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Uncertainty Quantification and Validation of Combined Hydrological and Macroeconomic Analyses

Theresa J. Brown, M. Jordan Parks, Jacquelynne Hernandez, Barbara J. Jennings, Paul G. Kaplan, and Stephen H. Conrad

Prepared by
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Abstract

Changes in climate can lead to instabilities in physical and economic systems, particularly in regions with marginal resources. Global climate models indicate increasing global mean temperatures over the decades to come and uncertainty in the local to national impacts means perceived risks will drive planning decisions. Agent-based models provide one of the few ways to evaluate the potential changes in behavior in coupled social-physical systems and to quantify and compare risks. The current generation of climate impact analyses provides estimates of the economic cost of climate change for a limited set of climate scenarios that account for a small subset of the dynamics and uncertainties.

To better understand the risk to national security, the next generation of risk assessment models must represent global stresses, population vulnerability to those stresses, and the uncertainty in population responses and outcomes that could have a significant impact on U.S. national security.

ACKNOWLEDGMENTS

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ACRONYMS, INITIALISMS, AND ABBREVIATIONS

CASoS	Complex Adaptive Systems of Systems
CCSM	Community Climate System Model
CPI	Corruption Power Index
DOE	Department of Energy
GDP	Gross Domestic Product
Gini	Gini Coefficient – Income Inequality
HDI	Human Development Index
ha	hectare
SNL	Sandia National Laboratories
TARWR	Total Actual Renewable Water Resources
USD	U.S. Dollars

1. INTRODUCTION

The large and growing body of scientific literature on global climate modeling focuses on the most probable future. Sandia National Laboratories (SNL) climate modeling and analysis projects fill a gap in climate research by concentrating on climate risks to populations. This risk-based scientific approach accounts for the full range of potential outcomes and explicitly includes uncertainty. A scientific approach is the most appropriate method for gaining understanding of natural systems and is achieved by applying physically sound theory, empirical observations, and valid models.

1.1 Related Projects

The physically sound theory for climate models is found within the flagship Department of Energy (DOE) Community Climate System Model (CCSM). Obtaining regional resolution in the CCSM requires high-resolution modeling, which SNL has recently achieved by integrating the highly scalable spectral element dynamical core into the CCSM (Taylor, et al., 2009). Figure 1-1 is an example of the model output. This model is being downscaled and results extracted for two regions, the Arctic and the Middle Rio Grande Basin, to identify the anticipated, but unknown, emergent regional consequences.

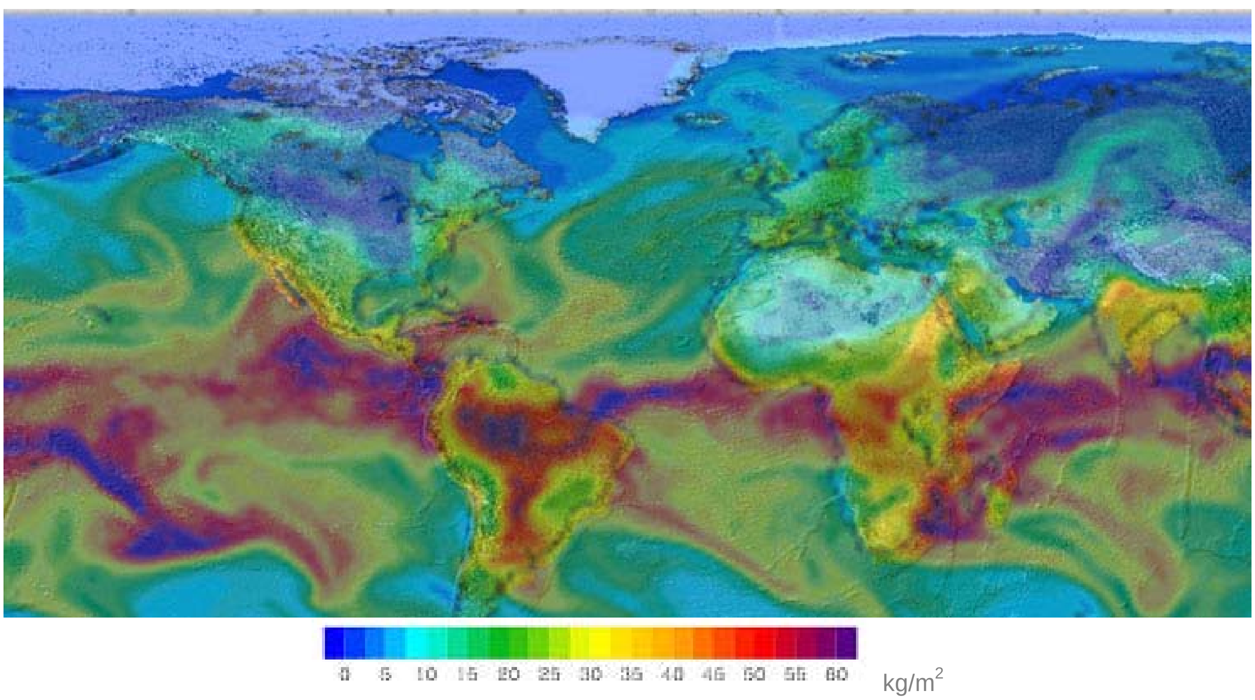

Figure 1-1. Precipitable Water from a CCSM Simulation Using the SNL Scalable Dynamical Core (shown over current surface)

The Arctic region modeling and analysis considers changes in socio-economic conditions due to increasing Arctic accessibility to natural resources and strategic locations and opening of shipping routes. In the Middle Rio Grande Basin study, the emphasis is on modeling changes in hydrologic conditions and agricultural productivity and the economic consequences of those physical and biological system changes.

1.2 Project Goals

This analysis addresses the specific applications of the climate risk modeling approach and reviews the conceptual model validity to determine whether the current modeling constructs sufficiently represent the range of effects that climate change can have on the economy in multiple regions. This is the conceptual model validity-testing stage. The first step in reviewing the validity of the conceptual model is evaluating whether processes and uncertainties beyond those in crop yield and water availability significantly increase the climate risks (Backus et al., 2010). The outcome of this first step will be used to identify comparisons or tests that can be performed to build confidence in the risk estimates produced by linked physical-economic models.

Climate risk is defined for this analysis as the probability and consequences of changes in climate conditions. The consequences for populations, such as reduced reliability of essential services (food, water, and electric power), economic losses, and geopolitical instabilities, are critical to understand when designing risk mitigation strategies. The timing, magnitude, and nature of the potential impacts will vary regionally as a function of the differences in the current physical, geopolitical, and economic conditions and the nature, magnitude, and timing of the climatic conditions in those locations.

Opening of Arctic transportation routes and access to natural resources resulting from warmer temperatures is a shock to the global economy (sudden structural change) and a stress on the geopolitical relationships between the countries with borders adjacent to those routes. Changes in climate will impact agricultural productivity and lead to structural changes in global food supply and manufacturing networks that could have a greater extent of impact than opening Arctic transportation routes and resources, but may not increase geopolitical tensions. Other impacts, such as reduced water supplies, will be regional in extent due to the inherently regional nature of water supply, but such impacts have the potential to cascade if the region involved is under another stress (geopolitical or economic). Thus the key question for this study to address is: Can a valid, generic modeling approach be developed to quantify climate risks?

To quantify the risk the probability of each potential consequence must be estimated. This probability is a function of the uncertainties in the stresses that will be experienced and the vulnerability to those stresses of the population and the physical and engineered systems. The severity of climate change is the primary source of parametric uncertainty in estimating the climate stresses. The uncertainty in the vulnerability to the stresses is due to lack of knowledge about how the population will respond. It is assumed that the wealth of the population that is impacted by those physical changes and the degrees of freedom the impacted population has to respond (migration, alternative resources) will have significant impacts on the population vulnerability.

Other questions evaluated in this project include:

- Does the current modeling construct sufficiently represent the range of effects that climate change can have on the economy and therefore the climate risks?
- Are there uncertainties beyond the amount of precipitation by state that will affect economic productivity?
- What comparisons or tests can be done to build confidence in the risk estimates produced by the linked hydrologic-economic models?
- What could be done to improve the climate risk analysis methodology?

These questions are explored through evaluation of the conceptual model validity and development of an integrated analysis and validation strategy that includes uncertainty analysis.

2. VALIDATION

Common model validation strategies include one or more of the following tests: comparison with other models; comparison with experimental results; comparison with real events (can be prediction of future events or replication of past events); and peer review to determine whether the key elements, processes, and outcomes are included and sufficiently documented (Gass, 1983; Anderson and Woesner, 1992; and Barlas, 1998). This analysis is a peer review of the existing conceptual modeling approach used by Backus et al. (2010) to determine whether the current modeling construct sufficiently represents the range of effects that climate change can have on the economy and therefore the climate risks.

2.1 Conceptual Model Validation

The near-term time frame Backus et al. (2010) evaluated for impacts of climate change is years 2010 to 2050. The models and analyses by Backus et al. (2010) are referred to as the 'current' models and analyses in this report. The impact analysis focused on the uncertainty in climate for the Continental U.S. during that time frame; therefore the models do not represent global risks such as sea level rise (which may start to have impacts on low-lying nations such as Egypt and Bangladesh within the time frame specified), the global capacity to offset agriculture production changes in the U.S., or the impacts that changes in the U.S. economy will have on other economies and populations. The current conceptual model illustrated in Figure 2-1 shows the major sectors and the relationships included in the models and analysis.

The current model represents the economic risk to the U.S. as a function of the uncertainty in the future precipitation and the resulting consequences in the economic productivity due to water availability. Insufficient water availability is the threat that could cause the economic consequences in the current model. Risk is a function of both probability and consequences of a specific set of circumstances. In the case of risks due to changes in global climate, the potential consequences can be categorized as environmental (increase in extreme weather events, changes in flora and fauna, reduction in species diversity, reduction in stream flows, reduced fresh water stored in lakes and/or ice) and population (displacement, reduced income, undernourished, reduced health, loss of wealth). The causes of the population impacts can be categorized by the impacts of climate change on lifeline services (food, water, shelter, emergency services) and the economic effects of the infrastructure and population consequences (changes in consumer demand, reduced agriculture productivity, reduced electric power reliability, reduced raw material availability, increased transportation costs). The probability of each type of consequence occurring depends on the environmental and population vulnerability to the threat and the probability the threat will be realized; it is more than a function of the uncertainty in the magnitude of the threat.

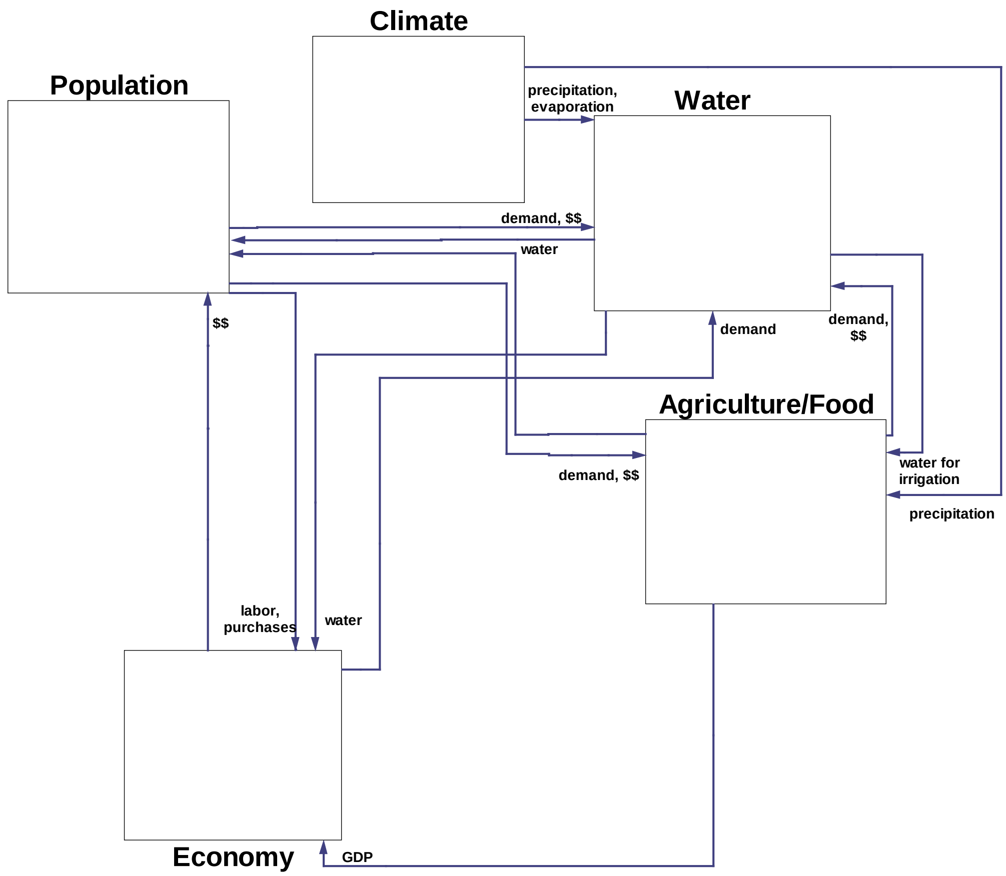

Figure 2-1. Conceptual Model of Key Sectors and Interactions in the Initial Economic Impact Analysis by Backus et al. (2010)

The current conceptual model is not sufficient to support all the decisions related to how the U.S. will or should invest in reducing climate risks. Key elements are missing from the evaluation of the threat to water supplies. There are dependencies between electric power, water supply and temperature that need to be included in the next generation of climate risk models. The models also need to be expanded to evaluate key assumptions regarding the ability of global agriculture and mining to offset changes in U.S. production. There are other assumptions in the current model that should be evaluated to determine their significance, particularly instantaneous building of electric power generation to offset increased peak demand due to changes in temperature, population and economic activities. Finally, the model needs to include the policy and controls that might be used to reduce the risks. The key systems and relationships needed to more completely evaluate the climate risks are shown in Figure 2-2.

The remaining sections of this report further expand the climate risk conceptual model and analysis process.

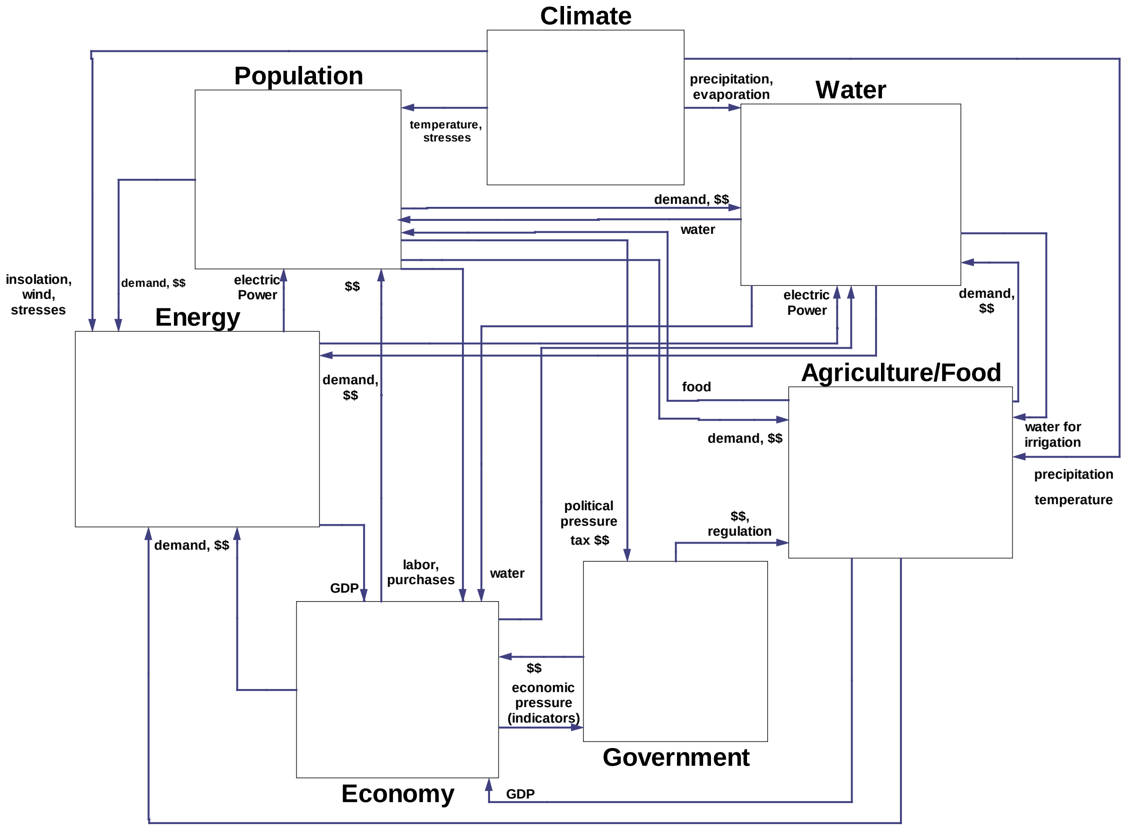

Figure 2-2. Enhanced Conceptual Model to Support Risk-based Decision Making

2.2 Climate Risk Validation Strategy

The validation strategy for climate risk modeling must exceed the standard confidence building measures used for models of physical systems. Climate risks are a function of physical, social, political, behavioral, and economic system interactions. Comparison to historical data won't build confidence in a model of future conditions that are beyond historical experience. Predictive comparisons that match the outcomes will build confidence in the model but not within the time frame required to support decision making. Comparisons to field tests and other models could provide limited testing of model performance, but it is not clear that would provide sufficient confidence in the model(s) to support decision making for an issue as broad, complicated, and contentious as reducing climate risks.

A new validation and analysis strategy is required for this problem in which the decision time frame is shorter than the time required for resolving the uncertainties, the implications are global, and complex, adaptive, interdependent systems are involved. Rather than asking whether the model can predict the future with sufficient accuracy, the question becomes whether the analyses sufficiently represent the uncertainty and processes to identify risk mitigation actions that are robust to that uncertainty. In this approach, the model validation strategy becomes an integral part of the analysis.

The steps to implement this validation strategy are:

1. Clearly state and document the analysis goals (decisions that need to be supported).
2. Develop and document conceptual model, including initial identification of potential risk mitigation actions based on changes to system structure, system controls, and/or modification of key system elements.
3. Review model design to verify it contains the key elements and relationships between those elements with respect to the decisions.
4. Develop numerical model (implement conceptual model in software).
5. Test the model(s) to verify that calculations are executed as designed and model behavior is appropriate [e.g., no numerical instabilities, mass is conserved, dynamics are reasonable/realistic in comparison to real-world events and/or other models, and internal consistency (e.g., CO_2 emissions are consistent with the climate model assumptions)].
6. Conduct model and parameter sensitivity analyses to identify assumptions and parameters that have the greatest influence on outcomes (consequences and/or probability of the consequences).
7. Simplify the model based on sensitivity analysis.
8. Quantify model and parameter uncertainties.
9. Evaluate risk mitigation action effectiveness and robustness to uncertainty
    - Base case (no interventions/modifications to system – uncertain outcomes)
    - Risk mitigation actions (comparison of intervention performance under uncertainty)
        - Reduction in magnitude of consequence (consequence)
        - Reduction in uncertainty of consequence (probability)
        - Reduce risk (probability and consequence)

There are few examples of validation for models of complex adaptive systems, interacting networks, or risk mitigation strategies for such problems. The strategy proposed here is based on a social-network-based study to design containment strategies for novel strains of influenza to prevent pandemics and large numbers of deaths (Perlroth et al., 2010; Davey et al., 2008; Davey and Glass, 2008) and the development and testing of complex adaptive systems of systems (CASoS) models of the global energy system (Glass et al., 2008).

3. VULNERABILITY

A key element missing from the current climate risk model is explicit representation of population vulnerability to climate changes. Economic vulnerability is implicitly included in the REMI model [Regional Economic Models Inc. (2009)], but that model neither extends beyond the boundaries of the U.S. nor includes global supply chain dynamics and the potential impacts of those dynamics on U.S. supply and demand. To support decision making, population vulnerability must be represented in the analysis in a way that enables quantification of the probability that climate changes (the threat) will cause specific consequences, aids identification of risk mitigation measures, and allows evaluation of the effectiveness of risk reduction actions (changes in the probability of the specified consequences as a function of protective measures or other risk mitigation actions). The vulnerability model must explicitly link population characteristics to consequences and threat. An initial analysis of the climate threats, potential consequences, and indicators of regional or national vulnerability is provided in Table 1.

Table 3-1. Climate Threats, Potential Consequences, and Population Vulnerability Indicators

Climate Threats	Potential Consequences	Vulnerability Indicators
Increased Annual Temperature	Reduced agricultural productivity leading to national food shortage	Per capita income, national per capita grain production
	Reduced agricultural productivity leading to national economic disaster	Agriculture contribution to national Gross Domestic Product (GDP)
	Reduced reliability of electric power supply leading to significant regional or national economic impacts	Electric power reliability, electric power dependence on surface water for cooling, fraction of population that has electric power
Reduced Annual Precipitation	Reduced agricultural productivity leading to national food shortage	Per capita income, national per capita grain production
	Reduced agricultural productivity leading to national economic disaster	Agriculture contribution to national GDP
	Reduced potable water supply leading to health impacts	Fraction of population that has access to potable water, per capita water supply
	Reduced water supply for economic activities leading to significant regional or national	Per capital water supply, per capita water use, per capita GDP

	economic impacts	
Sea Level Rise	Reduced land area for population leading to overcrowding, disease and decline or mass migration	Low-lying coastal land area relative to total land area, population density in low-lying coastal area, per capita income, income distribution
	Reduced land area for agriculture leading to national food shortage	Fraction of national agricultural land in low-lying coastal area
Ice Melt	Loss of water stored in ice reducing potable water supply and leading to health impacts	Fraction of potable water stored in ice, fraction of stored water used
	Reduced water supply for economic activities leading to significant regional or national economic impacts	Fraction of water supply stored in ice

3.1 Climate Vulnerability Models

A literature review of climate vulnerability models and vulnerability indicators provides the basis for a new climate vulnerability model centered on population risk. None of the models found in the literature search provide indicators for all threats and consequences of concern. (See Appendix A for an annotated bibliography of the literature reviewed.) The most complete model for analyzing population vulnerability was developed by Brenkert and Malone (2005), who use quantitative data to represent the vulnerability of nations as a function of economic capacity, human and civic resources, environmental capacity, settlement and infrastructure sensitivity, food security, ecosystem sensitivity, human health sensitivity, and water source sensitivity. In the Brenkert and Malone (2005) vulnerability model, each component has several indicators, such as GDP per capita and income inequality, for economic capacity. Adding other factors that influence the population vulnerability to climatic changes, such as geo-political stability, other stresses such as war and conflict, geographic factors, economic diversity, social capital factors (e.g., democracy scores, civil liberties, internal locus of control), education, and institutional measures, and tying each set of factors to the threat and consequences yields a model of vulnerability that can be used to perform an initial risk and risk mitigation options evaluation. The initial evaluation identifies the elements and relationships that must be included in the risk modeling and analysis.

Some indicators in the 2005 Brenkert and Malone model are based on components that are strongly correlated. This allows simplification of the model. Brenkert and Malone (2005) combine all factors into a single vulnerability value for each country. This allows creation of a ranked list, but does not preserve the relationships between threat, vulnerability, and consequence required for identification of potential risk reduction measures or analyses that will support decision making.

A simplified, disaggregated vulnerability model was developed for this project to illustrate the potential value of including a global population vulnerability model component in the next generation of climate risk models and analyses.

3.2 National or Regional Population-Based Climate Vulnerability Model

Individual nations or regions (states, for example) can be represented by their economic, social, geographical, technical, political, and infrastructure systems capacities to absorb or adapt to changes in climatic conditions. Representation of the initial conditions is based on data. Changes in vulnerability due to climate stresses can be estimated using models of those systems and their interactions.

3.2.1 Economic Capacity

Wealth generally increases the options a society has for adapting to stresses or changes in system structure. Financial resources provide access to technology, education, and knowledge, and insure survival. Wealth allows countries to adapt using research, infrastructure improvement and modification, and well-connected communication systems. With sufficient resources, societies can offset shortages through trading and recover from disasters through networks of emergency personnel and assistance programs (Brenkert and Malone, 2005). Conversely, poverty compounds the effects of climate stresses.

Economic capacity to adapt to stresses is represented by the current productivity, distribution in income, and diversity in the economic sectors that contribute economic production. Three factors are used to represent the initial population economic vulnerability to climate stress: the average economic productivity per person, the distribution of wealth in the population, and the diversity of the economic activity. The initial economic capacities are represented in the model using the following data:

- **GDP per Capita** - To measure the effects of wealth, GDP per capita is included as a proxy for economic capacity. This statistic is appropriate for comparisons between countries because it adjusts for population size and reflects general standards of living.

- **Gini Coefficient –** Although income is linked with a great many predictors of adaptive capacity, it is not sufficient to predict vulnerability. In countries with high levels of income inequality, GDP does a poor job of providing an overall evaluation. Those at opposite ends of the income spectrum have very different income levels that will lead to very different adaptive potentials (Kelly and Adger, 2000). To monitor this income discrepancy, the Gini index (Vision of Humanity, 2010; U.S. CIA, 2009; United Nations, 2009) will be used. Countries with high Gini Coefficients should have restricted adaptive options compared to those at the same GDP with lower Gini scores, because a higher percentage of their populations are impoverished.

- **Sector Breakdown of GDP –** Beyond the overall value of a country's GDP is the important consideration of the composition of the GDP. In adaptation research, income diversity for individuals as well as countries has been found to be a key adaptive strategy (McLeman et al., 2008; Brenkert and Malone, 2005; Cullen and Glaser, 2007). Countries with more diverse income distributions should prove more resilient to the impacts of global climate change. One specific indicator of vulnerability to climate stress is the percent of a country's GDP derived from agriculture. Agricultural productivity will be impacted by changes in climate and extreme weather events during the planting, growing, and harvest seasons. Therefore, countries with higher levels of dependence on agriculture as a percentage of GDP will be more vulnerable to climate change.

3.2.2 Infrastructure Capacity

Water supply, agriculture, and electric power are three infrastructure systems that will be the most directly impacted by changes in precipitation and temperature. Each is described below.

3.2.2.1 Water Supply

Water is a vital commodity, required for human life and a functioning society. It is included in different ways in other models of climate change vulnerability (Brenkert and Malone, 2005; Yale Center for Environmental Law and Policy, 2005; Kaly et al., 2003). Precipitation levels, which are strongly linked with economic outcomes, are more variable than temperatures (Backus et al., 2010). If climate change produces increased variation in precipitation levels or overall lower levels of precipitation, then those countries with greater existing water resources should be more resilient than those with lower levels. Financial resources and access to large volumes of saline water and electric power are one option for mitigating water supply limitations; because the mitigation is a function of economic and electric power capacity, the initial vulnerability of national water supplies is estimated based on the amount of water resources and use of those resources. Water supply vulnerability indicators used include:

- **Total Actual Renewable Water Resources (TARWR) –** This variable is designed to estimate the maximum renewable water available within each country. It takes into account existing upstream and downstream water agreements as well as dam holdings. The more water a country has in reserve, the more it can withstand future drought or rainfall inconsistency. This variable is also adjusted by per capita to consider population. This indicator does not include water stored in ice, snow or aquifers.

- **Percent of TARWR Currently Being Withdrawn –** Equally important as how much water a country has is how much is currently being used. This indicator measures how much of the TARWR is already allocated. A country using 97% of its TARWR will be far more vulnerable than one using only 5%. Some countries, such as Kuwait (2227%) and Libya (711%), already use far more fresh water than their countries have and rely on water imports, nonrenewable ground water, and desalinization (FAO, 2008). It is assumed that they will be even more vulnerable if precipitation is lower and/or temperatures increase, thereby increasing water demand in their region.

3.2.2.2 Food/Agriculture

Along with water, food is a basic necessity. During times of global economic hardship, a country's ability to produce food, rather than import it, will provide greater food security. Food is included in many vulnerability models (Brenkert and Malone, 2005; Yale Center for Environmental Law and Policy, 2005; Kaly et al., 2003). Food production is a tricky indicator. Over-reliance on agriculture as a percent of GDP leads to less economic resilience, but having a stable internal supply leads to greater food security. With respect to climate vulnerability, food production is a good indicator, but not as a primary driver of a country's economy. The following factors are used to indicate food infrastructure capacity:

- **Percent of Total Agricultural Land That Is Arable –** This measure is a proxy for how much potential farmable land remains in a country. It measures the potential to increase farming efforts to reduce dependence on foreign sources of food.

- **Agriculture Land per Capita** – Current levels of land in continuous and temporary production indicates the amount of agriculturally productive land available to support the population (World Bank, 2007).

- **Grains Produced per Year per Unit Area –** This is a proxy measure for overall food production per year per 1000 hectare (ha). It is an indicator of the efficiency and effectiveness of the food production infrastructure in the country. Those countries with higher outputs per ha should be less sensitive to impending climate change (Brenkert and Malone, 2005).

3.2.2.3 Electric Power

The model for electric power follows the same logic as the water and food infrastructures. Power generated within the country gives the country more capacity to adapt. The following indicators are used to estimate electric power vulnerability:

- **Imports as Percentage of Use –** This indicator measures how reliant the country is on other nations for energy. It includes fossil fuels, natural gas, electricity, etc. Some major exporters have negative values, making them very resilient from a national or regional energy perspective.

- **Renewable and Nuclear Generation as Percentage of Use –** Countries that use high percentages of renewable and nuclear generation will be less vulnerable to carbon emission limits and/or uncertainty regarding the future of carbon-based fuels for electric power generation.

Energy statistics are only available for about 75% of the countries in the model. As discussed in Section 2, it would be better to model electric power demand and supply as a function of the climate stress and interdependencies. This is particularly important for the nations and regions for which electric power supply reliability is an important factor in estimating the economic consequences.

3.2.3 Social Capital

In addition to the physical necessities of the people and businesses (as represented by infrastructures), social dynamics also play a role in vulnerability. Social capital is the term used to describe the ability of the citizens to adapt to change. It includes trust in institutions and in social networks, as well as the freedom to adapt and make choices without fear of government interference or persecution (Adger, 2003). Conflicts drain economies, destroy natural resources, and reduce social capital. War and conflict put countries in vulnerable states. This increased vulnerability could magnify the effects of climate change. Social vulnerability is represented using the following indicators:

- **Population Density –** Dense population strains the environment and the national infrastructure (Myers, 2002). A perpetually warmer and drier climate would adversely affect rural agricultural populations, causing them to migrate toward the more densely populated cities and exacerbating any existing problems.

- **Human Development Index (HDI) –** The HDI is a combination of variables designed to measure the development of countries. It is comprised of data on life expectancy, literacy, and GDP per capita. This measure is a proxy indicator of the levels of freedom, education, and civil liberties experienced by the citizens (Adger, 2003; United Nations, 1999).

- **Corruption Power Index (CPI) –** The CPI was designed to measure the perception of the people that their government can be trusted and has their best interest in mind (Transparency International, 2009). The ability of the government and private institutions to function effectively and the citizens' perception of those institutions are both critical. Citizens who trust their government will be more apt to cooperate with government-based adaptation programs, thus increasing the likelihood of success of such programs (Adger, 2003).

- **Overall Conflict Burden –** War and conflict drain economies, destroy natural resources, and undermine the social structures of the state. Therefore, countries experiencing global conflict will suffer increased vulnerability to the effects of climate change. In order to measure the general strain a country is experiencing due to states of war or conflict, an aggregate measure was constructed using weighting factors for the type of conflict. The most extreme state of national conflict, war (Stage 5 using the Heidelberg Institute's *Conflict Barometer* (Heidelberg Institute, 2009), is characterized by organized violent action and extreme devastation over a considerable time period and is assigned a weight of 1. Stage 3 and Stage 4 violent conflicts, with sporadic to organized violence but minimal devastation and a limited time frame, are weighted as 0.1. Stage 1 and Stage 2 conflicts have yet to result in violence, but they may have led to threats of violence or sanctions. They are potential future areas of violent conflict, they drain resources, and are given a weight of 0.01.

3.3 Climate Vulnerability Initial Results

The results for each threat are provided in this section as a series of maps and tables, along with initial interpretation of the vulnerability and indications for future models and analyses.

3.3.1 Global Economic Capacity

Evaluation of the initial economic capacities by country shows at least 17 countries producing gross domestic products of less than 1000 U.S. dollars (USD) per capita annually. These countries are in extreme poverty and will have the least economic capacity to adapt to climate stresses. The next generation of climate risk analysis should evaluate the potential stresses on the economies and populations in these poorest countries. The distribution of economic production is shown in Figure 3-1 and the economic capacity data sorted by GDP per capita are provided in Table 3-2. Countries with the greatest income should have the greatest capacity to adapt to changes in domestic supplies of essential goods (water, food, electric power). Estimates of the economic risks to the U.S. due to global economic impacts, should include evaluation of economic relationships between the U.S. and countries most likely to be impacted by climate change. The global impact analysis will improve understanding of the potential cascading impacts and unintended consequences of mitigation measures.

The distribution of income may alter the population's ability to adapt. Countries may have similar productivity, but those with a larger poor population will be more vulnerable. The Gini index provides an indicator of income distribution by country. Figure 3-2 shows current Gini by country. The comparison of Gini to GDP per capita exposes additional vulnerability in Namibia, Equatorial Guinea, Gabon, Angola, and Botswana. These countries are among the top 10 for income disparity with GDP per capita ranging from 6,600 USD for Namibia to 37,500 USD for Equatorial Guinea.

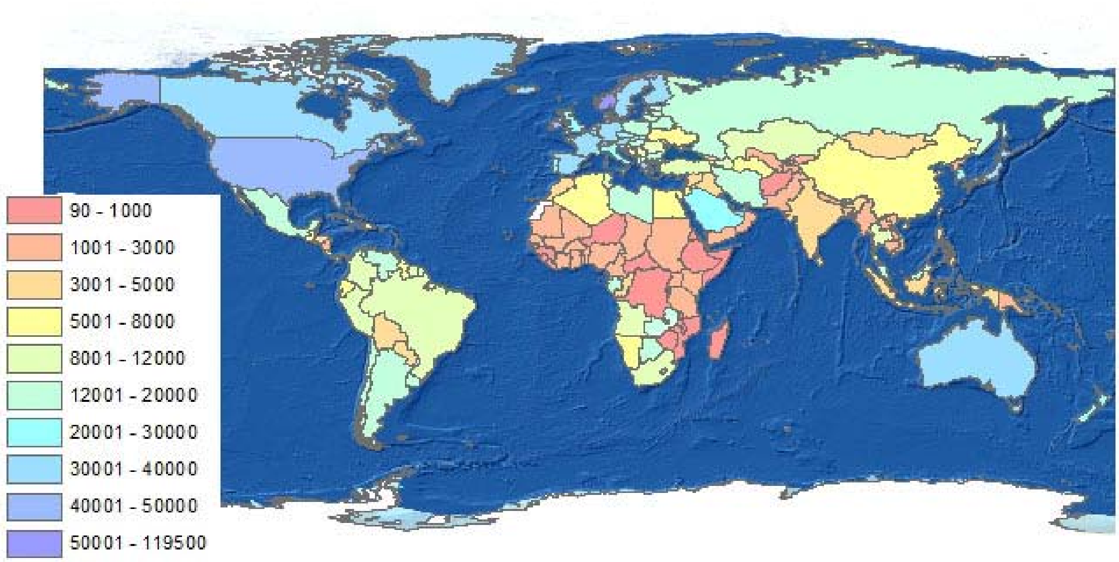

Figure 3-1. Gross Domestic Product per Capita (USD/person) (U.S. CIA, 2009)[1]

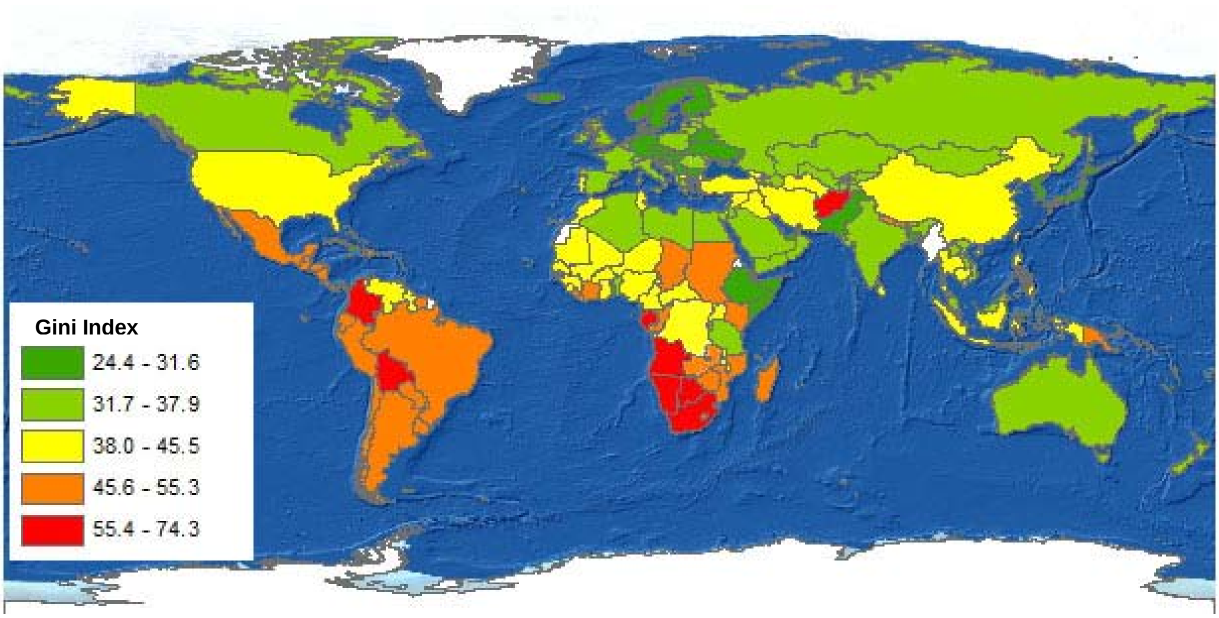

Figure 3-2. Income Distribution, the Gini Index (data for 2002-2009 from Vision of Humanity, 2010; U.S. CIA, 2009; United Nations, 2009)[2]

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[1] Note that there were no data available for Western Sahara or Montenegro.

[2] Note that there were no data available for Western Sahara, Eritrea, French Guiana, Montenegro, Greenland, or Myanmar.

The fraction of total economic productivity provided by agriculture is shown in Figure 3-3. Gabon's economy is almost entirely dependent on agriculture (98 percent from agriculture) and although it has one of the more productive economies (per capita) of the African nations, it has large income disparities. Other countries with more than 50 percent of their GDP from agriculture include Central African Republic, Democratic Republic of Congo, Guinea-Bissau, Somalia, and Liberia. All these countries (with the exception of Gabon) are among the lowest economic producers (GDP per capita). Understanding the climate uncertainties and impacts on agriculture in these countries is important.

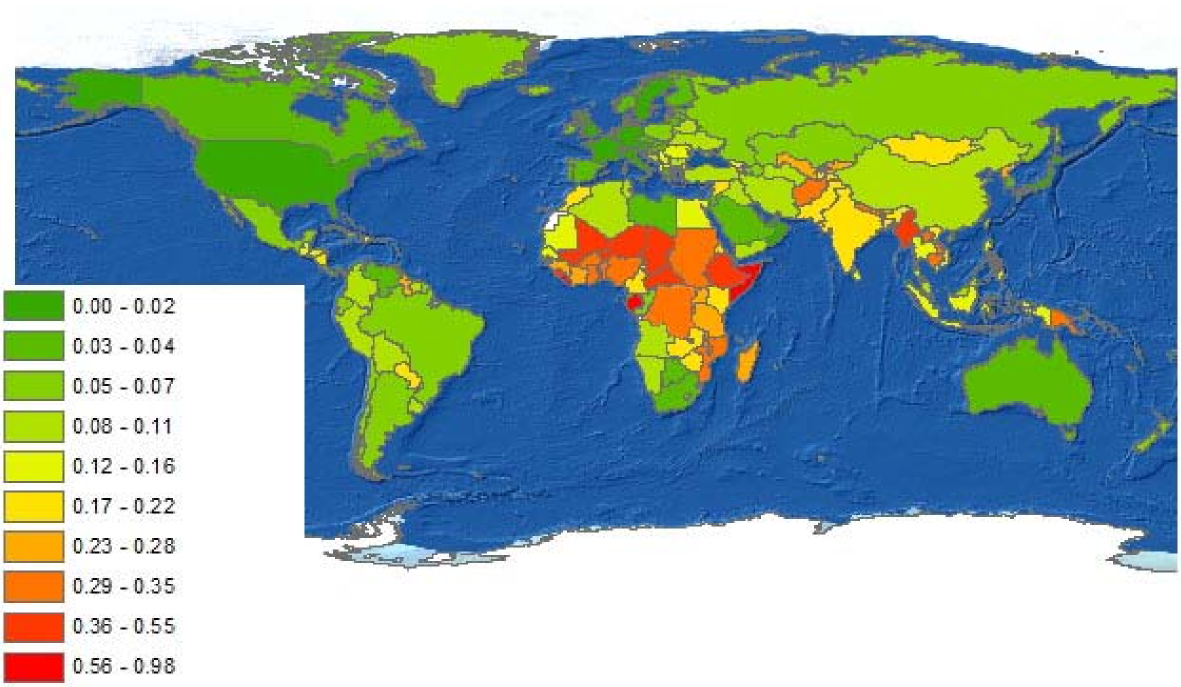

Figure 3-3. Fraction of GDP Due to Agriculture (U.S. CIA, 2009)

Table 3-2. Economic Capacity Indicators

Country	GDP per Capita (USD/person)	Agriculture as a Fraction of GDP	Gini Index
Zimbabwe	90	0.19	50
Burundi	300	0.33	33
Congo, Democratic Republic of the	300	0.55	44
Liberia	400	0.77	53
Somalia	600	0.65	30
Central African Republic	700	0.55	44
Niger	700	0.39	44
Eritrea	700	0.17	

Country	GDP per Capita (USD/person)	Agriculture as a Fraction of GDP	Gini Index
Malawi	800	0.35	39
Togo	900	0.47	24
Ethiopia	900	0.44	30
Sierra Leone	900	0.49	43
Mozambique	900	0.29	47
Guinea	1000	0.24	43
Rwanda	1000	0.42	47
Madagascar	1000	0.26	47
Afghanistan	1000	0.31	60
Comoros	1000	0.40	64
Guinea-Bissau	1100	0.62	36
Myanmar	1100	0.43	
Mali	1200	0.45	39
Burkina Faso	1200	0.30	40
Uganda	1200	0.23	43
Nepal	1200	0.35	47
Haiti	1300	0.28	60
Tanzania	1400	0.26	35
Gambia, The	1400	0.30	47
Bangladesh	1500	0.19	31
Benin	1500	0.33	37
Ghana	1500	0.34	43
Senegal	1600	0.14	39
Kenya	1600	0.20	48
Zambia	1600	0.20	51
Lesotho	1600	0.07	53
Côte d'Ivoire	1700	0.28	48
São Tomé and Príncipe	1700	0.14	
Korea, North	1900	0.23	31
Tajikistan	1900	0.20	34
Cambodia	1900	0.29	41
Chad	1900	0.47	52
Mauritania	2000	0.13	39
Laos	2100	0.30	33
Kyrgyzstan	2200	0.27	33
Moldova	2300	0.16	36
Nigeria	2300	0.33	43
Cameroon	2300	0.20	45
Papua New Guinea	2300	0.34	51

Country	GDP per Capita (USD/person)	Agriculture as a Fraction of GDP	Gini Index
Sudan	2300	0.32	51
Pakistan	2500	0.21	31
Oman	2500	0.01	32
Yemen	2500	0.10	38
Solomon Islands	2500	0.42	
Djibouti	2700	0.03	40
Uzbekistan	2800	0.27	37
Nicaragua	2800	0.18	52
Vietnam	2900	0.21	38
West Bank	2900	0.05	
Mongolia	3100	0.21	33
India	3100	0.17	37
Philippines	3300	0.15	44
Cape Verde	3600	0.09	
Iraq	3800	0.10	42
Wallis and Futuna	3800		
Congo, Republic of the	3900	0.05	47
Fiji	3900	0.09	
Indonesia	4000	0.15	39
Honduras	4100	0.12	55
Maldives	4300	0.06	
Georgia	4400	0.12	41
Swaziland	4400	0.08	51
Sri Lanka	4500	0.13	41
Syria	4600	0.18	42
Paraguay	4600	0.20	53
Bhutan	4700	0.22	32
Morocco	4700	0.19	41
Bolivia	4700	0.11	58
Guatemala	5100	0.14	54
Jordan	5200	0.04	38
Vanuatu	5300	0.26	48
Samoa	5400	0.12	
Armenia	5500	0.23	34
Réunion	5758	0.08	
Egypt	6000	0.14	32
Ukraine	6300	0.10	28
Tonga	6300	0.25	
Albania	6400	0.22	33

Country	GDP per Capita (USD/person)	Agriculture as a Fraction of GDP	Gini Index
Bosnia and Herzegovina	6400	0.10	36
Guyana	6500	0.25	45
China	6600	0.11	42
Namibia	6600	0.10	74
Turkmenistan	6700	0.10	41
Algeria	7100	0.08	35
El Salvador	7200	0.11	50
Ecuador	7500	0.07	54
Luxembourg	7900	0.00	31
Tunisia	8200	0.11	41
Thailand	8200	0.12	43
French Guiana	8298	0.07	
Belize	8300	0.29	49
Dominican Republic	8300	0.12	50
Jamaica	8400	0.06	46
Angola	8400	0.10	62
Peru	8500	0.08	50
Macedonia, Republic of	9100	0.12	39
Colombia	9200	0.10	59
Suriname	9500	0.11	53
Cuba	9700	0.04	30
Montenegro	9800		30
Brazil	10100	0.06	55
Dominica	10200	0.18	
Saint Vincent and the Grenadines	10200	0.10	
South Africa	10300	0.03	58
Grenada	10300	0.05	
Azerbaijan	10400	0.06	37
Serbia	10600	0.13	30
Saint Lucia	10900	0.05	43
Costa Rica	10900	0.06	47
Turkey	11400	0.09	43
Romania	11500	0.12	32
Kazakhstan	11800	0.06	34
Panama	12100	0.06	55
Belarus	12500	0.09	28
Bulgaria	12500	0.08	29
Iran	12500	0.11	38

Country	GDP per Capita (USD/person)	Agriculture as a Fraction of GDP	Gini Index
Uruguay	12600	0.09	46
Botswana	12800	0.02	61
Mauritius	13000	0.05	39
Venezuela	13000	0.04	43
Lebanon	13200	0.05	45
Mexico	13200	0.04	48
Libya	13400	0.03	36
Argentina	13400	0.06	50
Gabon	14000	0.98	60
Latvia	14400	0.04	36
Virgin Islands	14500	0.01	
Chile	14600	0.06	52
Saint Kitts and Nevis	14700	0.04	
Malaysia	14900	0.09	38
Russia	15100	0.05	38
Lithuania	15500	0.04	36
Croatia	17500	0.06	29
Barbados	17700	0.06	
Antigua and Barbuda	17800	0.04	
Poland	17900	0.05	35
French Polynesia	18000	0.04	
Estonia	18500	0.03	36
Hungary	18800	0.03	30
Saudi Arabia	20600	0.03	32
Seychelles	20800	0.03	
Cyprus	21000	0.02	29
Slovakia	21100	0.03	26
Trinidad and Tobago	21300	0.01	40
Portugal	21700	0.03	38
Malta	24300	0.02	26
United Kingdom	24800	0.01	36
Czech Republic	24900	0.02	26
New Zealand	27400	0.05	36
Slovenia	27700	0.03	31
Korea, South	28100	0.03	32
Israel	28400	0.03	39
Bahamas, The	29700	0.01	
Italy	29900	0.02	36

Country	GDP per Capita (USD/person)	Agriculture as a Fraction of GDP	Gini Index
Greece	31000	0.03	34
Taiwan	32000	0.02	33
France	32600	0.02	33
Japan	32700	0.02	25
Spain	33600	0.03	35
Finland	34100	0.04	27
Germany	34100	0.01	28
Greenland	35900	0.05	
Denmark	36000	0.01	25
Sweden	36600	0.02	25
Belgium	36800	0.01	33
Equatorial Guinea	37500	0.02	65
Canada	38200	0.02	33
Bahrain	38800	0.01	36
United Arab Emirates	38900	0.01	31
Austria	39200	0.02	29
Netherlands	39500	0.02	31
Iceland	39600	0.05	28
Australia	40000	0.04	35
Ireland	41000	0.05	34
Switzerland	41400	0.01	34
Hong Kong	42800	0.00	43
United States	46000	0.01	41
Brunei	51200	0.01	
Singapore	52200	0.00	42
Kuwait	52800	0.00	30
Norway	57400	0.02	26
Qatar	119500	0.00	39

3.3.2 Infrastructure Capacity

The results for the analysis of infrastructure capacity as a function of agricultural productivity, water supply, and electric power supply are provided, along with an initial analysis of the implications for the next generation of climate risk analysis.

3.3.2.1 Agricultural Productivity

Grain production per unit area is used to represent the relative food security of each country. Grain is used in numerous food products, sugars, and as cattle feed. The United States, China, India, Nigeria, Russia, and Brazil are the most agriculturally productive nations and have the greatest food security, as shown in Figure 3-4. The countries with low agricultural productivity tend to be small island nations or countries with a large percentage of their land area covered in ice, snow, or desert. From a climate perspective, countries that have significant grain production but are not among the most productive countries may have their food security significantly altered by climate changes. Examples include Canada, which could become more agriculturally productive with warming temperatures. Conversely countries that are already warm, such as Australia, could experience lower productivity and a reduction in food security. Understanding the uncertainties in climate impacts on agriculture productivity is most important where there could be a reduction in food security, particularly Australia, Indonesia, Argentina, Ethiopia, and Tanzania.

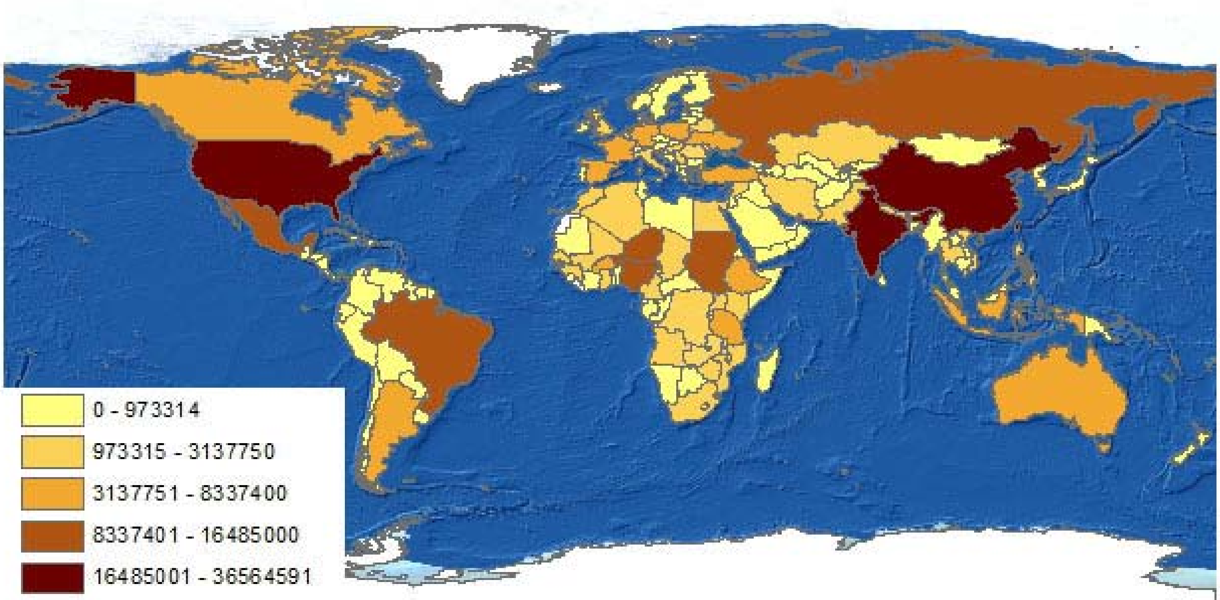

Figure 3-4. Grain Harvested in 2009 (tons/hectare) (FAO, 2009)

The results for all agriculture capacity conditions are provided in Table 3-3.

Table 3-3. Agricultural Capacity Initial Conditions

Country	Arable Land per Capita (1000 ha/person)	Fraction of Land That Is Agricultural	Fraction of Agricultural Land That Is Arable	Fraction of Land That Is Arable	Grains Harvested 2009 (tons/ha)
United States	0.10	0.45	0.42	0.19	36564591
China	0.11	0.59	0.28	0.16	34450397
India	0.14	0.61	0.94	0.57	27380000
Nigeria	0.25	0.86	0.50	0.43	16485000
Russia	0.86	0.13	0.57	0.08	14905300

Country	Arable Land per Capita (1000 ha/person)	Fraction of Land That Is Agricultural	Fraction of Agricultural Land That Is Arable	Fraction of Land That Is Arable	Grains Harvested 2009 (tons/ha)
Brazil	0.31	0.31	0.25	0.08	14899307
Niger	1.04	0.34	0.34	0.12	9905600
Mexico	0.23	0.55	0.25	0.14	9298417
Sudan	0.48	0.58	0.14	0.08	9047500
Ukraine	0.18	0.71	0.81	0.58	8337400
Ethiopia	0.18	0.35	0.43	0.15	7281213
Australia	2.10	0.55	0.10	0.06	6268566
Poland	0.33	0.53	0.80	0.42	6236580
Canada	1.37	0.07	0.77	0.06	5324200
Tanzania	0.22	0.39	0.30	0.12	4285000
France	0.30	0.54	0.66	0.36	4217400
Indonesia	0.10	0.27	0.77	0.21	4160659
Spain	0.28	0.57	0.61	0.35	4156210
Burkina Faso	0.35	0.41	0.47	0.19	4111233
Turkey	0.27	0.51	0.63	0.32	3832597
Germany	0.14	0.49	0.71	0.35	3682407
Argentina	0.82	0.49	0.25	0.12	3503023
Mali	0.39	0.32	0.13	0.04	3137750
Romania	0.40	0.59	0.67	0.39	3111625
Philippines	0.06	0.39	0.87	0.34	2683985
South Africa	0.30	0.82	0.16	0.13	2674760
Morocco	0.26	0.67	0.30	0.20	2452200
Chad	0.40	0.39	0.09	0.03	2371350
Zimbabwe	0.26	0.40	0.22	0.09	2223530
Kenya	0.14	0.47	0.21	0.10	2179766
Kazakhstan	1.47	0.77	0.11	0.08	2158860
Iran	0.24	0.30	0.39	0.11	1912293
Belarus	0.57	0.44	0.63	0.28	1859364
Mozambique	0.20	0.62	0.10	0.06	1780000
Pakistan	0.13	0.35	0.82	0.29	1760000
Hungary	0.46	0.65	0.82	0.53	1734455
Angola	0.19	0.46	0.06	0.03	1725384
Malawi	0.21	0.53	0.63	0.33	1715512
Uganda	0.37	0.65	0.60	0.39	1676000
Congo, Democratic Republic of the	0.11	0.10	0.34	0.03	1551251
Senegal	0.25	0.45	0.35	0.16	1507824

Country	Arable Land per Capita (1000 ha/person)	Fraction of Land That Is Agricultural	Fraction of Agricultural Land That Is Arable	Fraction of Land That Is Arable	Grains Harvested 2009 (tons/ha)
Italy	0.12	0.47	0.70	0.33	1419800
Ghana	0.18	0.65	0.44	0.29	1408338
United Kingdom	0.02	0.73	0.35	0.25	1359000
Serbia	0.45	0.57	0.71	0.41	1351230
Syria	0.24	0.76	0.41	0.31	1336753
Algeria	0.22	0.17	0.20	0.04	1327555
Thailand	0.23	0.39	0.96	0.37	1318596
Cameroon	0.32	0.19	0.78	0.15	1173000
Nepal	0.08	0.29	0.59	0.17	1167134
Vietnam	0.10	0.32	0.94	0.30	1088400
Guinea	0.23	0.42	0.56	0.12	1068434
Egypt	0.04	0.04	1.00	0.04	1058086
Zambia	0.43	0.34	0.21	0.07	1002605
Venezuela	0.09	0.24	0.16	0.04	973314
Benin	0.32	0.32	0.84	0.27	941152
Finland	0.43	0.08	0.99	0.07	916900
Guatemala	0.12	0.26	0.55	0.23	838000
Iraq	0.17	0.22	0.58	0.12	824025
Togo	0.16	0.67	0.72	0.48	794697
Paraguay	0.70	0.51	0.22	0.11	785070
Denmark	0.42	0.63	0.87	0.55	759200
Peru	0.13	0.17	0.21	0.04	724986
Czech Republic	0.29	0.55	0.77	0.42	713080
Sweden	0.29	0.08	0.84	0.06	657300
Colombia	0.05	0.38	0.08	0.03	628473
Korea, North	0.12	0.25	0.98	0.25	622150
Myanmar	0.22	0.18	0.97	0.18	614000
Lithuania	0.54	0.43	0.69	0.30	603500
Bulgaria	0.40	0.47	0.64	0.30	573148
Yemen	0.06	0.45	0.07	0.03	560200
Bolivia	0.38	0.34	0.10	0.04	534707
Moldova	0.50	0.75	0.86	0.65	529888
Austria	0.17	0.39	0.45	0.18	528992
Afghanistan	0.30	0.59	0.22	0.13	488000
Eritrea	0.13	0.75	0.09	0.06	465815
Somalia	0.11	0.70	0.02	0.02	465000

Country	Arable Land per Capita (1000 ha/person)	Fraction of Land That Is Agricultural	Fraction of Agricultural Land That Is Arable	Fraction of Land That Is Arable	Grains Harvested 2009 (tons/ha)
Côte d'Ivoire	0.14	0.64	0.35	0.22	453520
Greece	0.23	0.64	0.44	0.29	447830
Ecuador	0.09	0.27	0.33	0.09	411133
Slovakia	0.26	0.40	0.73	0.29	389545
Haiti	0.09	0.09	0.27	0.44	384000
Croatia	0.19	0.22	0.78	0.17	382275
Honduras	0.15	0.61	0.71	0.13	371541
Nicaragua	0.35	0.43	0.42	0.18	361504
El Salvador	0.11	0.75	0.59	0.44	357175
Uruguay	0.57	0.84	0.09	0.08	331470
Rwanda	0.13	0.78	0.77	0.60	327000
Tunisia	0.02	0.63	0.50	0.32	321600
Namibia	0.38	0.47	0.02	0.01	305000
Azerbaijan	0.22	0.58	0.44	0.25	304186
Chile	0.08	0.21	0.11	0.02	263184
Latvia	0.52	0.30	0.65	0.19	255200
Madagascar	0.16	0.70	0.09	0.06	252000
Central African Republic	0.45	0.08	0.39	0.03	238234
Bosnia and Herzegovina	0.27	0.42	0.52	0.22	228062
Norway	0.18	0.03	0.83	0.03	224130
Gambia, The	0.22	0.81	0.44	0.35	222240
Portugal	0.10	0.38	0.48	0.18	218600
Mauritania	0.14	0.39	0.01	0.00	217906
Cambodia	0.27	0.31	0.73	0.22	213000
Libya	0.28	0.09	0.13	0.01	210860
Ireland	0.24	0.62	0.25	0.15	210500
Cuba	0.32	0.60	0.60	0.36	204151
Kyrgyzstan	0.24	0.56	0.13	0.07	204113
Estonia	0.45	0.19	0.74	0.14	202794
Burundi	0.13	0.89	0.59	0.52	191500
Laos	0.19	0.09	0.59	0.05	175965
Uzbekistan	0.41	0.63	0.17	0.11	171500
Lesotho	0.15	0.76	0.13	0.10	157815
Georgia	0.11	0.36	0.23	0.08	143530
Saudi Arabia	0.14	0.81	0.02	0.02	140440
Belgium	0.08	0.45	0.63	0.29	133485

Country	Arable Land per Capita (1000 ha/person)	Fraction of Land That Is Agricultural	Fraction of Agricultural Land That Is Arable	Fraction of Land That Is Arable	Grains Harvested 2009 (tons/ha)
Bangladesh	0.05	0.70	0.93	0.65	132530
Sierra Leone	0.17	0.44	0.31	0.14	111400
New Zealand	0.20	0.46	0.08	0.03	108841
Japan	0.03	0.13	1.00	0.13	103852
Macedonia, Republic of	0.21	0.42	0.43	0.18	87575
Botswana	0.13	0.46	0.01	0.00	85250
Korea, South	0.03	0.19	0.97	0.18	80146
Turkmenistan	0.30	0.69	0.06	0.04	76300
Armenia	0.13	0.57	0.28	0.16	75484
Netherlands	0.06	0.57	0.57	0.32	69900
Guinea-Bissau	0.19	0.55	0.21	0.20	69625
Tajikistan	0.11	0.33	0.18	0.06	67445
Slovenia	0.09	0.25	0.41	0.10	67333
Albania	0.18	0.41	0.62	0.25	63400
Switzerland	0.05	0.39	0.28	0.11	61751
Sri Lanka	0.05	0.37	0.81	0.30	56930
Bhutan	0.19	0.15	0.28	0.04	52710
Panama	0.16	0.30	0.31	0.09	48616
Swaziland	0.15	0.78	0.14	0.11	48409
Cyprus	0.13	0.17	0.99	0.17	37390
Cape Verde	0.10	0.19	0.68	0.13	34385
Jordan	0.02	0.11	0.23	0.03	32389
Congo, Republic of the	0.14	0.31	0.05	0.02	25550
Belize	0.22	0.07	0.67	0.04	20650
Gabon	0.23	0.20	0.10	0.02	20000
Israel	0.04	0.23	0.75	0.17	19100
Dominican Republic	0.08	0.52	0.52	0.27	18677
Lebanon	0.03	0.67	0.42	0.28	17850
Luxembourg	0.13	0.51	0.48	0.24	16562
Costa Rica	0.04	0.54	0.18	0.10	11227
West Bank	0.03	0.62	0.60	0.37	10953
Malaysia	0.07	0.24	0.96	0.23	6340
Guyana	0.55	0.58	0.34	0.02	4600
Oman	0.02	0.06	0.06	0.00	4595
Montenegro	0.28	0.38	0.37	0.14	3960

Country	Arable Land per Capita (1000 ha/person)	Fraction of Land That Is Agricultural	Fraction of Agricultural Land That Is Arable	Fraction of Land That Is Arable	Grains Harvested 2009 (tons/ha)
Mongolia	0.33	0.75	0.01	0.01	3490
Papua New Guinea	0.04	0.02	0.82	0.02	2900
Qatar	0.02	0.06	0.30	0.02	2025
Comoros	0.13	0.81	0.90	0.73	2000
Réunion		0.19	0.77	0.14	1550
Jamaica	0.07	0.47	0.55	0.26	1514
Vanuatu	0.16	0.12	0.71	0.09	1450
São Tomé and Príncipe	0.06	0.59	0.98	0.58	1300
Trinidad and Tobago	0.15	0.11	0.87	0.09	1200
Kuwait	0.01	0.09	0.12	0.01	1050
Fiji	0.20	0.23	0.59	0.14	911
Malta	0.02	0.28	1.00	0.28	400
Grenada	0.02	0.38	0.92	0.35	320
Saint Vincent and the Grenadines		0.36	0.86	0.31	210
Bahamas, The	0.02	0.01	0.86	0.01	180
Dominica	0.07	0.31	0.91	0.28	145
Barbados	0.06	0.44	0.89	0.40	105
Maldives	0.01	0.43	0.92	0.40	96
Mauritius	0.07	0.50	0.93	0.46	95
Antigua and Barbuda	0.09	0.30	0.69	0.20	42
French Guiana		0.00	0.70	0.00	40
Suriname	0.11	0.01	0.78	0.00	12
Djibouti	0.00	0.73	0.00	0.00	6
Saint Lucia		0.18	0.91	0.16	0
Singapore	0.00	0.00	0.00	0.00	0
Greenland		0.01	0.00	0.00	No data
Brunei	0.01	0.02	0.73	0.02	No data
Solomon Islands	0.03	0.03	0.90	0.03	No data
United Arab Emirates	0.70	0.07	0.49	0.03	No data
Virgin Islands	0.07	0.11	0.50	0.06	No data
Equatorial	0.20	0.12	0.68	0.08	No data

Country	Arable Land per Capita (1000 ha/person)	Fraction of Land That Is Agricultural	Fraction of Agricultural Land That Is Arable	Fraction of Land That Is Arable	Grains Harvested 2009 (tons/ha)
Guinea					
French Polynesia	0.01	0.12	0.56	0.07	No data
Seychelles	0.01	0.13	1.00	0.13	No data
Bahrain	0.00	0.14	0.60	0.08	No data
Saint Kitts and Nevis		0.19	0.80	0.15	No data
Iceland	0.02	0.23	0.00	0.00	No data
Liberia	0.11	0.27	0.23	0.06	No data
Samoa	0.14	0.30	0.97	0.29	No data
Wallis and Futuna	0.01	0.43	1.00	0.43	No data
Tonga	0.39	0.43	0.87	0.38	No data

3.3.2.2 Water Supply

The per capita water supply varies greatly as does the per capita water use. The countries with large volumes of water supply and who use only a small fraction of the water available each year have water security, as long as there is the capacity to store water. It is important to identify what fraction of the supply is stored in ice and vulnerable to melting with higher temperatures. Additional information is required to understand which countries have already adapted their economies and water use in ways that make them less vulnerable to reductions in precipitation. Additional indicators for the water-poor countries are needed to identify countries that have for access to renewable saline water sources and sufficient economic and electric power capacity to utilize desalinated water. It will be important to understand the dynamics between water, electric power, and economics to analyze the risks. Climate risk models that include potential variability in precipitation, ability to use stored water to offset years with low precipitation and water use as a function of the climate conditions will provide a much better estimate of the risks to water supplies.

Table 3-4. Water Supply and Consumption Data

Country	Water (m^3/inhabitant/yr)	Ratio of Water Use to Water Supply (local)
French Guiana	609091	
Iceland	539683	0.01
Guyana	315858	0.01
Suriname	236893	0.01
Congo, Republic of the	230152	

Country	Water (m^3/inhabitant/yr)	Ratio of Water Use to Water Supply (local)
Papua New Guinea	121788	
Bhutan	113537	0.52
Gabon	113260	
Solomon Islands	87476	
Canada	87255	0.02
Norway	80134	0.01
New Zealand	77305	0.01
Peru	66338	0.01
Bolivia	64215	
Belize	61628	0.01
Liberia	61165	0.01
Chile	54868	0.01
Paraguay	53863	
Laos	53747	0.01
Colombia	47365	0.01
Venezuela	43846	0.01
Panama	43542	0.01
Brazil	42886	0.01
Uruguay	41505	0.02
Equatorial Guinea	39454	
Nicaragua	34692	0.01
Fiji	33827	
Central African Republic	33280	
Cambodia	32695	0.01
Russia	31883	0.02
Ecuador	31481	0.04
Sierra Leone	28777	
Costa Rica	24873	0.02
Croatia	23853	
Australia	23346	0.05
Guinea	22984	0.01
Brunei	21684	
Malaysia	21470	0.02
Myanmar	21104	0.03
Finland	20739	0.02
Argentina	20410	0.04
Congo, Democratic Republic of the	19967	
Guinea-Bissau	19683	0.01
Sweden	18903	0.02
Madagascar	17634	0.04

Country	Water (m^3/inhabitant/yr)	Ratio of Water Use to Water Supply (local)
Slovenia	15816	
Latvia	15693	0.01
Cameroon	14957	0.00
Georgia	14704	0.03
São Tomé and Príncipe	13625	
Albania	13268	0.04
Mongolia	13177	0.01
Honduras	13107	0.01
Indonesia	12483	0.03
Ireland	11720	0.02
Hungary	10388	0.05
Vietnam	10232	0.08
Bosnia and Herzegovina	9939	
Romania	9920	0.11
United States	9847	0.16
Mozambique	9699	
Estonia	9553	0.01
Austria	9320	0.03
Slovakia	9278	
Zambia	8336	0.02
Namibia	8319	0.02
Angola	8213	
Guatemala	8132	0.02
Mali	7870	0.07
Bangladesh	7567	0.03
Lithuania	7498	0.01
Nepal	7296	0.05
Switzerland	7095	0.05
Kazakhstan	7061	0.31
Greece	6667	0.11
Luxembourg	6445	
Portugal	6434	0.16
Botswana	6372	0.02
Thailand	6332	0.21
Belarus	5992	0.05
Netherlands	5506	0.09
Philippines	5302	0.17
Turkmenistan	4901	1.00
Gambia, The	4819	
Kyrgyzstan	4263	0.42

Country	Water (m^3/inhabitant/yr)	Ratio of Water Use to Water Supply (local)
Mexico	4212	0.17
El Salvador	4113	0.05
Azerbaijan	3972	0.35
Côte d'Ivoire	3941	0.01
Chad	3940	0.01
Swaziland	3861	0.23
Mauritania	3546	0.15
Jamaica	3473	0.04
Cuba	3402	0.22
Japan	3378	0.20
France	3284	0.20
Korea, North	3239	0.12
Italy	3210	0.23
Moldova	3207	0.20
Senegal	3177	0.06
Macedonia, Republic of	3136	
Benin	3047	0.01
Ukraine	3035	0.27
Turkey	2890	0.18
Trinidad and Tobago	2881	0.08
Bulgaria	2805	0.41
Zimbabwe	2558	0.21
Armenia	2525	0.36
Iraq	2512	0.85
Spain	2506	0.32
Sri Lanka	2492	0.25
United Kingdom	2392	0.07
Afghanistan	2389	0.36
Tajikistan	2338	0.75
Niger	2288	0.07
Ghana	2278	0.02
Togo	2276	0.01
Tanzania	2266	0.05
Mauritius	2149	0.26
China	2112	0.19
Dominican Republic	2110	0.16
Uganda	2085	0.01
Nigeria	1893	0.03
Iran	1876	0.68
Germany	1872	0.25

Country	Water (m^3/inhabitant/yr)	Ratio of Water Use to Water Supply (local)
Uzbekistan	1854	1.16
Belgium	1728	
Somalia	1647	0.22
Poland	1617	0.26
India	1608	0.34
Sudan	1560	0.58
Burundi	1553	0.02
Ethiopia	1512	0.05
Lesotho	1475	0.02
Korea, South	1447	0.37
Haiti	1421	0.07
Comoros	1412	0.01
Eritrea	1279	0.09
Czech Republic	1274	0.20
Pakistan	1273	0.82
Malawi	1164	0.06
Denmark	1099	0.21
Lebanon	1074	0.28
South Africa	1007	0.25
Rwanda	977	0.02
Morocco	918	0.43
Cyprus	905	0.27
Burkina Faso	821	0.06
Kenya	792	0.09
Syria	791	0.83
Egypt	703	0.95
Cape Verde	601	0.09
Antigua and Barbuda	598	
Oman	503	0.85
Saint Kitts and Nevis	471	
Tunisia	452	0.61
Djibouti	353	0.06
Algeria	340	0.52
Barbados	314	1.13
Israel	252	0.87
West Bank	202	
Jordan	153	0.91
Bahrain	150	2.06
Singapore	130	
Malta	124	0.35

Country	Water (m^3/inhabitant/yr)	Ratio of Water Use to Water Supply (local)
Maldives	98	
Libya	95	7.11
Saudi Arabia	95	9.36
Yemen	92	1.61
Bahamas, The	59	
Qatar	45	3.81
United Arab Emirates	33	18.67
Kuwait	7	22.27

3.3.2.3 Electric Power Supply

As discussed in the conceptual model validation section, the current models do not consider the effects of temperature on the demand and supply sides of electric power. Also, significant assumptions about the nature and timing of new electric power generators require evaluation. This is particularly important for countries with economic productivity dependent on reliable electric power generation. (See Table 3-2 for countries in which agriculture is a small fraction of the GDP.) Assumptions about the next generation of electric power generation require re-evaluation based on the proven natural gas reserves, in particular shale gas reserves. The dynamics between surface water temperature and generator operations is another electric power supply issue that needs to be evaluated to improve quantification of the potential economic consequences of increased temperatures in countries in which there are environmental constraints on operations. This is particularly important for the U.S., which has environmental restrictions on water discharge temperatures and imports more than a quarter of the electric power used.

Table 3-5. Energy Security Initial Conditions

Country	Electric Power Imports % of Use	Renewable and Nuclear Energy as % of Total Electric Power Generation
Singapore	100.00	0.00
Malta	99.88	0.12
Hong Kong	99.65	0.00
Luxembourg	98.08	0.36
Moldova	97.36	0.09
Cyprus	97.00	2.17
Jordan	96.15	1.46
Morocco	95.45	0.96
Lebanon	94.79	1.70
Ireland	90.65	1.51
Jamaica	89.85	0.36

Country	Electric Power Imports % of Use	Renewable and Nuclear Energy as % of Total Electric Power Generation
Israel	87.89	3.41
Belarus	85.71	0.01
Italy	85.19	4.61
Japan	82.38	15.33
Portugal	81.59	5.72
Korea, South	80.88	16.94
Dominican Republic	80.50	1.52
Namibia	79.05	8.68
Spain	78.93	13.35
Panama	75.39	11.15
Belgium	74.81	22.19
Turkey	72.73	4.58
Chile	72.54	6.46
Armenia	70.99	28.97
Gambia, The	67.90	18.01
Austria	67.14	10.27
Slovakia	66.52	24.87
Greece	62.25	1.72
Hungary	61.74	14.79
Uruguay	61.70	21.91
Latvia	61.41	5.14
Tajikistan	59.44	37.74
Lithuania	58.93	28.71
Germany	58.63	12.79
Croatia	56.53	3.98
Finland	56.27	20.13
Honduras	55.34	4.00
Senegal	52.79	0.71
Slovenia	52.72	24.08
Albania	51.36	11.14
Kyrgyzstan	51.01	41.19
Switzerland	50.91	40.95
Bulgaria	50.71	20.36
Macedonia, Republic of	50.36	3.21
France	48.64	45.56
Cuba	47.90	0.10
Costa Rica	47.35	34.98
Sri Lanka	45.33	3.65
Botswana	45.25	0.00
Philippines	43.98	23.82

Country	Electric Power Imports % of Use	Renewable and Nuclear Energy as % of Total Electric Power Generation
Thailand	42.90	0.67
El Salvador	42.04	27.40
Nicaragua	40.79	6.76
Ukraine	40.59	18.20
Benin	38.54	0.00
Serbia	38.31	5.72
Guatemala	35.67	3.77
Sweden	33.39	46.16
Ghana	31.93	3.38
Bosnia and Herzegovina	29.71	6.14
Cambodia	29.41	0.08
Romania	29.19	8.74
United States	28.84	10.80
Haiti	27.76	0.47
Eritrea	26.49	0.00
Czech Republic	26.29	15.39
Poland	25.19	0.26
India	24.20	2.72
Netherlands	23.59	1.78
Pakistan	23.57	3.93
Estonia	21.96	0.18
Kenya	19.56	6.43
Iceland	19.25	80.63
Bangladesh	17.46	0.47
United Kingdom	16.60	8.22
New Zealand	16.50	25.94
Togo	14.61	0.33
Peru	13.25	11.99
Nepal	10.75	2.51
Tunisia	10.59	0.09
Ethiopia	8.52	1.27
Brazil	8.48	15.10
Zambia	8.21	11.31
Zimbabwe	8.19	4.74
Tanzania	7.53	1.18
China	7.25	3.22
Congo, Democratic Republic of the	-1.76	3.94
Korea, North	-7.13	6.21
Argentina	-12.11	6.17
Côte d'Ivoire	-12.71	1.55

Country	Electric Power Imports % of Use	Renewable and Nuclear Energy as % of Total Electric Power Generation
Mongolia	-15.03	0.00
South Africa	-18.80	2.27
Mozambique	-20.05	15.09
Egypt	-22.34	2.09
Uzbekistan	-23.36	1.13
Syria	-24.03	1.54
Malaysia	-29.98	0.77
Vietnam	-32.52	4.61
Mexico	-36.25	6.27
Denmark	-37.60	3.28
Cameroon	-39.47	4.54
Myanmar	-52.96	1.93
Canada	-53.39	20.90
Paraguay	-69.94	
Indonesia	-73.67	3.68
Iran	-74.69	0.84
Russia	-83.09	8.58
Bahrain	-93.95	0.00
Kazakhstan	-104.62	1.06
Nigeria	-117.20	0.52
Yemen	-128.81	0.00
Australia	-133.10	1.29
Sudan	-136.00	0.85
Trinidad and Tobago	-142.01	0.00
Ecuador	-144.94	6.58
Bolivia	-176.96	3.66
Venezuela	-188.38	11.21
Colombia	-201.58	13.17
Iraq	-216.86	0.13
United Arab Emirates	-245.40	0.00
Turkmenistan	-265.67	0.00
Saudi Arabia	-266.74	0.00
Oman	-282.91	0.00
Azerbaijan	-337.40	1.70
Algeria	-345.70	0.05
Qatar	-364.21	0.00
Libya	-470.01	0.00
Kuwait	-481.61	0.00
Gabon	-548.70	3.73

Country	Electric Power Imports % of Use	Renewable and Nuclear Energy as % of Total Electric Power Generation
Brunei	-629.82	0.00
Norway	-696.41	43.17
Angola	-793.34	2.59
Congo, Republic of the	-890.92	2.29

3.3.3 Social Capital Initial Indicators

When a simple weighting scheme is applied to the violent and nonviolent conflicts in which each nation is engaged (Heidelberg Institute, 2009), the countries currently at war within their own borders are highlighted (Figure 3-5, countries shown in red). Afghanistan, Pakistan, India, Somalia and Yemen will have less ability to adapt to climate stresses. Columbia, Indonesia, and Russia are also heavily engaged in conflicts and are more vulnerable to climate risks that require planning and government resources to adapt effectively and reduce the risk.

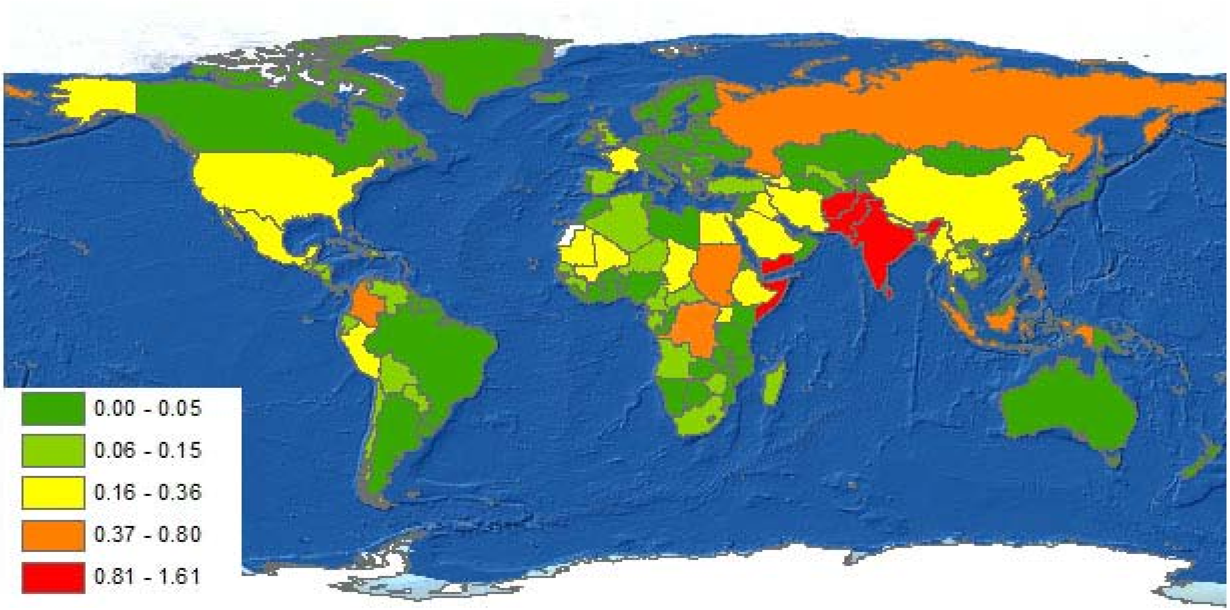

Figure 3-5. Social Capital - Weighted Index of Overall Conflict Burden

4. UNCERTAINTY

The only way to develop a climate-risk analysis that will identify risk reduction actions that are robust to uncertainty is to include the uncertainties explicitly. The current model explicitly propagates the uncertainty in precipitation through the analysis to represent the economic risk to the U.S. due to precipitation changes. This approach ignores behavioral uncertainties, such as how the population will respond to higher temperatures and changes in economic conditions. The behavioral response to temperature is not included and the population response to changes in economic conditions is fixed, based on historical changes in consumer spending and assumptions regarding economic prioritization of water use and economically driven population movements. Key components needed in the models and analyses include electric power demand as a function of temperature and economic activity; water demands as a function of temperature, precipitation, and energy generation; effect of surface water temperature on electric power generation operations; and the potential effects of changes in electric power, water, and economic activity on consumer behavior. Further analysis of population movements in response to the composite effects on water, electric power, and economics is required to evaluate the effects of uncertainties in those behaviors on the estimated risk. While it is not necessarily important for evaluating the risks to the U.S., other national economies are highly dependent on agriculture. In those regions, the uncertainty in the timing and magnitude of weather events relative to growing season could have significant impacts on the estimated risks.

The vulnerability model aids identification of uncertainties that will have a greater influence on national-level risks. An analysis of the U.S. vulnerability to identify the important uncertainties produces the following results:

- **U.S. Economic Vulnerability to Crop Loss Is Low –** Therefore it is not necessary to model crop loss in detail for national-level decisions. The economic uncertainties are tied to other economic sectors and global supply chains.

- **U.S. Water Capacity is Good –** However, the current analysis (Backus et al., 2010) shows the uneven distribution of water supplies in the U.S. and areas that are at risk for water supply shortages. The current models also indicate that the water supply shortfall will be offset by reduction in agricultural and industrial water use and increased imports of those goods. This will decrease national food security, but the economic risks are low. The impacts of climate on U.S. food security and resulting risks are uncertain and further analysis of the global food supply chain and economic dynamics might be needed to support national-level decision making.

- **U.S. Electric Power Capacity is Somewhat Vulnerable –** In order to better understand the risk to electric power supply, it will be necessary to model the effects of temperature and precipitation changes on hydroelectric generation capacity, electric power demand, constraints on power generation due to limits on cooling water discharge as a function of surface water temperatures and the time required to alter the generation and transmission system to adjust to these changes. The potential for carbon dioxide emission limits, with or without carbon credits trading, creates additional uncertainties that impact the construction of new power generators. Newly proven reserves of natural gas in shale formations (shale gas), creates more of an economic driver for using natural gas-fired generation (cheaper construction, less delay, apparently ample domestic fuel); however, uncertainty in carbon emissions limits may delay construction of new natural gas-fired generation and delay shale gas exploration. It will be important to evaluate all these uncertainties to provide analyses that support decision making.

- **Social Capital is moderate –** The U.S. is engaged in several violent conflicts and non-violent conflicts that draw on governmental resources that maybe needed to address the local to regional climate impacts. Analysis of the climate risks to the U.S., that provides a better understanding of the government resource needs and evaluates the risk reduction options, will improve the information available for decision making.

The most important uncertainties to quantify and include in the next generation of climate risk analysis for the U.S. are the ones associated with electric power and global supply-chains. Impacts due to climate change are uncertain, vary from country to country and require new models to identify and evaluate the potential dynamics and changes in the economic system structure. Agent-based models provide one of the few ways to evaluate the potential changes in behavior in coupled economic-physical systems and to quantify and compare risks.

5. CONCLUSIONS

Changes in climate can lead to instabilities in physical and economic systems, particularly in regions with marginal resources. Global climate models indicate increasing global mean temperatures over the decades to come and uncertainty in the local to national impacts means perceived risks will drive planning decisions. The current generation of climate impact analyses provides estimates of the economic cost of climate change for a limited set of climate scenarios that account for a small subset of the dynamics and uncertainties.

To improve understanding of the risk to national security, the next generation of risk assessment models must represent global stresses, population vulnerability to those stresses, and the uncertainty in population responses and outcomes that could have a significant impact on U.S. national security. Dependencies between electric power, water supply, and temperature need to be represented in the next generation of climate risk models. The dynamics between surface water temperature and generator operations should be evaluated to improve quantification of the potential economic consequences of increased temperatures in countries with environmental constraints on cooling water discharge. Assumptions about the next generation of electric power generation require re-evaluation based on the proven natural gas reserves, in particular shale gas reserves which may alter the economic drivers, and carbon dioxide emissions. Assumptions in the current model should be evaluated to determine their significance, particularly instantaneous building of electric power generation to offset changes in electric power demand due to changes in temperature, population, and economic activities.

The models and analyses should include the policy and controls that might be used to reduce the risks. Future climate risk models should add a test at each time step to verify that the modeled changes in economic activity do not significantly alter the carbon dioxide emissions and to check for internal consistency between the global climate model and the consequence models. The models also need to be expanded to evaluate key assumptions regarding the ability of global agriculture and mining to offset projected changes in U.S. production due to reduced water availability.

Global supply-chain dynamics are a challenge for the current macro-economic models. Agent-based models provide one of the few ways to evaluate the potential changes in behavior in coupled social-physical systems and to quantify and compare risks. A good next step in evaluating the potential economic impacts to the U.S. is to identify and model the economic relationships with countries that are most likely to have significant changes due to climate impacts, those that are most vulnerable due to physical characteristics (e.g., Bangladesh, Egypt), low economic productivity, disparities in wealth (e.g., Afghanistan, Namibia, Angola, Botswana), and those that could experience a reduction in food security and increase the competition for global food resources (e.g., Australia, Indonesia, Argentina, Ethiopia, and Tanzania).

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Appendix A: Literature on Climate Adaptation and Vulnerability

The following literature on climate, modeling, and adaptation to climate changes was reviewed with respect to the anticipated climate change effects, their timing, and their causes. Although many of these documents were not cited, they influenced the problem discussion and the design of models, testing, and analyses proposed in this report.

Adger, W. N. (2003). Social capital, collective action, and adaptation to climate change. *Economic Geography*, 79(4), 387-404. <http://www.uea.ac.uk/env/people/adgerwn/EconGeog2003.pdf>

> The author presents adaptation to climate change as a "dynamic social process" that is largely determined by the ability of the people to act collectively. Adaptive capacity is influenced by both collective action and social capital. They define social capital as "describing relations of trust, reciprocity, and exchange; the evolution of common rules; and the role of networks." It enables people to act collectively, because of the presence of networks and the trust that reinforces those networks. The chart on p. 395 explains all the relationships between the various aspects of social capital, how it relates to the state, and how that relationship produces or hinders collective action that can lead to adaptation. It presents multiple case studies to illustrate this relationship.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit and K. Takahashi (2007). Assessment of adaptation practices, options, constraints and capacity. *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 717-743. <http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch17.html>

Adger, W. N., Huq, S., Brown, K., Conway, D., and Hulme, M. (2003). Adaptation to climate change in the developing world. *Progress in Developmental Studies,* 3(3), 179-195. <http://www.oceandocs.net/odin/bitstream/1834/833/1/Neil%20Adger.pdf>

> The article focuses on climate change adaptation in developing countries. It is a review article that covers a wide variety of topics including vulnerability, adaptive capacity, collective action, and institutional flexibility and innovation. Each of these areas is central to the argument that developing countries are more at risk to climate change than developed countries. The article concludes with a discussion of various institutional means undertaken to help mediate the effects of climate change in these countries. The most funding is going into creating the development of National Adaptation Plans of Action (NAPAs) in the least developed countries (LDCs). These are generally managed by the Global Environmental Fund (GEF) and funded by large donations (generally $400 million or more) from developed countries. The process contains three stages: Stage I consists of support and planning; Stage II consists of detailed planning and capacity building; and Stage III consists of actual implementation of adaptations. Most

developing countries have at least begun, and a great many have finished Stage I planning. Only a few have completed or even begun Stage II.

Anand, P. (2002). "Decision-Making When Science is Ambiguous." Science 295: 1839.

Anderson, M. P., and W. W. Woesner (1992). "The role of the postaudit in model validation." Advances in Water Resources 15(3): 167-173.

Backus, George, Tom Lowery, Drake Warren, Mark Ehlen, Geoffrey Klise, Verne Loose, Len Malczynski, Rhonda Reinert, Kevin Stamber, Vince Tidwell, Vanessa Vargas, and Aldo Zagonel (2010). Assessing the Near-Term Risk of Climate Uncertainty: Interdependencies Among the U.S. States. Sandia Report. Albuquerque NM, Sandia National Laboratories: 257.

Barlas, Y. (1998). "Formal aspects of model validity and validation in system dynamics." System Dynamics Review 12(3): 183-210.

Barnett, J. and Adger, W.N. (2007). Climate change, human security, and violent conflict. *Political Geography*, 26, 639-655.
<http://waterwiki.net/images/7/77/Climate_change,_human_security_and_violent_conflict.pdf>

The authors tap research on vulnerability to climate change, "livelihoods and violent conflict," and the role of the government in development and peacemaking. They explain their proposed model in which climate change (by creating a scarcity of resources such as food and water) weakens the ability of the people to receive the resources they need to maintain their livelihoods. Climate change also undermines the ability of the government to function as a means of helping people maintain their livelihoods. Taken together, these factors may indirectly increase the likelihood of violent conflict within the affected region. They conclude with the observation that their model is not empirically proven, and they outline a course of research to support it.

Barnett, J. and Webber, M. (2009). Accommodating migration to promote adaptation to climate change. *Commission on climate change and development.*
<http://www.akhiljyotish.org/pdf/Accommodating%20Migration.pdf>

The authors contend that the great majority of immigration will be to and within developing countries, and this can be a positive outcome, both for the immigrant and the country. However, if people are forced to move against their will, this has a higher tendency to incite violence. Policy may be able to mitigate some of the risks that create conflict during migration. These policy recommendations include ensuring that migrants have equal rights and opportunities in their host communities, reducing the costs of moving money and people between areas of origin and destination, facilitating mutual understanding among migrants and host communities, clarifying property rights where they are contested, ensuring that efforts to assist migrants include host communities, and strengthening regional and international emergency response systems.

Buhaug, H., Gleditsch, N. P., and Theisen, O. M. (2008). Implications of climate change for armed conflict. *The World Bank: Social Dimensions of Climate Change.*

<http://community.apan.org/cfsfilesystemfile.ashx/__key/CommunityServer.Components.PostAttachments/00.00.00.28.96/Implications-of-CC-for-Armed-Conflict.pdf>

The report presents three main processes through which climate change can lead to conflict. These include intensification of natural disasters, increasing resource scarcity, and sea-level rise. Five mechanisms are proposed: economic instability, political instability, social fragmentation, migration, and inappropriate response. The authors state that the research supporting the link between climate change and armed conflict is weak and has yet to be statistically verified. More research must be performed to support this relationship. The relationship is theoretical and scarcity is generally one factor that adds to the likelihood of conflict. Scarcity can serve to weaken the infrastructures that are vital to coping with climate change and in preventing armed conflict. Natural disasters and rising sea levels have similar impacts on conflict, such that they serve to exacerbate existing political or economic issues and thus increase the likelihood of war. The complete model is summarized in their Figure 6 as a series of stresses and social states.

Cullen, S. H. and Glaser, S. M. (2007). Trends and triggers: climate change and civil conflict in Sub-Saharan Africa. *Political Geography, 26.* *<http://weber.ucsd.edu/~chendrix/research/HSCC2005/Hendrix_GlaserHSCC.pdf>*

The authors examine not just gradual temperature increase (long-term climate change), but variability of rainfall (short-term climate change). They find that both are positive predictors of violence in Sub-Saharan Africa. They contend that the often weak relationship between climate change and violence is due to a lack of consideration of trigger events. They posit that these climate events, such as wild swings in rainfall amounts, matter more in the creation of conflict then do changes in long-term climate averages. They analyze projected climate data for the region and conclude that rainfall is not expected to decrease significantly over the near future. Therefore, reduction in violence in the region may be achieved by reducing the population's almost total reliance on precipitation-based farming for subsistence.

Ehleringer, J. R., Cerling, T.E., Dearing, M.D. eds. (2005). A History of Atmospheric CO_2 and Its Effects on Plants, Animals and Ecosystems. New York NY, Springer.

Gass, S. I. (1983). "Decision-Aiding Models: Validation, Assessment, and Related Issues for Policy Analysis." Operations Research 31(4): 603-631.

Gleditsch, N. P., Nordas, R., and Salehyan, I. (2007). Climate change and conflict: the migration link. *Coping with Crisis Working Paper Series - the International Peace Academy.* *<http://www.ipinst.org/media/pdf/publications/cwc_working_paper_climate_change.pdf>*

The most plausible link between climate change and conflict is environmentally induced migration. Rising sea levels, heavy flooding, intense droughts, and desertification will create these climate refugees. Climate change may lead to direct emigration, or it may create resource conflict in one region, which causes emigration. Direct migration may lead to some sporadic violence, but is unlikely to escalate to full-scale conflict. Refugees displaced by conflict, however, are more likely to join in insurgent-like activities upon arrival. One avenue that creates conflict is income inequality. The agricultural population will be hit harder than the urban population, creating relative deprivation and conflict. It was found that the presence of refugees tripled the likelihood of armed conflict (defined as having 25 or more deaths). Refugees from conflict zones frequently engage in cross-border attacks against their home governments, and pursuit by state forces jeopardizes national security and the safety of local populations. To prevent migration-based conflicts, the authors advocate for improvement of immigration systems and infrastructures at the local and national level and encourage international agencies, such as the UN High Commissioner for Refugees and the International Organization for Migration, to assist countries in improving these systems. It also presents three scenarios (worst case/catastrophic, middle case, and best case) that might be useful to consider for the model.

Guzmán, J.M., Martine, G., McGranahan, G., Schensul, D., and Tacoli, C., Eds. (2009). *Population Dynamics and Climate Change.* International Institute for Environment and Development and The United Nations Population Fund. <http://unfpa.dexero.com/webdav/site/global/shared/documents/publications/2009/pop_dynamics_climate_change.pdf#page=203>

Hatfield, K. J. B., B. A. Kimball, D.W. Wolfe, D. R. Ort, R. C. Izaurralde, A. M. Thomson, J. A. Morgan, H. W. Polley, P. A. Fay, T. L. Mader, and G. L. Hahn (2008). Chapter 2: Agriculture. The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity, Washington, DC, U.S. Climate Change Science Program. Synthesis and Assessment Product 4.3 (SAP 4.3): 21-74.

Homer-Dixon, T. (2007). Terror in the weather forecast. *The New York Times,* 24 April. <http://www.ipb.org/disarmdevelop/environment/Terror%20in%20the%20Weather%20Forecast.pdf>

The article provides a very good overview of the research on climate change and its relationship to armed conflict. It's also useful because it shows that this issue is becoming more mainstream, and the public should be growing more and more aware. His main point is that the worsening climate conditions will act as an amplifier to regions already experiencing strain from other forces. Climate change may push areas affected by ethnic tension, wealth disparities, or political oppression into all-out war. He also mentions that climate change will disrupt outputs of crops and hurt economies, which will weaken governments and hinder their abilities to quell uprisings or prevent civil wars. He ends by advocating that climate change be added to the world's security agenda, before it is able to sow conflict globally.

Huq, S., Rahman, A., Konate, M., Sokona, Y., and Reid, H. (2003). *Maintaining adaptation to climate change in least developed countries (LDCs).* The International Institute for Environment and Development. Russell Press, Nottingham, UK. <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.99.3789&rep=rep1&type=pdf>

Kelly, P. M. and Adger, W. N. (2000). Theory and practice in assessing vulnerability to climate change and facilitating adaptation. *Climatic Change*, 47, 325-352. <http://nome.colorado.edu/HARC/Readings/Kelly.pdf>

The authors discuss approaches to the assessment of vulnerability to climate variability and change and attempt to clarify the relationship between the concepts of vulnerability and adaptation. In this study, the social and economic well-being of society are at the center of the analysis, focusing on the socio-economic and institutional constraints that limit the capacity to respond. From this perspective, the vulnerability or security of any group is determined by resource availability and by the entitlement of individuals and groups to call on these resources. Results for the study come from field research in coastal Vietnam. Four priorities for action are identified that would improve the situation of the most exposed members of many communities: poverty reduction; risk-spreading through income diversification; respecting common property management rights; and promoting collective security. (Summary adapted from Abstract)

Konikow, L. F. and J. D. Bredehoeft. (1992). "Ground-water models cannot be validated." Advances in Water Resources 15: 75-83.

Lonergan, S. and Kavanagh, B.(1991). Climate Change, water resources and security in the Middle East. *Global Environmental Change*, 1(4), 272-290. <http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6VFV-466GMN0-3C-1&_cdi=6020&_user=5817265&_pii=095937809190055X&_orig=search&_coverDate=09%2F30%2F1991&_sk=999989995&view=c&wchp=dGLbVtb-zSkWb&md5=85cbd73ce24154a2a9b66d0e7de60a06&ie=/sdarticle.pdf>

The article discusses the relationship between climate warming, natural resources (water), and security with its emphasis on the Middle East. Using projections of different models, the temperature of the Middle East is projected to rise 15-30%. Precipitation simulations were wildly different and thus not used, but evaporation was found to increase in all models from a low of 2.5% to a high of 20%. It provides several historical examples of disputes over water leading to violence or almost leading to violence.

McLeman, R., Mayo, D., Strebeck, E., and Smit, B. (2008). Drought adaptation in rural eastern Oklahoma in the 1930s: lessons for climate change adaptation research. *Mitigation and Adaptation Strategies for Global Climate Change,* 13, 379-400. <http://www.uoguelph.ca/gecg/images/userimages/McLeman%20et%20al.%20(2008).pdf>

Many nonclimatic factors that affected rural Oklahoma in the 1930s are similar to those that affect third-world countries today. Climatic events during the “dust bowl” of the 1930s are analogous to possible future effects of climate change. The area analyzed, rural eastern Oklahoma, is one that is predicted to see increased extreme heat events, a decrease in precipitation, and declines in agricultural productivity. The authors analyze the adaptive actions taken by Oklahomans during the dust bowl to make inform the debate on future adaptive actions in response to climate change. Findings are organized in a four-part typology: 1) Technological adaptation: none (farmers had little money, no incentive to improve land because most were tenants). 2) Government programs: AAA (Agricultural Adjustment Act - reduce total cotton production for incentives, designed to increase price of cotton), WPA (Works Progress Administration - most effective, provided jobs, although demand exceeded supply, also improved infrastructure), and CCC (Civilian Conservation Corps - generally jobs taken by eldest son, and payment was remitted back to household, programs each provided some relief, but none was universally effective), FSA (Farm Securities Administration - provided commodity trucks that distributed non-perishable goods, also relief camps for homeless former tenant farmers). 3) Changing farm practices: farmers could not change crops because crop infrastructure and locations were already designed to maximize output of corn and cotton; cooperation increased among farm neighbors, traditionally female activities increased in importance (eggs and cream could be sold or bartered; vegetable gardens provided food, a wider variety of perishable items were canned). 4) Farm financial practices: bartering increased markedly, credit was only available from local vendors, but only if one had good standing and a reputation for repayment; production of moonshine became common; seeking labor on other farms occurred (Rio Grande area, West Texas), but by the late 1930s had all but ceased because those farms were also struggling; others abandoned farms completely; in the 1930s 300,000 people left Oklahoma with California the most popular destination (1/3 ended up there).

McLeman, R. and Smit, B. (2006). Migration as an adaptation to climate change. *Climatic Change*, 76, 31-53. <http://perceval.bio.nau.edu/downloads/grail/climate_seminar/section3/McLeman_and_Smit06.pdf>

The article examines migration as an adaptive response to climate change and uses a framework based on theories of human migration behavior. It provides a good literature review of previous examples of human groups migrating due to climate fluctuations. It is based on the concepts of vulnerability, exposure to risk, and adaptive capacity. The model posits that when a climatic change occurs, if the communities' institutions can promote adaptation such that no major lifestyle changes are necessary, then no migration occurs. If it cannot, then people migrate out. This cycle is also affected by migration into the community by others from the surrounding area. The authors present a good overview of theories of human migration. The theories are incorporated into the model in the form of capital endowments, which could be good relations with extended family or ownership of land. They analyze 1930s dustbowl migrations from OK to CA and find that those with pre-existing family or social contacts in CA were more likely to migrate there. Those who stayed in OK generally had strong local networks of friends and extended families. Also more common among those who stayed were land owners, who could use their land in various ways to make money and thus did not need to relocate.

McMichael, A. J., Campbell-Lendrum, D. H., Corvalán, C. F., Ebi, K. L., Githeko, A. K., Scheraga, J. D., and Woodward, A. (Eds,) (2003). Climate change and human health: risks and responses. World Health Organization, 220-233. <http://www.bmj.com/cgi/content/full/328/7451/1324>

Mortreux, C. and Barnett, J. (2009). Climate change, migration and adaptation in Funafuti, Tuvalu. *Global Environmental Change*, 19, 105-112. <http://www.landfood.unimelb.edu.au/rmg/geography/papers/barnett13.pdf>

The article assesses current attitudes toward migration of the people of Tuvalu (a small island nation on a series of atolls in the South Pacific). Many of the more extreme projections show this nation completely underwater in the next 100 years. The authors find that people are aware of the dangers of climate change, but do not wish to leave

because of it. Three main factors affected the decision-making of the islanders. The first is a strong belief in God as a protector. Many felt that because of the story of Noah's Ark, God would not flood the world again. Therefore they would be safe, and thus did not need to leave the island. The second main factor was a general disbelief that climate change was occurring because citizens had yet to notice it (in the form of rising seas). This may be due to the youth of the population (39% are 19 or younger). Elders have noticed the rising of the seas. The final issue was an unyielding attachment to the island. Many people stated that it was their home, and they would rather "go down with it" than move.

Mukheibir, P. and Ziervogel, G. (2007). Developing a municipal adaptation plan (map) for climate change: the city of Cape Town. *Environment & Urbanization*, 19(1). <http://www.erc.uct.ac.za/Research/publications/07Mukheibir-Ziervogel%20MAP%20for%20CC.pdf>

This report was created because the municipal government of Cape Town felt that the national plan regarding climate change was inadequate to meet the needs of the city. The authors present a ten-step list to guide the development of a local plan on p. 146. There is a nice diagram of this process on p. 147. The study presents areas where the city is most vulnerable, including water supply, storm water control, fires, and sea level rise at coastal zones. Each vulnerability is then paired with a list of actions to mitigate that problem. For water shortage they propose restrictions, tariffs, leak reduction, awareness campaigns, incentives, regulations, dam and aquifer projects, water recycling, rain harvesting, use of sea water where possible for sewage and swimming pools, and desalinization. For storm water control they recommend improved monitoring and forecasting, flood retention ponds and weirs, storm drain maintenance, and development of storm-resistant infrastructure. For fire control they propose burning underbrush, increasing fire-fighting capabilities, removing plantations, controlling invasive plant species, fire breaks between forest and residential areas, and erosion protection. To protect coastal areas they recommend mapping sites with GIS to rate vulnerability, maintaining buffer zones, establishing more stringent set-back lines for development, and coastal protection measures such as breakwaters, revetments, and sea walls.

Myers, N. (2002). Environmental refugees: a growing phenomenon of the 21st century. *Philosophical Transactions of the Royal Society of London B*, 357, 609-613. <http://rstb.royalsocietypublishing.org/content/357/1420/609.full.pdf>

Provides an overview of this "new" phenomenon of environmental refugees and includes several possibly useful statistics. In 1995 there were 20 million environmental refugees versus 25 million "normal" refugees. In 1995, 1 in 5 Haitians had left their homes due to increased population density coupled with a lack of productive farm land. Also in 1995, 135 million people were threatened by severe desertification, and 550 million were subject to chronic water shortages.

National Research Council (1999). Global Environmental Change. Washington DC, National Academies Press.

National Research Council (2005). Radiative Forcing of Climate Change. Washingon DC, National Academies Press.

National Research Council (2006). Surface Temperature Reconstructions for the Last 2,000 Years, National Academies Press.

National Research Council (2010). Adapting to the Impacts of Climate Change. Washington DC, The National Academies Press.

Nel, P and Righarts, M. (2008). Natural disasters and the risk of violent civil conflict. *International Studies Quarterly*, 52(1). <http://archive.sgir.eu/uploads/Righarts-Natural%20Disasters%20and%20Violent%20Civil%20Conflict.pdf>

> The study uses available data for 187 political entities for the period 1950-2000. They found that natural disasters significantly increase the risk of violent civil conflict both in the short and medium term, specifically in low- and middle–income countries that have intermediate to high levels of inequality, mixed political regimes, and sluggish economic growth. Rapid onset disasters related to geology and climate pose the highest overall risk. Given the likelihood that rapid climate change will increase the incidence of some types of natural disasters, more attention should be given to mitigating the social and political risks posed by these cataclysmic events. (Summary adapted from abstract).

Raleigh, C., Jordan, L., and Salehyan, I. (2008) Assessing the impact of climate change on migration and conflict. *The World Bank: Social Dimensions on Climate Change.* <http://siteresources.worldbank.org/EXTSOCIALDEVELOPMENT/Resources/SDCCWorkingPaper_MigrationandConflict.pdf>

> The study finds that large-scale migration due to gradual climate change or sudden natural disaster is unlikely due to five major findings. 1) Disasters vary in their potential to force migration. As much as disasters, infrastructure and national variables shape responses. Developing an understanding of social, economic, and political forces is vital to predicting post-disaster behavior. 2) People in developing countries incorporate environmental risk into their livelihoods. People develop diversified means of subsistence as their main defense against environmental change. Likely migration in the developing world would generally be internal and temporary. 3) During periods of chronic environmental degradation, such as increased soil salinization or land degradation, the most common responses by individuals and communities is to intensify labor migration patterns. By doing so, families increase remittances and lessen immediate burdens to provide. 4) With the occurrence of a sudden disaster or the continued effects of a prolonged one, communities engage in "distress migration patterns." These patterns are shaped by the severity of the crisis, its geography, the ability of the individual household to respond, evacuation opportunities, existing and vulnerabilities, available relief, and government policies. Three main options are generally available: A) Receive support through one's social network, B) Rely on government agencies to access aid and resettlement options, or C) Relocate to a camp for temporary or long-term resettlement. 5) Because the most common environmental relocation pattern is internal and temporary, risks for conflict are low. However in countries or regions with unstable governments or

demographic groups, the risk for civil war and small-scale communal conflicts are elevated.

Raleigh, C. and Urdal, H. (2006). Climate change, environmental degradation and armed conflict. *Paper presented to the 47th Annual Convention of the International Studies Association*, San Diego, CA. Panel: Resource Scarcity and Armed Conflict.

The article presents an approach to assess the impact of environment on domestic armed conflict by using geo-referenced (GIS) data and small geographical, rather than political, units of analysis. It addresses factors assumed to be strongly influenced by global warming: land degradation, freshwater scarcity, and population density and change. The preliminary results indicate that the relationships between local level demographic/ environmental factors and conflict are not uniform. High levels of population growth in already densely populated areas do not appear to increase the risk of conflict, while land degradation appears to have some effect. Also, water scarcity in densely populated areas appears to increase the risk of conflict generally, but decrease the risk of territorial conflict. (Summary adapted from abstract)

Republic of the Maldives (2006). National Adaptation Plan of Action (NAPA). *Ministry of Environment, Energy, and Water*. <*http://www.maldivesmission.ch/fileadmin/Pdf/Environment/Maldives_NAPA_Nov.2006_1.pdf*>

Provides a great example of what countries are already doing to adapt to the changing climate. The Maldives is a small island nation under threat from rising sea levels and the increasing likelihood of extreme storms. The plan covers the measures they will take to preserve their country and their way of life. First, they intend to shore up their coastline, through flood control, the installation of hard barriers to reduce erosion, and the protection of their barrier reefs. Next they want to protect their main source of income, tourism, by reinforcing their airport, and diversifying the attractions the nation has to offer, to reduce its dependence on the marine environment. To protect water resources, they plan to increase rain water harvesting, protect aquifers from salinization by increasing flood control, and acquire solar desalinization technologies. Finally, they plan to diversify their food sources, by increasing poultry farming=and increasing agriculture and mariculture, to reduce their dependence on wild-caught tuna, for which the catch varies dramatically.

Reuveny, R. (2007). Climate change induced migration and violent conflict. *Political Geography*. 26, 656-673. <http://130.238.7.16/h/heax7669/Samh%E4llets%20Geografi/Artiklar/Reuveny.pdf

The author argues there are three basic responses to climate change; stay in place and do nothing (while absorbing the costs), stay in place and mitigate costs, or leave affected areas. Developed countries will most likely mitigate costs with technology and institutional redesign. Due to a lack of wealth and available technology, underdeveloped countries will not be able to mitigate impacts to the same extent and will thus suffer the costs, or leave, which may create conflict. People conduct a cost-benefit analysis in determining whether to leave, and where they will go if they choose to leave. Push and pull forces operate to either drive people out of regions (push) or attract them to others (pull). There are four channels through which conflict can flow: Competition, Ethnic

Tension, Distrust, and Fault Lines. (Existing conflicts may become exaggerated when formerly separate but competing groups are thrust together.) Conflict is more likely when two or more of these channels are operating. The author provides a solid list of examples of conflict created by migration, along with data such as origin→destination, environmental factors, other push factors, number of people migrating, and the specific types of conflict at the destination (p. 663-667). He found that 19 of 38 cases included no significant violence; of those 19, 14 were intrastate migrations. Also, those moving to developed countries exhibited no violence.

Salehyan, I. (2008). From climate change to conflict? No Consensus yet. *Journal of Peace Research*, 45(3), 315-326. <http://emergingsustainability.org/files/resolver%20climate%20change%20and%20conflict.pdf>

The article argues that studies on the link between climate change and violence are too deterministic and too certain that the relationship exists despite the lack of a strong causal linkage. The author advocates more research, specifically on social and political variables that are often overlooked by scholars looking to make the case that something must be done about climate change by making doomsday predictions about resource wars. The main influences on the relationship are the government's ability to regulate resources, manage the environment, and contain conflict. The authors present five main caveats to the climate change and conflict relationship. 1) Armed conflict is a very rare reaction to scarcity. For every example like Darfur, there are many other regions under similar conditions of hunger and water shortage in which genocide and conflict do not ensue. 2) Although local skirmishes are fairly common in response to scarcity, they rarely intensify into sustained, armed conflict. They are normally dealt with effectively by local authorities. 3) States are usually to blame for environmental degradation and scarcity. Democratic states have been shown to be the most protective of the environment and least likely to be engaged in resource scarcity conflict. 4) Violent conflict is a poor or suboptimal reaction to scarcity, given that wars generally destroy more resources than they capture. 5) The fifth criticism is very weak, based on one case, and not worth consideration.

Schwartz, P., and Randall, D. (2003). An abrupt climate change scenario and its implications for the United States National Security. *Report Prepared for the Department of Defense.* <http://famguardian.org/Subjects/Environment/Articles/ClimateChange-20090131.pdf>. Accessed 9/6/2010.

This report was commissioned as a worst-case scenario and presented to the U.S. Department of Defense. After review from climate change experts, it was found that the scenario presented would most likely occur in localized areas rather than globally, and the magnitude of the climate change impact would most likely be smaller. Their scenario includes drought, drops in temperature due to slowing of the Earth's thermohaline conveyor, and an increase in extreme weather events. They posit that these events will reduce the Earth's human carrying capacity by reducing available food, water, and energy. This will then create problems regarding migration and border management for

developed countries, global conflict over resources, and a general worldwide economic downturn.

Smit, B., Burton, I., Klein, R. J. T., ang Wandel, J. (2000). An anatomy of adaptation to climate change and variability. *Climatic Change,* 45, 223-251. <http://www.uoguelph.ca/gecg/images/userimages/Smit%20et%20al.%20(2000)_Climatic%20Change.pdf>

The study attempts to systematically specify and differentiate types of adaptation with a framework around three central questions: 1) What is being adapted to? 2) Who or what is adapting? 3) How does adaptation occur? The study characterizes climate change as steady trends over time (e. g., global warming) and also climate instability and variability. There are three general types of models used in studying adaptation: 1) Conceptual models of the adaptation process, 2) Numerical impact assessment models, and 3) Empirical adaptation studies. This piece is more about how to study adaptation than about actual adaptation that has gone on or will go on in the real world.

Stern, N. (2007). The Economics of Climate Change. Cambridge NY, Cambridge University Press.

Tol, R. S. J. (2009). "The Economic Effects of Climate Change." Journal of Economic Perspectives 23(2): 29-51.

United Nations Department for Economic and Social Affairs: Division of Sustainable Development: Small Island Developing States. Updated June 18, 2007. http://www.un.org/esa/sustdev/sids/sidslist.htm. Accessed 9/12/2010.

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