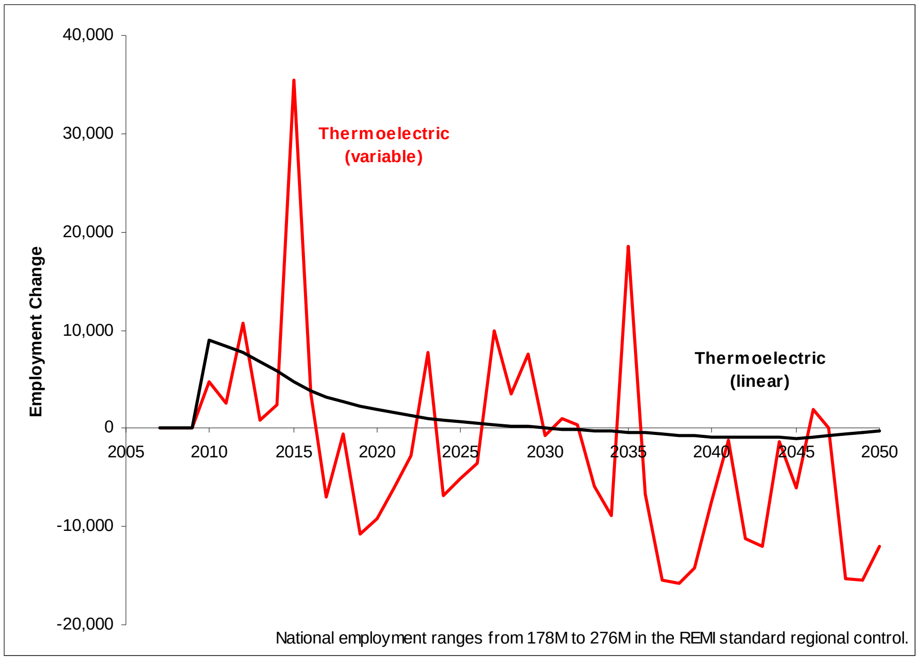
The Effects of Data Variability

An additional analysis was conducted using inputs to the Electricity Production Sector to explore how the variability of the data affects the REMI results. The results from the simulation using the year-to-year hydrology forecasts is compared to a scenario created by linearly changing water availability to Electricity Production between 1 and the minimum of the 2010 to 2050 values for each state. The hydrology forecast used is the same data used in the previous subsection—the most extreme, with a one percent chance of the severity of the drought being exceeded. Figure 11 shows the difference in national employment between the simulations and REMI's standard regional control using the Sandia hydrology model's simulated water availability and using a

---

[62] In REMI's standard regional control simulation, West Virginia's total output in 2050 is $203B and its total output in mining is $16B.

linear trend over time. When using the hydrology forecasts, year-to-year data is highly variable. Employment increases over 35,000 in 2015, while decreases nearly reach a loss of 16,000 jobs. When the simulation is conducted using a linear trend, increases in employment initially spike above 9,000, but then return to a relatively steady decrease of around -1,000.



National employment ranges from 178M to 276M in the REMI standard regional control.

Figure 11: Change in National Employment based on Simulated Thermoelectric Sector Water Availability Data: 2010-2050.

Figure 12 shows the change in GDP for the same simulations. The pattern is similar to the change in employment, except the magnitude of GDP changes become slightly larger in the second half of the simulation for both the variable and linear data.

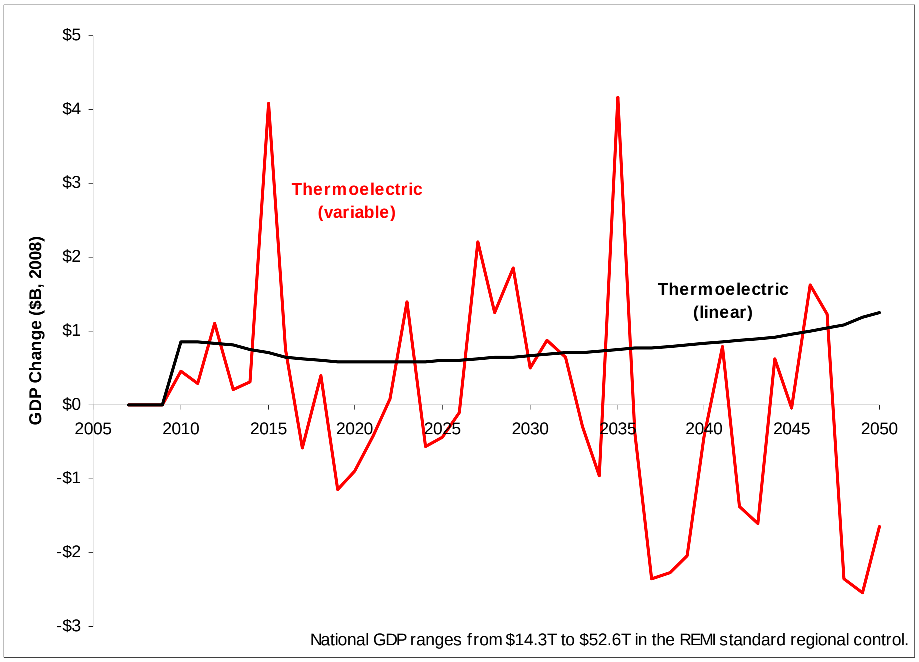


Figure 12: Change in National GDP based on Simulated Thermoelectric Sector Water Availability Data: 2010-2050.

Figure 13 shows changes in Real Disposable Personal Income for the same simulations. Although the simulation using the hydrology forecasts continues to exhibit greater variability than the simulation using the linear trend, it is much steadier than the path of employment or GDP using the hydrology forecasts.

Real Disposable Personal Income is driven by prices changes, which are affected by increases in production costs. These changes in the price index accumulate gradually over time, leading to a steady decrease in Real Disposable Personal Income. The variability of the hydrology forecasts means that GDP fluctuates from year to year, which results in slight fluctuations of the variable forecast from the linear forecast. Furthermore, the variable forecast is slightly higher than the linear forecast because GDP in the variable forecast is higher than it is in the linear forecast in the earlier years of the simulation.

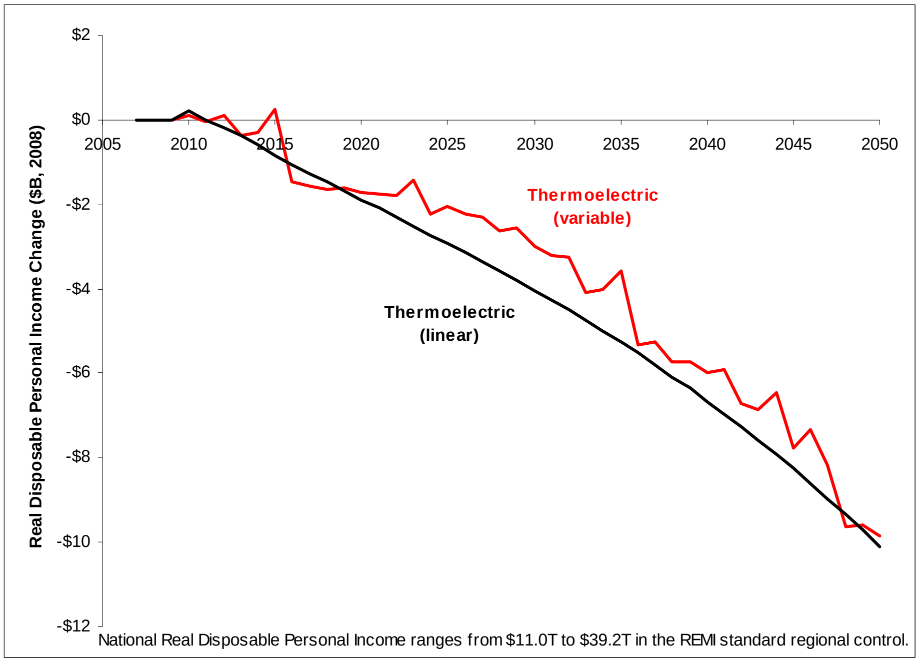


Figure 13: Change in National Real Disposable Income based on Simulated Thermoelectric Sector Water Availability Data: 2010-2050.

The results of these simulations suggest that the economic consequences of global climate change—like any change that will have large year-to-year variability—may cause more substantial year-to-year disruptions than climate change would cause if it followed a perfectly linear trend. Additionally, the economic methodology (which assumes that firms make permanent retrofits to mitigate reductions in water availability) and the actions of the REMI model cause the variable simulation to have permanently lower levels of real disposable personal income.

3.3 Detailed Estimates of Impact

The economic methodology described in Section 2.2 was applied to the forecasts from the Sandia hydrology models. These hydrology models evenly allocate water to each sector based on the relative demand of each sector. A range of drought severities was forecast by the hydrology models. In addition, a baseline forecast was run to estimate the economic effects of decreased water availability due solely to increases in population and economic activity, as forecast by REMI's standard regional control, under the assumption of no global climate change.

Figure 14 presents an illustration of how the Sandia hydrology models forecast hydrological consequences based on probabilities. The dark black line in the figure is a stylized representation of a possible probability distribution that may be estimated by the hydrology models. The left axis represents the cumulative probability, which can be interpreted as the probability that the drought will be more severe than the corresponding point on the horizontal axis. For each probability, the hydrology models forecast rainfall, and further hydrology modeling translates these rainfalls into changes in agricultural productivity and water availability (see Figure 3). The baseline forecast, which assumes no global climate change, is not pictured in this figure; it would lie to the right of the pictured graph because the entire probability distribution estimated by the Sandia hydrology models forecasts drought due to global climate change.

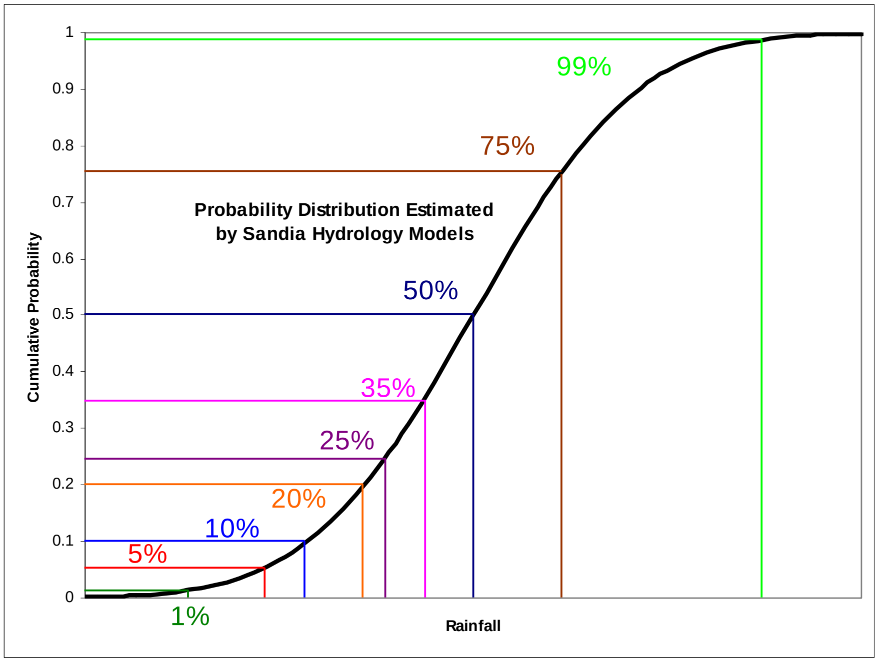
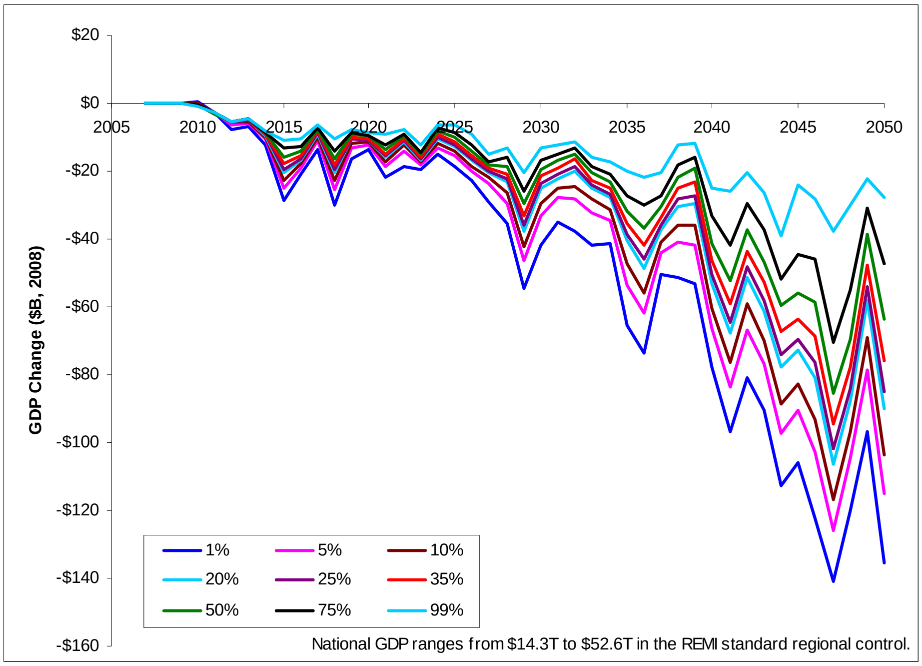


Figure 14: Range of Drought Severities Analyzed using the Sandia Hydrology Model

The forecasts of the Sandia hydrology models are used to calculate direct economic impacts, which feed into the REMI macroeconomic model using economic methodology developed within this report. The results of the macroeconomic modeling are analyzed at the aggregate, national level and at the state level to gauge differences between different regions.

National Results

A time-series chart of impacts to Gross Domestic Product (GDP) is shown in Figure 15. The results of the economic impact analysis show that under a realizable scenario (with a one-percent chance that the drought induced by global climate change will be more extreme), net changes in national gross domestic product (GDP) between 2010 and 2050 reach $1.9 trillion. In the most likely scenario analyzed (the median, “50%” line, with a fifty percent chance that the induced drought will be more extreme), economic impacts remain substantial, about half the size of the most extreme scenario. Even the low-probability, best-case scenario (99%) simulation experience substantial negative impacts, about a quarter the size of the worst-case simulation. In total, these alternative scenarios suggest that the economic impacts of global climate change-induced drought are likely to be negative.



National GDP ranges from $14.3T to $52.6T in the REMI standard regional control.

Figure 15: Change in National GDP
(Excludes GDP Directly from Crops), by Climate Change Probability: 2010-2050

Net changes in employment-years (i.e. the net change in employment added across all years), GDP (measured by REMI, which does not include GDP directly due to crop production), GDP directly due to crop production (i.e., the value added of by farms that grow crops, which is not accounted by REMI because the farm sector is exogenous), and real disposable personal income are shown in Table 9. Although these economic impacts are a small fraction of overall economic activity of the period, they are substantial. Decreases in employment years range from a loss of 13.0.M in the least probable extreme drought scenario to about 6.6M in the most probable, median scenario. GDP losses range from a loss of about $1.9T to a loss of about $0.9T. GDP losses due to crops is relatively small, ranging from a loss of $0.16T to a loss of $0.13T. (Recall from the earlier factor analysis that GDP losses from the downstream industries that use crops were much greater.) Losses in real disposable personal income range from about a $1.7T loss to a $1.0T loss. Losses in the most probable scenario remain substantial, as the economic impacts are about half as large as the lowest probability scenario. Even the low-probability, best-case simulation (99%) experiences substantial losses that are about a quarter as large as the most severe simulation. Thus it is probable that the economic consequences of drought induced by global climate change will be negative.

Even the baseline simulation, which does not include global climate change, experiences a small amount of economic losses.[63] These losses exist because REMI's baseline projections of economic growth do not account for limitations in water availability that exist even without global climate change.

---

[63] Baseline losses are -1,874 employment years, -$316B in GDP contribution, and -$225B in real disposable personal income. In the baseline, crop productivity is nearly unchanged, so there is almost no impact to the GDP directly due to crops.

Table 9: Change in Employment-Years, GDP, and Real Disposable Personal Income: 2010 - 2050[64]

Simulation	Employment Years (k)		U.S. GDP (B, 2008 USD, no crops)		U.S. GDP ($B, 2008 USD, from crops)[65]		Real Disposable Personal Income ($B, 2008 USD)	
1%	-12,961	-0.15%	-$1,899	-0.16%	-$159	-0.01%	-$1,727	-0.19%
5%	-10,819	-0.12%	-$1,583	-0.13%	-$152	-0.01%	-$1,494	-0.16%
10%	-9,764	-0.11%	-$1,426	-0.12%	-$148	-0.01%	-$1,376	-0.15%
20%	-8,587	-0.10%	-$1,247	-0.10%	-$144	-0.01%	-$1,241	-0.14%
25%	-8,166	-0.09%	-$1,183	-0.10%	-$142	-0.01%	-$1,193	-0.13%
35%	-7,468	-0.08%	-$1,076	-0.09%	-$138	-0.01%	-$1,113	-0.12%
50%	-6,601	-0.07%	-$943	-0.08%	-$134	-0.01%	-$1,011	-0.11%
75%	-5,463	-0.06%	-$767	-0.06%	-$132	-0.01%	-$881	-0.10%
99%	-3,815	-0.04%	-$508	-0.04%	-$130	-0.01%	-$684	-0.08%

Figure 16 to Figure 19 display these four variables. The paths of these variables are highly erratic, reflecting the high variance of the year-to-year forecasts of the Sandia hydrology models. During all years except 2010—where impacts are nearly zero—impacts are monotonic, becoming worse with simulations of greater drought severity. All variables demonstrate impacts that are generally downward sloping, thus impacts are becoming larger in magnitude throughout time. As a result, if a discount rate of greater than zero were applied to the net economic effects in Table 9, the magnitude of these impacts could be reduced substantially because a discount rate would heavily discount the most severe economic impacts, which occur forty years into the future.

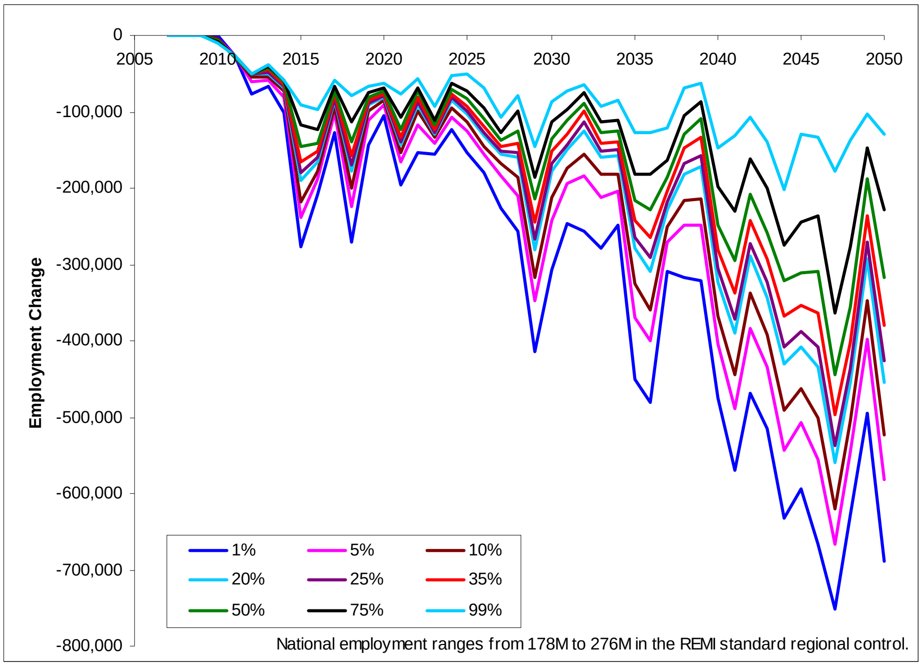
Figure 20 shows a chart of the loss of national GDP contributions of the industries that lose the most GDP due to drought in the most severe scenario (the 1% simulation). Mining and Manufacturing both have the largest losses of any economic sector, although the losses are relatively more severe in Mining because Mining is forecast to be a much smaller fraction of the economy.[66] Mining has the greatest losses due to the shutdowns in its operations due to a lack of consumptive water availability. Other sectors with large losses follow a similar pattern as mining over time, indicating that mining is driving a large portion of the losses. Other large losses are in retail trade, health care and social assistance, and finance and insurance, which are consumer-oriented sectors that suffer from the losses of jobs and income to employees of shuttering mining operations. The only sector with positive economic effects is Utilities, which is mainly due to the increases in economic activity (e.g., construction of new power plants and labor for those facilities) in the Utilities sector to compensate for net losses in hydroelectric production.

---

[64] Assumes a discount rate of zero.

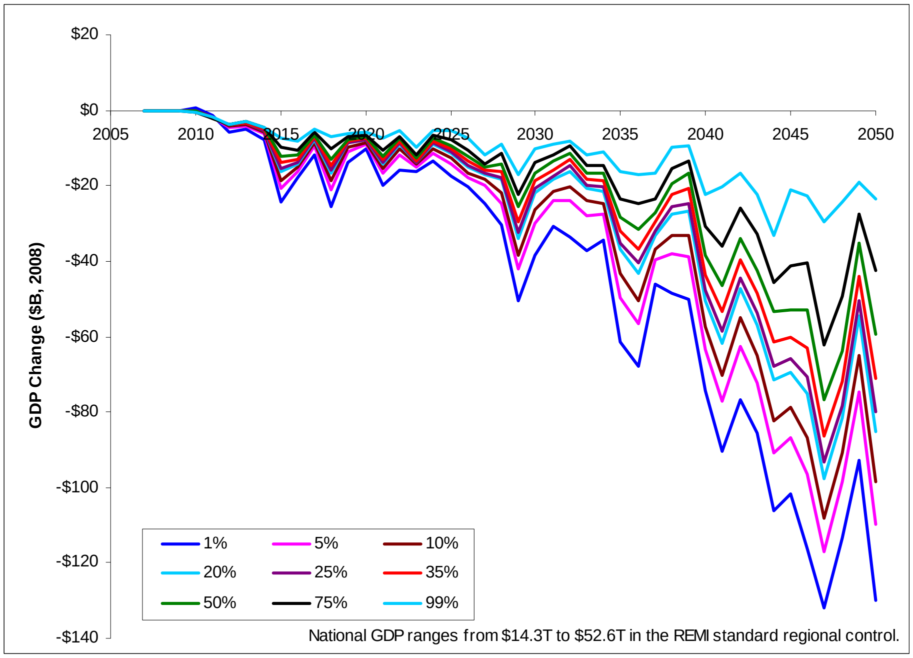
[65] This calculation assumes that changes in soy and corn production can be used as proxies for total crop production and uses a ratio of 0.801 of change in GDP directly due to changes in crop production to corn and soy production.

[66] In 2050, REMI's forecast GDP in its standard regional control is $6.8T for Manufacturing and $111B for Mining, which reflects REMI's forecast that Manufacturing will grow about 340 percent between 2007 and 2050, while Mining will remain nearly constant.



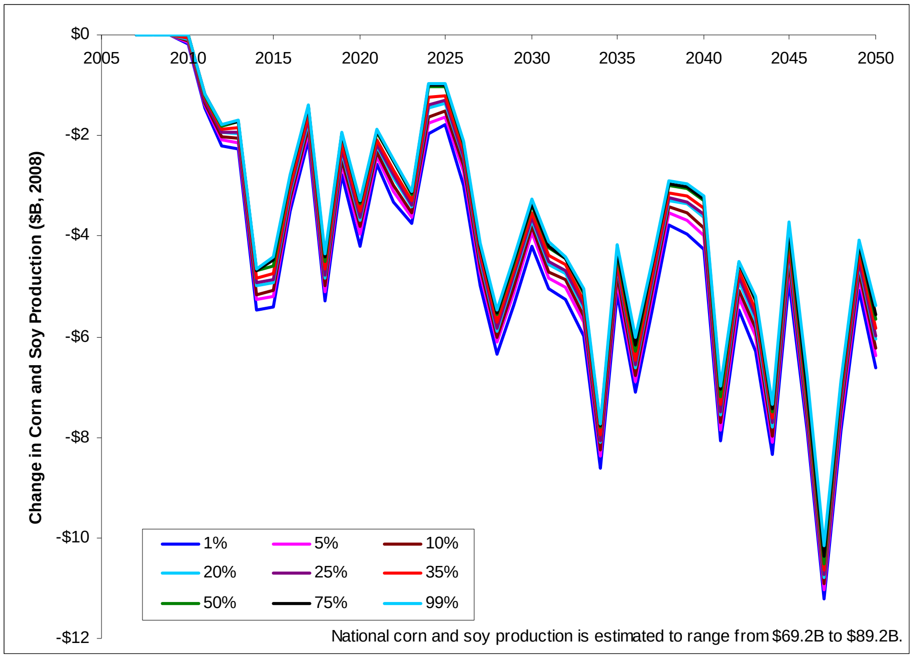
National employment ranges from 178M to 276M in the REMI standard regional control.

Figure 16: Change in National Employment, by Climate Change Probability: 2010-2050



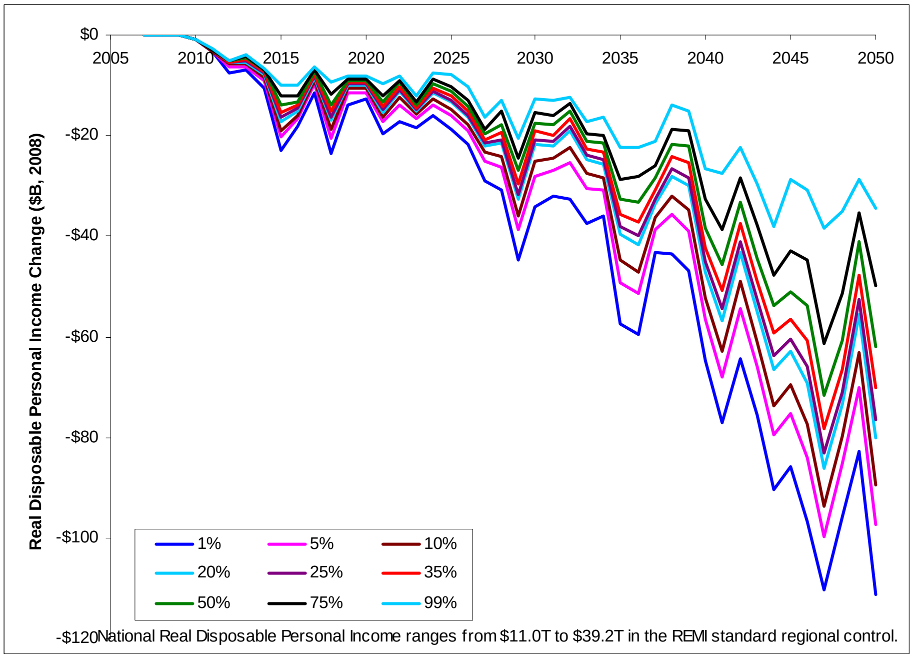
National GDP ranges from $14.3T to $52.6T in the REMI standard regional control.

Figure 17: Change in National GDP
(Excludes GDP Directly from Crops), by Climate Change Probability: 2010-2050



National corn and soy production is estimated to range from $69.2B to $89.2B.

Figure 18: Change in Corn and Soy Production, by Climate Change Probability: 2010-2050



National Real Disposable Personal Income ranges from $11.0T to $39.2T in the REMI standard regional control.

Figure 19: Change in National Real Disposable Personal Income, by Climate Change Probability: 2010-2050

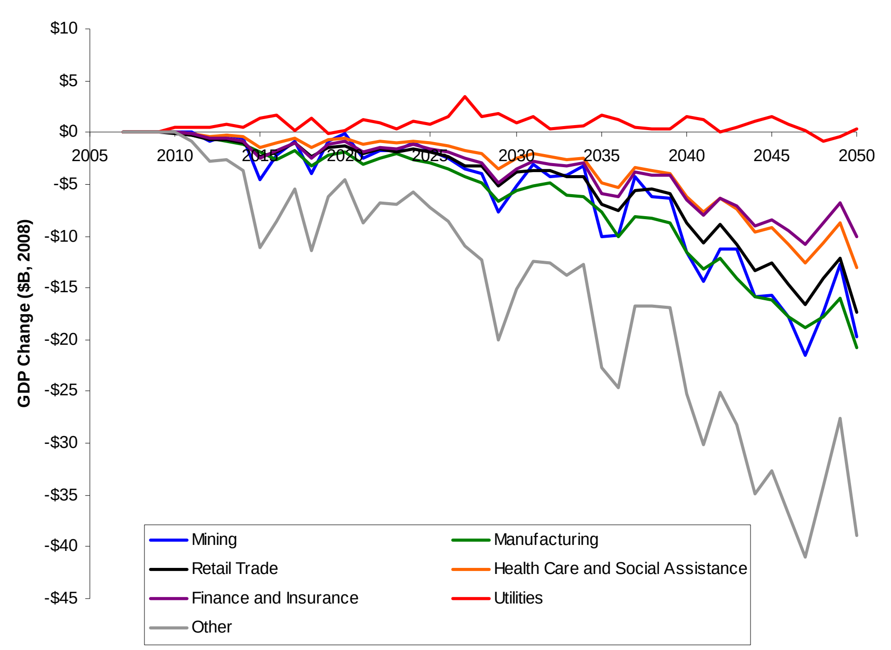


Figure 20: Changes in National GDP, by Private, Non-Farm Sectors (2010-2050): 1% Simulation

Regional Results

The national-level results from the previous section show that economic impacts for the entire nation are negative. However, this aggregate look at the economic impacts of drought induced by climate change may ignore important regional differences that create winners, losers, and big losers. Examining regional differences are particularly pertinent for this analysis because drought caused by climate change will vary in severity across the country and different regions contain different mixes of industry, which will suffer to different extents from drought. For example, heavy consumers of water tend to cluster together near sources of water, thus there is little water-intensive industry in most Western, arid states.

Figure 21 through Figure 23 show maps of state-level impacts to three of the economic measures analyzed in the previous subsection. To make the economic impacts comparable across large and small states, impacts have been divided by the forecast totals in REMI’s standard regional control simulations to generate a percentage change. Economic impacts are examined for the most severe scenario (1 percent probability that the drought will be more extreme). Less severe scenarios demonstrate less severe economic impacts, but maintain similar patterns of economic impact.

These maps show that all states suffer negative economic impacts for all variables, except for three states in the Northwest (Washington, Oregon, and Idaho). These states have slightly positive impacts; however, their slight gains are at the expense of the misfortune of others because these three states experience the largest increases in population (Figure 24), which transfers economic activity to these states. These gains are also due to the increases in demand for Utilities that result from reduced hydroelectric power production. Economic impacts are particularly severe in interior states that do not have the ability to substitute to desalinated water, and most acute in states like West Virginia with large concentrations of mining. For example, the GDP contribution of West Virginia is about 2.6 percent less than they would be without the consequences of drought.

Figure 24 shows a map of state-level population changes in 2050. Unlike the economic impacts, population impacts create a similar number of "winners" and "losers." National population changes very little as a result of drought (there is a loss of about 1,700 people in the 1% simulation), so regional population changes are almost entirely the result of Americans moving from one state to another for economic reasons. There is a strong regional pattern with states in the Southeast and Southwest losing population and states on the West Coast, the western Midwest, and the Northeast gaining. Once again, interior states with the greatest concentrations of mining lose the most, with West Virginia losing 3.6 percent of forecast population.

States that gain population are not necessarily "winners" in a normative sense because greater population may have negative, non-monetary impacts that are not modeled within this report. For example, all states adjacent to the Atlantic Coast in the Northeast are gaining in population, but these states may become more susceptible to hurricanes due to changes in global climate.

Lastly, Figure 25 shows the predicted change in value of corn and soy production across states. An even stronger regional pattern emerges here, with large percentage losses across all Southern, Southwest, and Eastern states. The Midwest, which produces most corn and soy, experiences only minor losses, while the Northwest experiences gains.

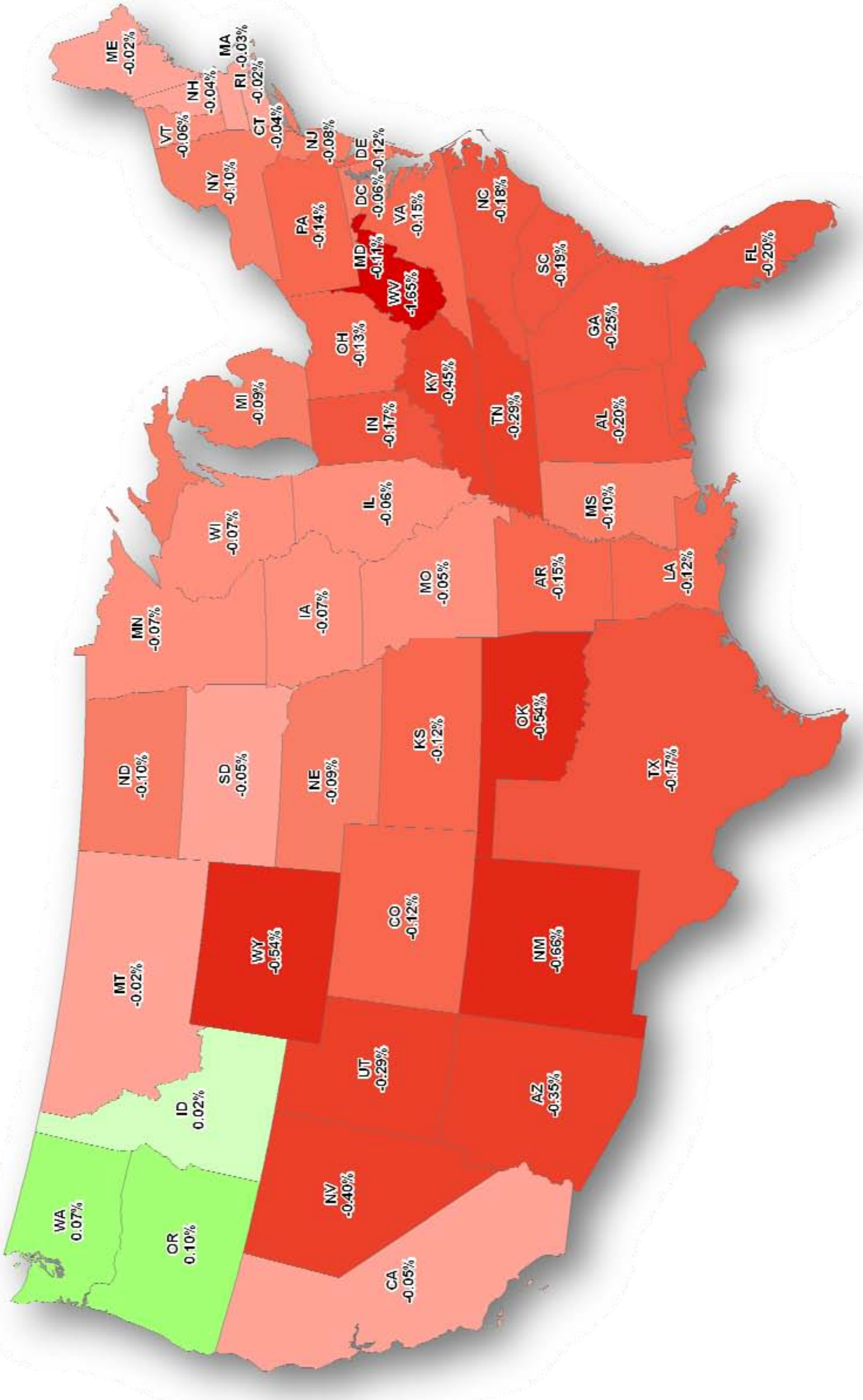


Figure 21: Percent Change in Employment-Years (2010-2050), by State: 1% Simulation

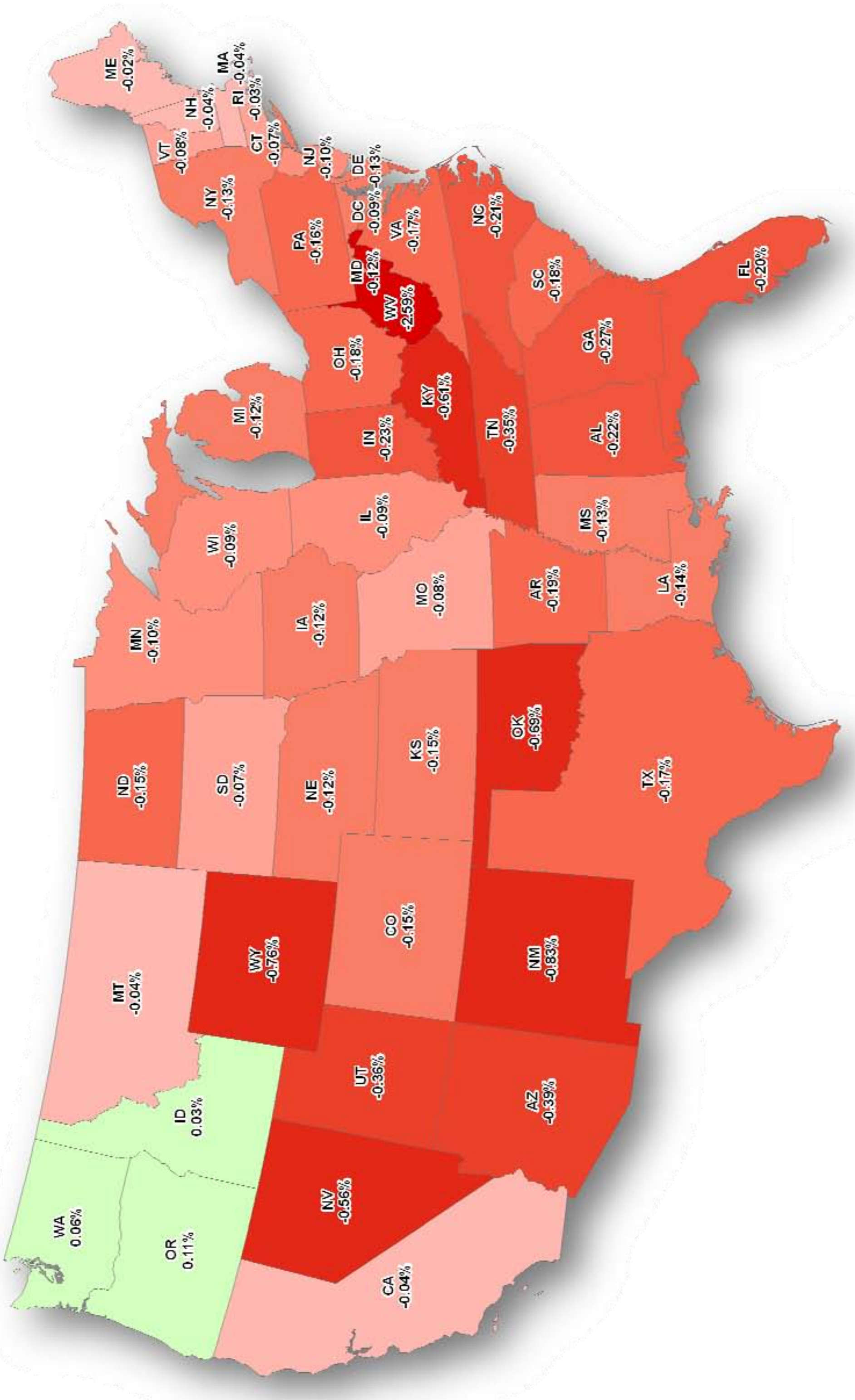


Figure 22: Percent Change in GDP (2010-2050), by State: 1% Simulation

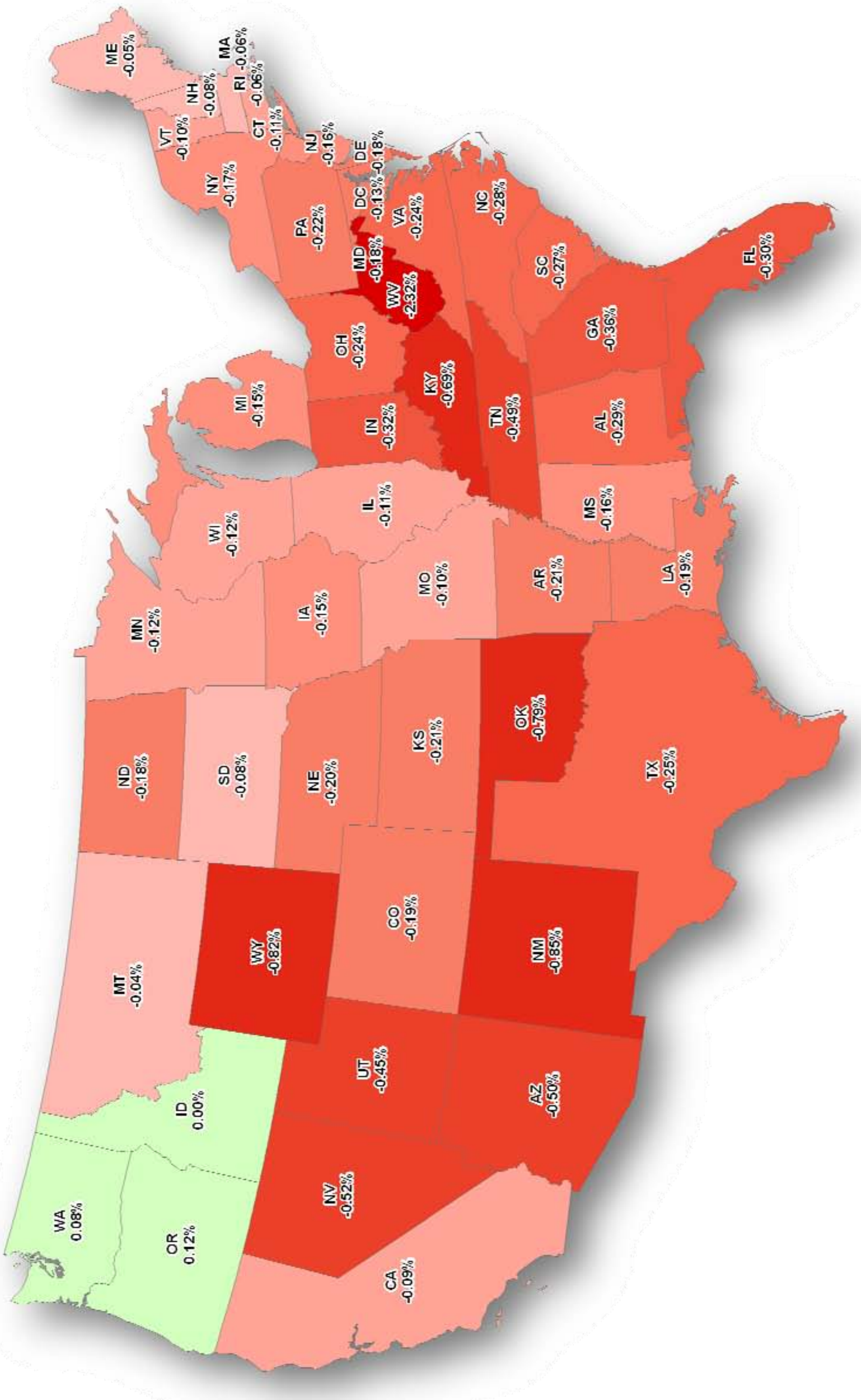


Figure 23: Percent Change in Real Disposable Personal Income (2010-2050), by State: 1% Simulation

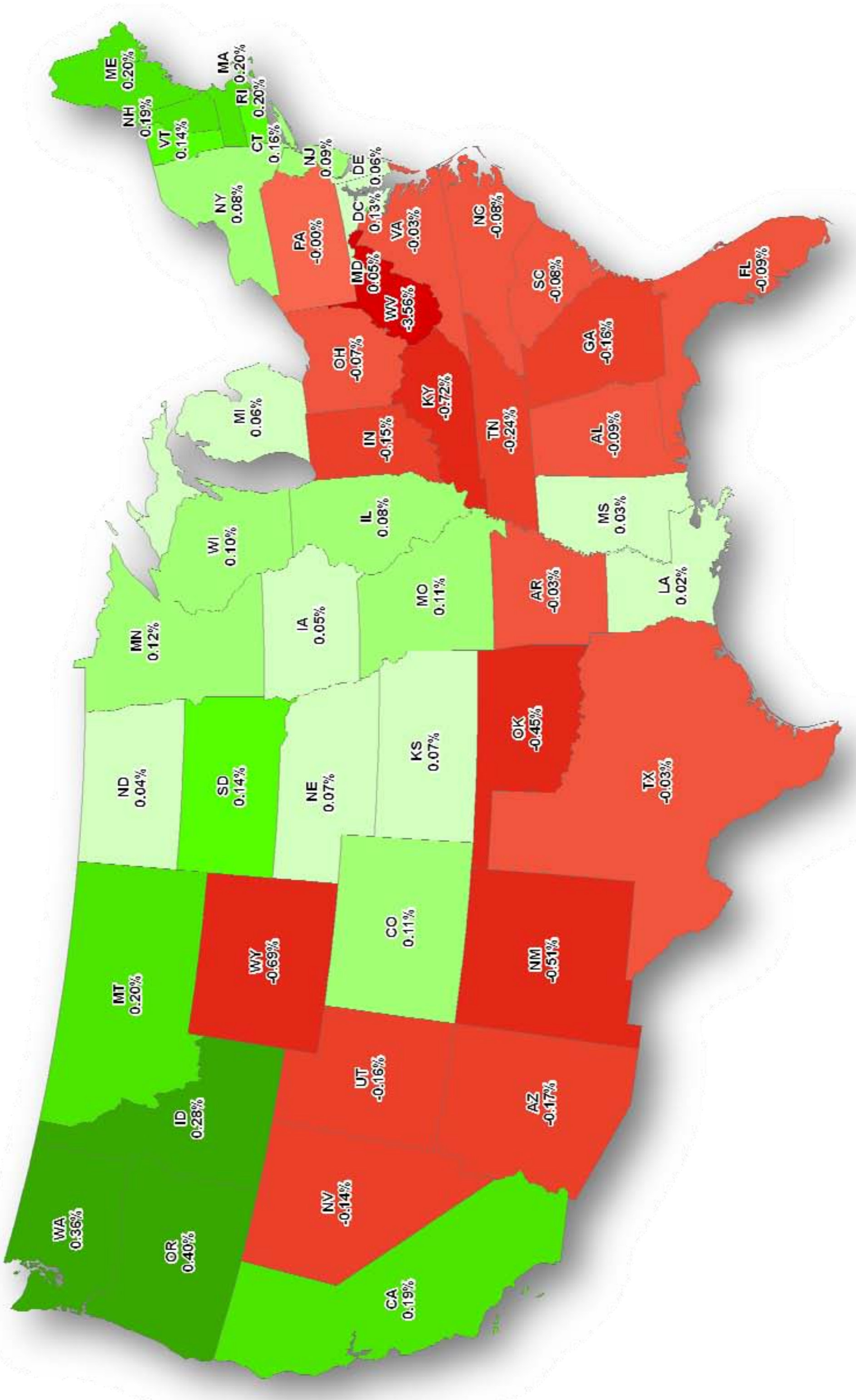


Figure 24: Percent Change in Population (2010-2050), by State: 1% Simulation

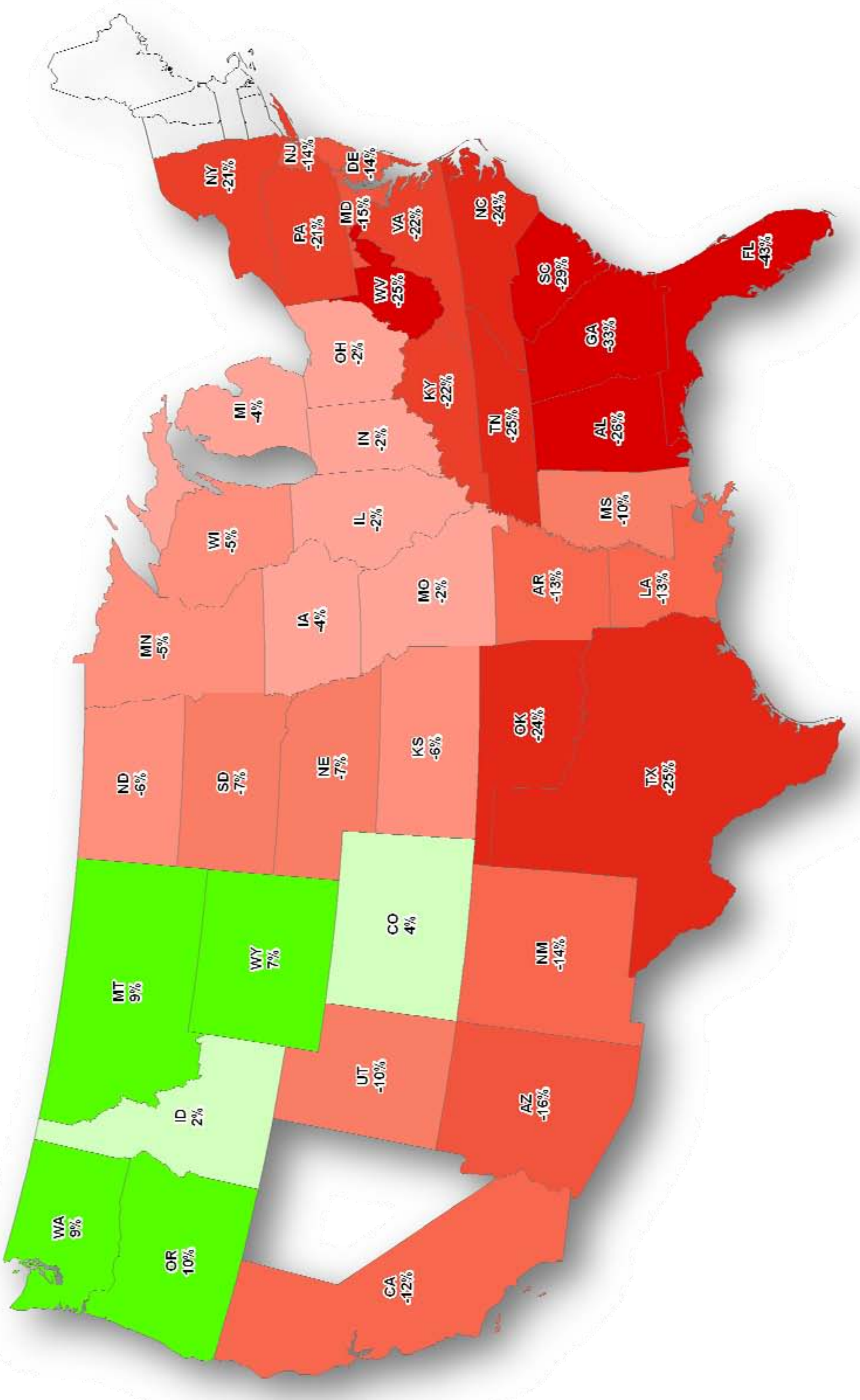


Figure 25: Percent Change in Corn and Soy Production (2010-2050), by State: 1% Simulation

4 Summary

This report quantifies some of the potential economic impacts of a subset of potential consequences of global climate change, namely changes in domestic agricultural productivity, changes in water available for consumption to large consumers of water, and changes in hydroelectric power consumption caused by global climate change-induced drought in the United States. While most previous research on climate change has examined best estimates of consequences, this report examines a range of realizable outcomes of different severities to gain a better understanding of the range of possible economic consequences.

To quantify the economic impacts of this subset of consequences of climate change, an economic methodology was developed to translate changes in agricultural production and reductions in consumable water (estimated by Sandia hydrology models) to economic impacts that can be simulated through 2050. The economic impacts quantified by this report are substantial. For example, net GDP losses between 2010 and 2050 reach $1.9 trillion. Furthermore, there are also significant regional disparities in the economic and demographic outcomes of states. Some of the largest economic impacts analyzed in this report are the result of water-conserving reductions in mining production. Alternate water allocation schemes or water-conserving mining technologies not accounted for in the economic methodology may reduce economic impacts substantially.

Several caveats to this report suggest future research directions. First, to reiterate, only a subset of potential consequences of global climate change to the contiguous United States have been forecast by the Sandia hydrology models (see Figure 2). There are many additional consequences that may produce substantial economic impacts. To quantify these impacts, it will be necessary to create additional climate simulations with a greater scope and to augment the economic methodology to map these climatologic effects to economic effects. Second, an improved set of economic methods and tools should be developed to better assess future economic impacts of climate change. The current methodology is limited to simulating future impacts to 2050, which may be insufficient for many consequences of global climate change that become especially severe in the second half of the century. Third, the ability of the economic methodology to account for the inevitable changes in the structure of both the domestic and international economies is extremely limited. Fourth, a deeper analysis of water allocation schemes should be conducted; the Sandia hydrology models analyzed in this report allocate water to sectors via a single scheme that may be unrealistic (and almost certainly suboptimal) in the event of severe water shortages.

Finally, the most likely scenarios analyzed in this report (with a 50 percent probability that global climate change induced drought will be worse) lead to substantial economic impacts that are about half as large as those in the worst-case simulation. Even the best-case simulation results in negative economic impacts. These results suggest that negative economic impacts due to global climate change are probable—at least for the drought consequences analyzed in this report. The first two caveats suggest that quantifying future economic effects of global climate change is a problem with an enormous scope with wide-ranging structural uncertainties. One promising strategy to lessen these inevitable impacts is by engaging in research to discover policies that best engender economic and societal resilience to a wide variety of possible consequences (with a range of severities) of global climate change).

This page intentionally blank

References

American Water Works Association. (2009) “Water Use Statistics”, http://www.drinktap.org/consumerdnn/Default.aspx?tabid=85, accessed May 27, 2009.

Chicago Mercantile Exchange. (2009) http://www.cmegroup.com/, accessed on May 19, 2009.

EconStats. (2009) “Implicit Price Deflator, BEA release: 04/29/2009,” http://www.econstats.com/gdp/gdp__a4.htm, accessed May 28, 2009.

Environmental Protection Agency. (2009) “Outdoor Water Use in the United States”, *WaterSense*, http://www.epa.gov/watersense/pubs/outdoor.htm, accessed May 27, 2009.

Field, C.B., Mortsch, L.D., Brklacich, M. , Forbes, D.L., Kovacs, P., Patz, J.A., Running, S.W., and Scott, M.J. (2007) “North America,” *Climate Change 2007: Impacts, Adaptation and Vulnerability*, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., and Hanson, C.E., Eds., Cambridge University Press, Cambridge, UK, pp. 617-652.

Gleick, P.H. (1996) “Basic Water Requirements for Human Activities: Meeting Basic Needs,” *Water International*, v. 21, pp. 83-92.

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A. (2004) “Estimated Use of Water in the United States in 2000,” USGS Cicular 1268, Revised Feb. 2005, http://pubs.usgs.gov/circ/2004/circ1268/, accessed May 27, 2009.

LAZARD. (2008) *Levelized Cost of Energy Analysis—Version 2.0*, June, 2008, http://www.narucmeetings.org/Presentations/2008%20EMP%20Levelized%20Cost%20of%20Energy%20-%20Master%20June%202008%20(2).pdf, accessed June 24, 2009.

Maulbetsch, J.S. (2006). “Water Conserving Cooling Status and Needs”, July 25, 2006, http://www.sandia.gov/energy-water/West/Maulbetsch.pdf , accessed May 27, 2009.

Miller, J.E. (2003) *Review of Water Resources and Desalination Technologies*, Sandia National Laboratories SAND Report # 2003-0800, http://www.prod.sandia.gov/cgi-bin/techlib/access-control.pl/2003/030800.pdf, accessed May 17, 2009.

NationalMaster. (2009) “Time Series > Economy > GDP deflator > Canada,” http://www.nationmaster.com/time.php?stat=eco_gdp_def-economy-gdp-deflator&country=ca-canada, accessed May 28, 2009.

National Research Council Committee on Advancing Desalination Technology, *Desalination: A National Perspective*, The National Academies Press, Washington, D.C. http://www.nap.edu/catalog.php?record_id=12184

Northwest Power and Conservation Council. (2009) "Appendix B: Draft Economic Forecast," February 13, 2009, http://www.nwppc.org/library/2009/2009-03.pdf, accessed June 24, 2009.

Powers Engineering. (2009) "Once-Through Cooling and Energy", http://www.cacoastkeeper.com/assets/pdf/Energy_OTC_Fact_Sheet.pdf, accessed on May 27, 2009.

Regional Economic Models, Inc. (2009) "REMI PI+," v. 1.0.114, March 24, 2009 build, 51 region, 70 sector model, Amherst, MA.

Statistics Canada. (2008) "Industrial Water Use 2005", Catalogue no. 16-401-X, March 2008, http://www.statcan.gc.ca/pub/16-401-x/16-401-x2008001-eng.pdf, accessed May 28, 2009.

Statistics Canada. "National economic accounts: Input-output," "Input and output, by industry and commodity, M-level aggregation," "2005 total outputs per industry," http://www.statcan.gc.ca/nea-cen/list-liste/io-es-eng.htm, accessed May 28, 2009.

Stroeve, J., Holland, M.M., Meier, W., Scambos, T., and Serreze, M. (2007) "Arctic sea ice decline: faster than forecast," *Geophysical Research Letters*, 34, L09501, 2007.

Treyz, G.I., Rickman, D.S., and Shao, G. (1991) "The REMI Economic-Demographic Forecasting and Simulation Model," *International Regional Science Review*, 14(3), pp. 221-253.

U.S. Census Bureau, Bureau of Economic Analysis. (2007) "The Use of Commodities by Industries after Redefinitions," 2007 summary-level table, http://www.bea.gov/industry/iotables/table_list.cfm?anon=82430, accessed May 27, 2009.

U.S. Census Bureau, Bureau of Economic Analysis. (2007) "BEA Industry-by-Industry Total Requirements after Redefinitions," 2007 summary-level table, accessed May 27, 2009.

U.S. Department of Agriculture, National Agriculture Statistics Service. (2009) *Crop Values 2008 Summary*, February 2009, http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu02-13-2009.pdf, http://usda.mannlib.cornell.edu/usda/nass/CropValuSu/2000s/2009/CropValuSu-02-13-2009.zip, accessed October 2, 2009.

U.S. Department of Agriculture. (2009) "Grain Transportation Report," http://www.ams.usda.gov/GTR), accessed May 14, 2009.

U.S. Department of Energy, EAI. (2007) "2007 Net Generation by State by Type of Producer by Energy Source (EIA-906)," http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html, accessed May 27, 2009.

U.S. Department of Energy, EIA. (2009) "Annual Steam-Electric Plant Operation and Design Data (EIA-767)," http://www.eia.doe.gov/cneaf/electricity/page/eia767.html, accessed May 27, 2009.

U.S. Global Climate Change Research Program. (2009) *Climate Change Impacts in the United States*, Cambridge University Press, 2009.

U.S. Global Climate Change Research Program. (2009) *Global Climate Change Impacts in the United States*, Cambridge University Press, p. 56.

Weitzman, M. (2009) "On Modeling and Interpreting the Economics of Catastrophic Climate Change." The Review of Economics and Statistics, XCI(1), February 2009.

World Bank, International Comparison Project. (2008) "Tables of Results", Washington, D.C., http://siteresources.worldbank.org/ICPINT/Resources/icp-final-tables.pdf, accessed May 28, 2008.

Yang, X. and Dziegielewski, B. (2007) "Water Use by Thermoelectric Power Plants in the United States," *Journal of the American Water Resources Association*, v 43(1), pp. 160-169.

DISTRIBUTION LIST

1 MS 0899 Technical Library, 9536 (electronic copy)
2 MS 1138, Lillian A. Snyder
2 MS 1138, Drake E. Warren
1 MS 1138, Verne W. Loose
1 MS 1138, Vanessa N. Vargas
5 MS 1138, Mark A. Ehlen