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Risk Assessment of Climate Systems for National Security

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Risk Assessment of Climate Systems for National Security

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Abstract

Climate change, through drought, flooding, storms, heat waves, and melting Arctic ice, affects the production and flow of resource within and among geographical regions. The interactions among governments, populations, and sectors of the economy require integrated assessment based on risk, through uncertainty quantification (UQ). This project evaluated the capabilities with Sandia National Laboratories to perform such integrated analyses, as they relate to (inter)national security. The combining of the UQ results from climate models with hydrological and economic/infrastructure impact modeling appears to offer the best capability for national security risk assessments.

ACKNOWLEDGMENTS

This work was funded though Laboratory-Direct Research and Development (LDRD) project 141510.

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NOMENCLATURE

AR5	IPCC Assessment Report 5 (2013)
CAM	Community Atmosphere Model
CASoS	Complex Adaptive, System of Systems
CCSM	Community Climate System Model (precursor of CESM)
CESM	Community Earth Systems Model
CLM	Community Land Model
CMIP3	Coupled Model Intercomparison Project
DHS	Department of Homeland Security
DNS	Direct Numerical Simulation
DOD	Department of Defense
DOE	Department of Energy
EUCOM	European Command
FPU	Food Production Units (area)
GCM	Global Circulation Model
HPC	High-Performance Computing
IAM	Integrated Assessment Model
IFPRI	International Food Policy Research Institute
IMPACT	International Model for Policy Analysis of Agric. Commodities and Trade
IPCC	Intergovernmental Panel on Climate Change
MOGA	Multi-Objective Genetic Algorithm
NCA	National Climate Assessment
NCAR	National Center for Atmospheric Research
NORTHCOM	U.S. Northern Command
PACOM	Pacific Command
PCMM	Predictive Capability Maturity Model
PPE	Perturbed Physics Ensemble
QCT	Qualitative Choice Theory
SNL	Sandia National Laboratories
SSM	Statistical Surrogate Model
SST	Sea Surface Temperature
UCM	Unintended Consequences Model
UQ	Uncertainty Quantification
USCG	U.S. Coast Guard
V&V	Verification and Validation
WSM	Water Simulation Model

1. INTRODUCTION

The purpose of this research was twofold. The first part of the effort surveyed those Sandia National Laboratories' (SNL's) analytical and modeling/simulation (M/S) capabilities that would facilitate the evaluation of the climate change impacts that affect national and international security. Additional exploratory work on expanding and focusing those capabilities established where research could most contribute to climate impact assessment, balanced with the cost of maturing or maintaining the relevant analytical tools.

The second part of the effort took the down-selected subset of capabilities and enhanced existing tools or developed new capabilities that would allow comprehensive climate-impact assessments. The impacts assessments are to focus on risks, as opposed to prediction. Because of the emphasis on national security risks, the emphasis is on how physical phenomena affect human populations and how those populations respond. Therefore, the analytical tools must be able to quantify the implications of uncertainty in physical and behavioral phenomena on the risk of experiencing undesirable outcomes.

The areas of consideration were:

- Predictive Capability Maturity Model
- Uncertainty Quantification Methods
- Aerosols and Cloud Formation Uncertainty
- Infrastructure Vulnerability and Adaptation
- Emergent Atmospheric Phenomena
- Global Hydrology Dynamics
- International Consequence Simulation
- Assessing the Risk from Climate Change

Each of these topics has their own section within the report.

The US Executive branch, many members of Congress, and Defense and Intelligence communities recognize that climate change has considerable potential to create high-consequence security threats. They further recognize the gap between climate science and the engineering risk-based analyses needed to characterize the national security threat. National security issues arising from perceptions of climate change already produce geopolitical tensions within the Arctic, Russia, China, and Africa. From population migration, to the loss of economic viability, to the new access to critical resources, to the disruption of strategic supply chains, climate change produces destabilization hazards across countries. To understand geopolitical issues, the defense community must understand the dynamics of regional climate change and its concomitant effects on human and nation-state behavior. Moreover, they must understand and accommodate the inescapable uncertainty in physical and human-behavioral modeling before we can assign any level of confidence (validation) to the results that analyses produce. This effort focused on extending SNL's existing climate capabilities to perform regional analyses and a comprehensive characterization of potential security threats.

Because the U.S. government and international climate scientists now recognize the risk of climate change as more severe than had previously been assessed, new concerns focus on risk assessment. Current scientific efforts focus almost exclusively on establishing best-estimates for the future physical phenomena associated with climate change. The greatest consequences occur in the tail of the currently best-understood uncertainty distributions for climate change responses (e.g. local precipitation).

Climate change could have a dramatic effect on the nation's economy. Policies that do not consider uncertainty and feedback consequences could have severe counterproductive impacts. The work reported here describes improvements in the ability to quantify and attribute uncertainly, thereby helping prioritize climate science research. An integrated risk assessment can determine what aspects of uncertainty most affect societal consequences.

This work takes a risk assessment approach that necessarily focuses on the uncertainty. Risk is often dominated by low probability, high consequence events. The term "consequence" pertains to societal impacts, not physical ones. Current climate science does not address the actual impact of crossing a tipping point or the precursor fingerprint signatures that could corroborate its existence. Current climate science has not developed formal UQ methods to substantiate the improvement in the quantification of uncertainty or the quality of analysis. Existing hydrological models cannot assess the physical consequences of extreme changes over existing conditions. Current socioeconomic models cannot address the pan-national migration of populations and commerce due to physical changes in the environment. Existing (climate change) Integrated Assessment Models (IAM) are not compatible with risk assessment methods. Our climate + hydrology + socioeconomic + Uncertainty-Quantification (UQ) approach extends the simulation capabilities to address tail phenomena and allow risk-informed decision making. Only now are national security organizations (DOD, DHS, Intelligence Community) realizing the issues – but do not yet how to address them. The climate science community is only now experiencing pressure to make the understanding of uncertainty a priority.

SNL has an interest in developing the methods to perform meaningful risk assessments on issues important to national security. To this end, there is the need to develop an integrated set of climate, hydrology and socioeconomic consequence models that deal with the realizable phenomena by enhancing Sandia's existing models. Hydrology is the primary vector of climate risk (Backus, et.al, 2012). The climate-science community has only recently realized the need to address climate risk. The methods to viably perform the UQ experiments on climate models, the metrics to define the meaning of the UQ experiments, hydrology models to deal with extreme changes in topology and water balances, and socioeconomic models to simulate pan-national responses to destabilizing physical conditions, are simply not yet available.

2. PREDICTIVE CAPABILITY MATURITY MODEL

Climate-induced, national-security risks stem from the impacts on and response of populations, economies, and governments to changes in environmental conditions. The modeling and simulation (M&S) of the risk requires both physical and behavioral analyses. Determining the confidence in these analyses is more difficult than with conventional engineering analyses, because even the physical modeling involves operations in regimes outside historical ranges. Data to specify behavioral computational models generally must come from natural experiments, because laboratory experiments are either impossible or have ethical ramifications. Therefore, the conventional methods to assess model validity for a particular use require enhancements to accommodate the combined physical and behavioral elements.

The particular use of concern is producing risk assessments for the national security impact of climate change. During the last few decades, M&S has become the mainstay of risk assessments. M&S efforts typically rely heavily on large scale computer codes to solve complex, nonlinear differential equations or integro-differential equations. Through efforts at SNL over the last two decades, the application of M&S to complex systems has conclusively demonstrated a number of elements that are crucial to predictive capability (Oberkampf et.al. 2007). The Oberkampf work emphases that with continually increasing resources devoted to the development of an M&S capability and increasing reliance placed on M&S in decision making, it is necessary to develop improved methods for assessing the quality of M&S activities. SNL has developed the Predictive Capability Maturity Model (PCMM) for computational M&S, which is a structured method for assessing the level of maturity of M&S efforts (Oberkampf et.al. 2007). The Predictive Capability Maturity Model (PCMM) can be used to assess the level of maturity of computational modeling and simulation (M&S) efforts. Importantly, the PCMM is a structured method for assessing the maturity of an M&S effort that is directed toward an application of interest. The PCMM does not assess whether the M&S effort, the accuracy of the predictions, or the performance of the engineering system satisfies or does not satisfy specified application requirements. The purpose of the PCMM is to contribute to decision making for some engineering system applications. In the context of climate risk assessments, the PCMM could address six contributing elements to M&S: (1) representation and spatial/temporal fidelity, (2) engineering and behavioral fidelity, (3) code verification, (4) solution verification, (5) model validation, and (6) uncertainty quantification and sensitivity analysis. For each of these elements, attributes are identified that characterize four increasing levels of maturity.

These six elements are important in judging the trustworthiness and credibility of an M&S effort that deals primarily with the numerical solution describing the dynamic system of interest. Representation and spatial/temporal fidelity is directed toward the level of detailed characterization of the system being analyzed or specification of the interacting components of that system. Physical and behavioral model fidelity deals primarily with (1) the degree to which models are theory based, (2) the degree to which the models are calibrated, (3) the degree to which the models are being extrapolated from the validation and calibration database to the conditions of the application of interest, and (4) the quality and degree of coupling of multi-scale effects that exist in the application of interest. Code verification focuses on (1) correctness and fidelity of the numerical algorithms used in the code relative to the mathematical model; (2) correctness of the source code; and (3) configuration management, control, and testing of software through Software Quality Engineering (SQE) practices. Solution verification deals with (1) assessment of numerical solution errors in the computed results and (2) assessment of confidence in the computational results as the results may be affected by human errors. Model validation concentrates on (1) thoroughness and precision of the accuracy assessment of the computational results relative to the experimental measurements; (2) completeness and precision of the characterization of the experimental conditions and measurements; and (3) relevancy of the experimental conditions, physical hardware, and measurements in the validation experiments compared to the application of interest. Uncertainty quantification and sensitivity analysis focuses on (1) thoroughness and soundness of the uncertainty quantification effort, including the identification and characterization of all plausible sources of uncertainty; (2) accuracy and correctness of propagating uncertainties through a computational model and interpreting uncertainties in the system response quantities of interest; and (3) thoroughness and precision of a sensitivity analysis to determine the most important contributors to uncertainty in system responses.

The combined physical and behavioral models used for climate risk include mechanisms and processes that are only recently recognized. Data to verify the model results or the model theory is often limited, and primarily the result of natural (as opposed to designed) experiments. For many of the dynamics, there are no constitutive laws that can act as the foundation for results. Nonetheless, ongoing research is developing ever more complete and comprehensive sets of historical data. With new data, any failure of the models to having predicted those observations raises concerns that the models are missing key mechanisms, contain flawed structures, or the discrepancy between model and data is inconsistent with uncertainty criteria. How can PCMM guide a statistical means to quantify the progress in validating the modeling system? The first point to realize is that validation is not an all or nothing option, but rather is a measure of confidence in model results over a metric spanning 0.0 to 1.0. The initial modeling would have a high degree entropy and the distribution of its validity quantified using maximum entropy methods. The PCCM would move to the right as entropy declines. Each step of maturity is then defined though the stabilization of calibration and parameterization, where new data/structure no longer changes moments of the uncertainty distribution.

3. UNCERTAINTY QUANTIFICATION METHODS

The purpose of this effort was to develop methods for generating statistically meaningful metrics on uncertainty in model results. Climate models are computationally intensive, thereby limiting the numbers of simulations available for uncertainty quantification (UQ). Further, the overarching concerns of this LDRD focus on risk. Risk is associated more with the tails of a distribution than with its central tendencies. The LDRD research considered five new methods to establish the shape and uncertainty within the –fat tail” of climate uncertainty distributions:

- Pareto Optimal Ensembles
- Gaussian Process Models
- Polynomial Chaos Expansion
- Stochastic Collocation
- Gaussian Random Field

The Pareto Optimal approach uses MOGA (Multi-Objective Genetic Algorithm) to determine the UQ surface of parameter tests that best fit observed data (Dalbey 2010, Swiler et al. 2011). When UQ forecast runs (equilibrium response to CO2) adequately near the Pareto Optimal surface, they represent tail conditions where the other four methods can be used to develop surrogate models that characterize the tail uncertainty. Figure 3.1 depicts that over process.

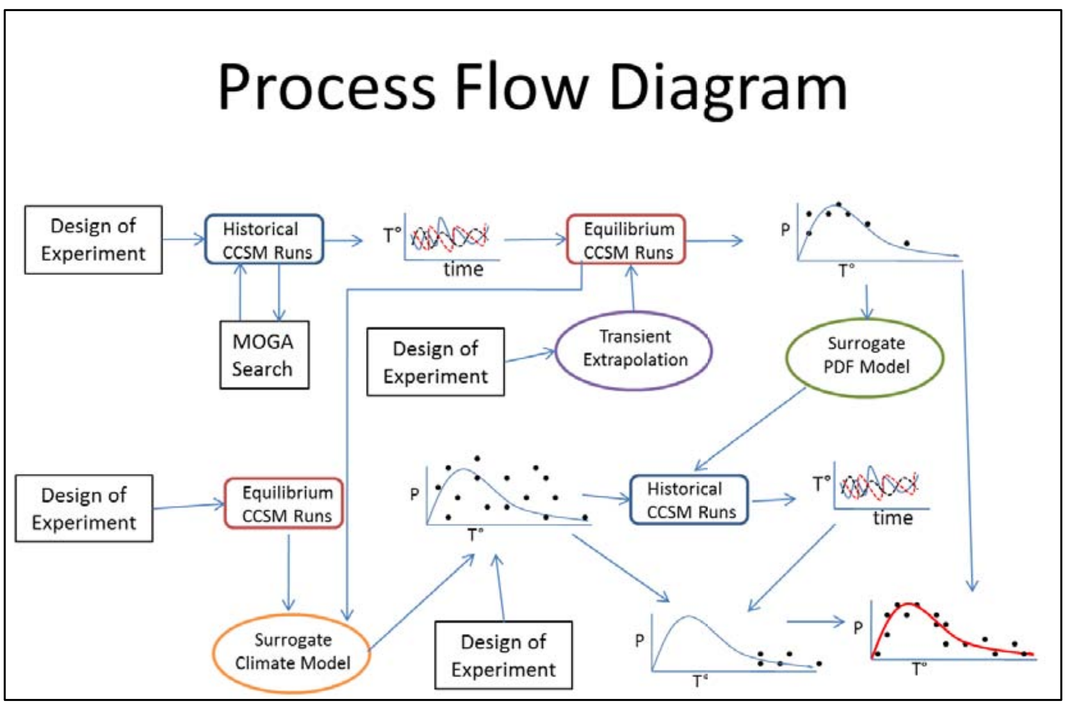


Figure 3.1: Tail UQ Approach

Figure 3.2 illustrates a typical Pareto frontier. The origin would represent a set of parameters that produce an optimal results for all objectives simultaneously. For model calibration, the closer the parameter set is to the origin, the better. A dominated design point is any solution that is inside the pareto frontier. The MOGA algorithm uses DAKOTA to look for a solution better that a dominated design point to improve the determination of the frontier.

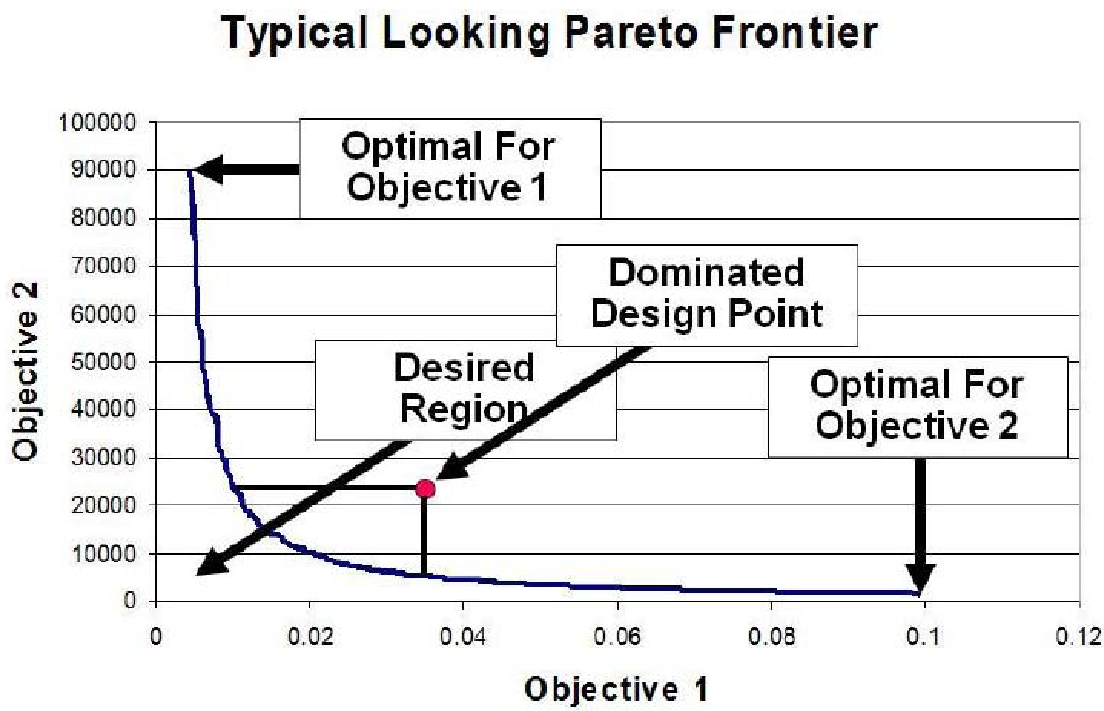
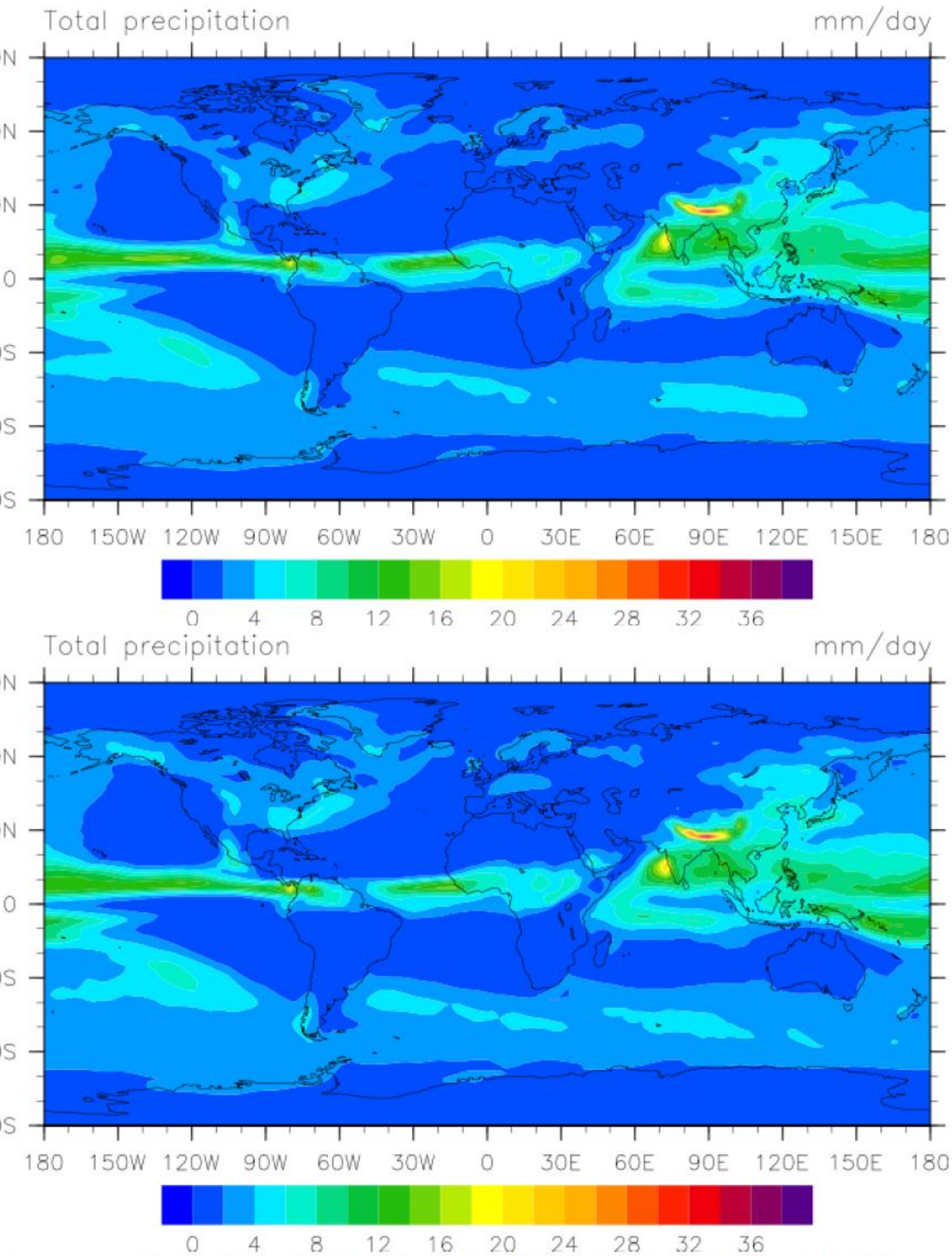


Figure 3.2 Pareto Optimal Frontier (from Swiler 2011)

Figure 3.3 shows a comparison of a the current best parameter estimation of the Community Earth Systems (climate) Model (CESM) with a MOGA derived solution, showing how well the MOGA independently converges on a set of parameters with comparable skill.



Comparison of J-J-A average Precipitation (in mm/day) at Year 75, with Default parameters (top) and MOGA solution 7 (bottom).

Figure 3.3: MOGA Parameterization (from Swiler 2011)

Figure 3.5 shows the use of Polynomial Chaos Expansion and Stochastic Collocation to model the tail of climate distributions. In this case the, Beta-Jacobi has much lower errors out on the tail – characterized by the distance γ from the reference measurement Collocation point as compared to other polynomials (Sarsyan et al. 2009, 2010a, 2010b, 2011, 2012; Safta et al. 2009,2010a, 2010b).

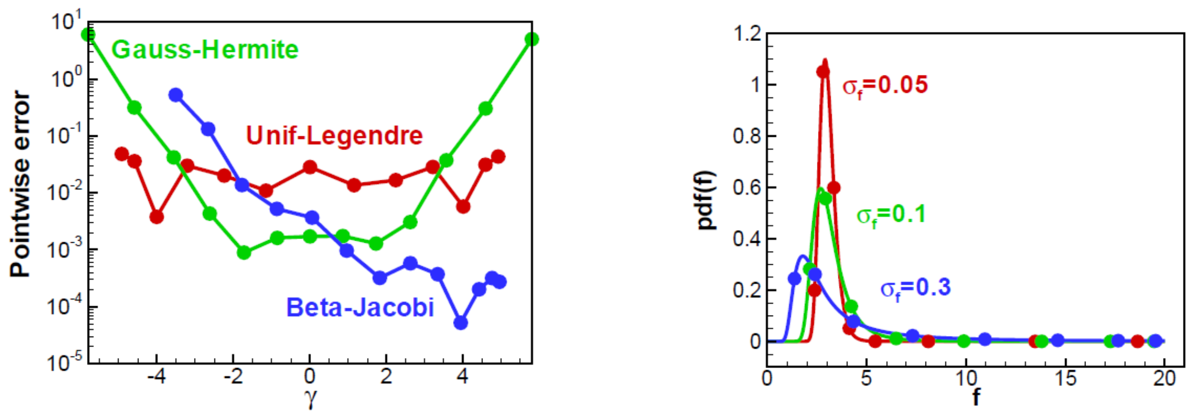
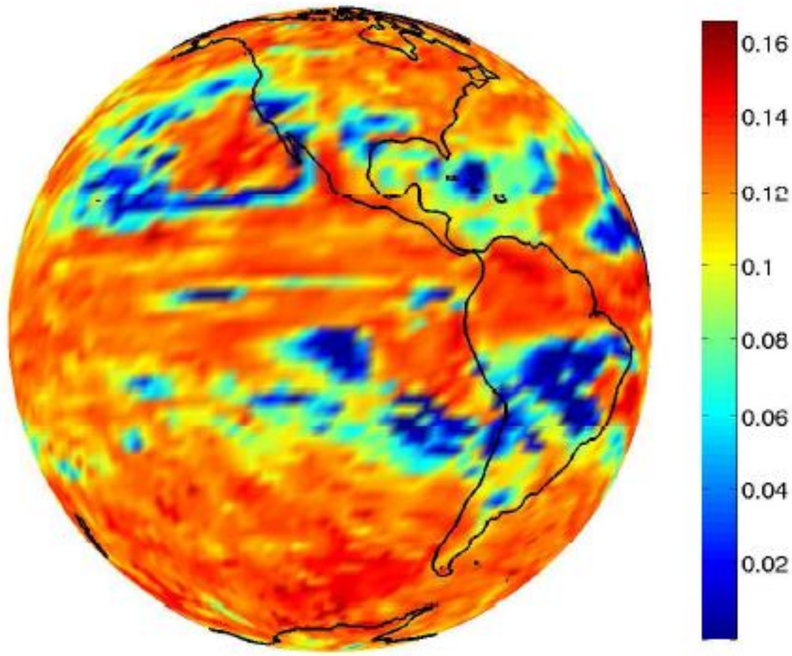


Figure 3.4: Polynomial Chaos Estimation

Lastly LDRD researchers formulated risk assessment in climate change impact studies in a framework similar to that used in safety engineering, by acknowledging that probabilistic risk assessments focused on low-probability, high-consequence climate events are perhaps more appropriate than studies focused simply on best estimates. To aid in this study, they developed specialized statistical surrogate models (SSMs) that can be used to make predictions about the tails of the associated probability distributions. The SSM represents each climate variable output of interest as a space/time random field, calibrated to available spatial and temporal data from existing climate databases, or calibrated from a collection of outputs from Global Circulation Models. Due to its reduced size and complexity, the realization of a large number of independent model outputs from a SSM becomes computationally straightforward, so that estimates of low-probability, high-consequence climate events becomes feasible. A Bayesian framework was also developed to provide quantitative measures of confidence, via Bayesian credible intervals, in the use of the proposed SSM as a statistical replacement for the associated GCM (Field et al 2012, 2011a, 2011b).

Figure 3.5 shows the results of an example exceedance probability for precipitation where the concern in for the probability of exceeding a reduction in precipitation below one standard deviation.



Estimate of exceedance probability $p_3 = \Pr\left(\bar{A} \leq -1\right)$ using the statistical surrogate model calibrated for data on precipitation rate.

Figure 3.5: Random Field Modeling of Exceedance Probability.

4. AEROSOLS AND CLOUD FORMATION UNCERTAINTY

Cloud and aerosol dynamics generate greatest uncertainty in climate models. This effort used theory to model experiments and world data. Through its combustion work, Sandia has a strong stochastic 1D transport (turbulence) and aerosol modeling capability. A new method for economical simulation of turbulence in an air column has enabled cloud science advances (Kerstein 2010, 2102; Krueger ad Kerstein 2010; Lignell et al. 2012; Schmidt et al. 2012, 2011a, 2011b, 2011c, 2009). . These advances allow

- Cloud parameterization and basis for UQ
- Enable simulation of cloud growth and lifetimes
- Enables parameter studies and uncertainty quantification

In the Explicit Mixing Parcel Model of mixing effects on cloud-droplet evolution, turbulent advection of fluid is implemented by permutations (``triplet maps") of the fluid cells in chosen segments of the 1D domain, each representing an individual eddy. This captures motions as small as the smallest turbulent eddies (Kolmogorov microscale), but there is important droplet-inertia phenomenology, such as droplet clustering that increases droplet collision rates, at much smaller scales. The researchers developed and demonstrated a 3D triplet map for droplets (and an associated drag-law representation) that captures clustering behaviors at small Stokes numbers St (such as those of cloud droplets). There is excellent agreement between the results (for radial distribution functions and collision kernels) at small St and direct-numerical-simulation (DNS) results that omit gravity, and good agreement with DNS results that include gravity. (Kerstein 2010).

Numerical simulations using the One-Dimensional-Turbulence model are compared to water-tank measurements emulating convection and entrainment in stratiform clouds driven by cloud-top cooling. Measured dependences of the entrainment rate on Richardson number, molecular transport coefficients, and other experimental parameters were reproduced. Additional parameter variations suggest more complicated dependences of the entrainment rate than previously anticipated. A simple algebraic model indicates the ways in which laboratory and cloud entrainment behaviors might be similar and different. On a 10 m domain, the method captures cloud droplet evolution mechanisms entrainment of dry air (shaded) into a parcel causes evaporation (Schmidt et al. 2012). To what degree is the evaporation homogeneous (all droplets affected) vs. inhomogeneous (some disappear, others unaffected)? The answer is sensitive to evolution details that are affordably captured by the new model. These details have important climate implications (cloud albedo and geographical/diurnal/seasonal distribution).

Figure 4.1 shows the different domains of cloud formation captured in the model. Figure 4.2 show how the model captures 3D phenomena in a 1D environment.

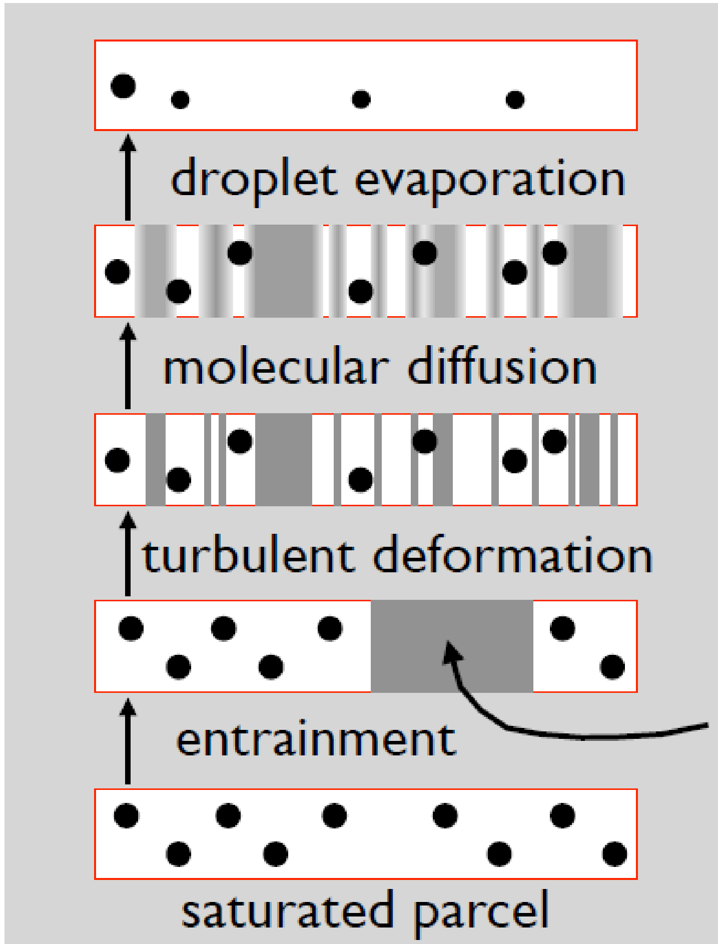


Figure 4.1: Cloud Phenomena

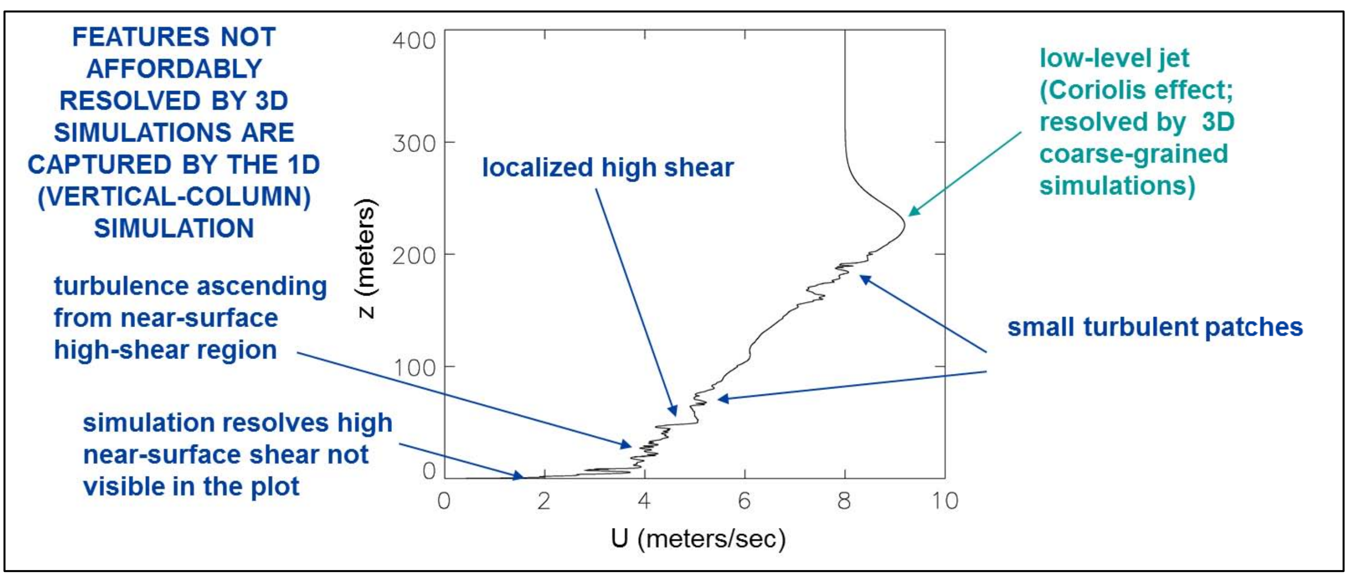


Figure 4.2: 1D Simulation of 3D Phenomena

5. INFRASTRUCTURE VULNERABILITY AND ADAPTATION

The focus of this task was the simulation of cascading dependencies when climate change events affect critical infrastructures.

5.1 Infrastructure and Climate Risk Assessments

Climate assessments that neglect infrastructure vulnerability, interdependencies, and resilience miss fundamental elements of economic and societal risk. The SNL experience in simulating infrastructure and international risks is fully applicable to climate assessments. Resiliency behaviors, recovery dynamics, and enduring consequences affect future economic conditions and mitigation.

The cornerstone of the methods development is to provide salient infrastructure information that improves infrastructure analyses for climate risk assessments. Global, national, regional, local – all viewpoints and multiple approaches are required to understand the climate-risk problem space. Needed integration occurs within the analysis and via abstracting from one set or scale of model results to provide input for other models and analyses. It is not an either-or situation. To provide information useful to the climate risk assessment, infrastructure modeling must consider the impacts to the population, the economy, and consider which infrastructures to include in the analysis.

Through the use of regional archetypes, infrastructure-centric modeling provides generalizable model modules of climate impacts on infrastructure and populations that can be replicated and connected as needed to evaluate risks and potential mitigations/adaptations. A way to start the process is to build modules parameterized to the readily available and understandable (to US researchers) US detail, and then abstracting for other countries to create a global representation. The characterization of regional archetypes is a function of the projected climate changes; environmental, infrastructure, economic and societal conditions.

Superstorm Sandy showed the necessity to evolve from a focus on acute problems to solving chronic problems and, thereby reducing the incidence of acute situations. Using resilience analysis to design and implement effective adaptation strategies for climate change adds the cost and reliability perspectives to the process of mitigating risk over the long-term (Vugrin et al., 2011a,2011b, 2012). Inherently, infrastructure modeling uses the causal simulation of combined physical science, infrastructure, and societal systems. Additionally, more recent work includes data-anchored, individual-through-societal, cognitive modeling. Perceptions are more important than physical reality for capturing the responses and behaviors of a society to climate risks.

Uncertainty quantification is an essential element for analyzing physical-societal systems, especially in the context of climate change. The climate-related impacts on society and the economy are dominated not by the best-estimate, average conditions but by the ―routine extremes" of the tail events. Storms, droughts, and heat-waves have a greater impact than the average increased temperature and reduced precipitation conditions. It is relatively easy to adapt to small changes in environmental circumstances; it can be catastrophic to be unprepared for inevitable extreme events.

Complex Adaptive, System of Systems (CASoS) analyses are best able to address global socioeconomic interdependences and system stability in the context of perturbations and stressors, e.g., climate (Brown 2011). CASoS analyses capture the myriad of transactions that affect the production and flow of critical resources/good throughout the global trading system as depicted in Figure 5.1. Many types of infrastructure are best represented as a network. Energy is a prime example as shown in U.S. pipeline system of Figure 5.2. The basis for most CASOS analyses is the network representation.

A network analysis can then show the likelihood and quantification of a loss of delivery capacity, such as is depicted in Figure 5.3 for an earthquake. The subsequent cost of lost economic production due to the loss of energy, the subsequent cost of repair, and the possible resulting shift in economic activity and population through the region become sources of new risk or resilience.

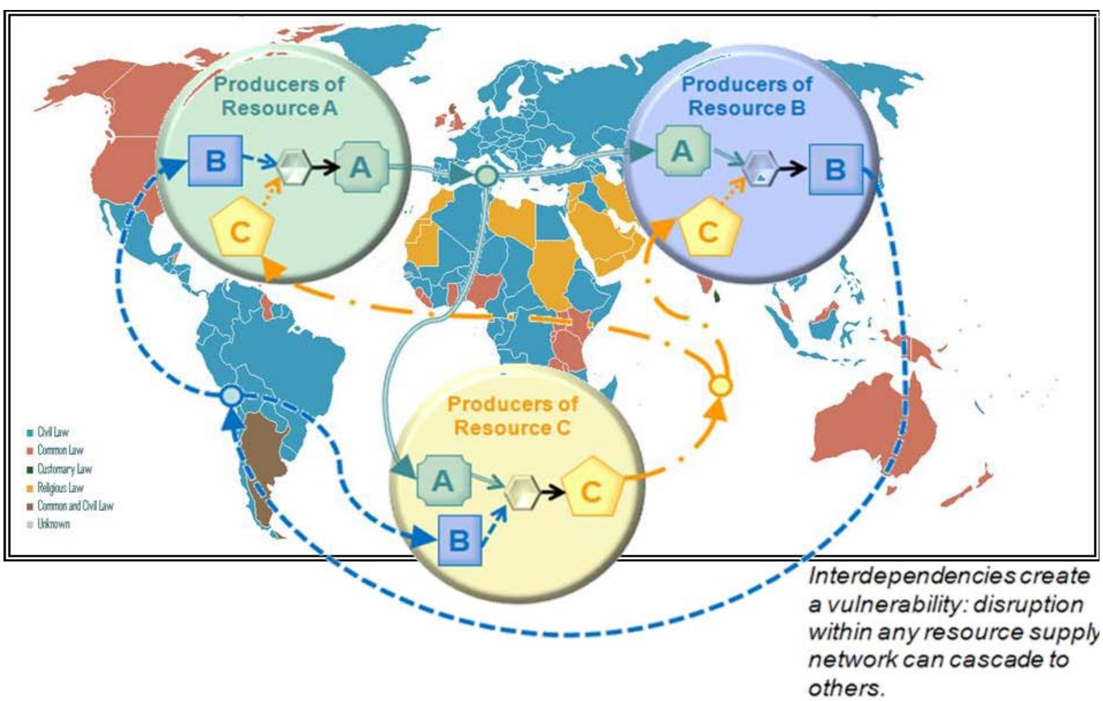


Figure 5.1: CASoS Representation

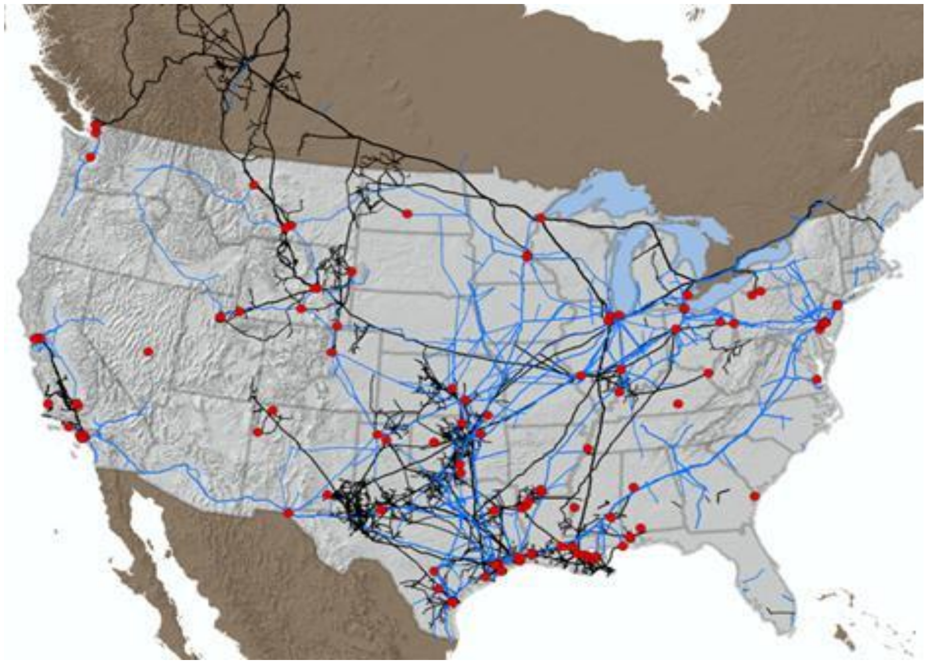


Figure 5.2: Pipeline Network

Through CASoS analyses, it is possible to design policy that enhances system resilience. Future work would also necessarily include the interactions among infrastructures beyond energy and water. Figure 5.4 illustrates the interconnection among other infrastructures.

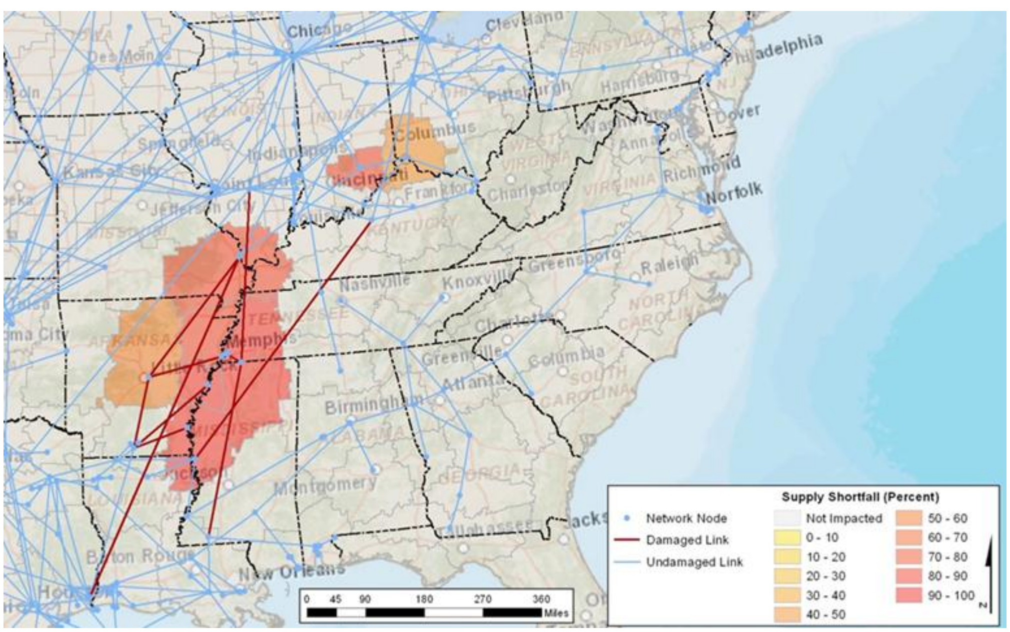


Figure 5.3: Energy Supply Disruption (Earthquake)

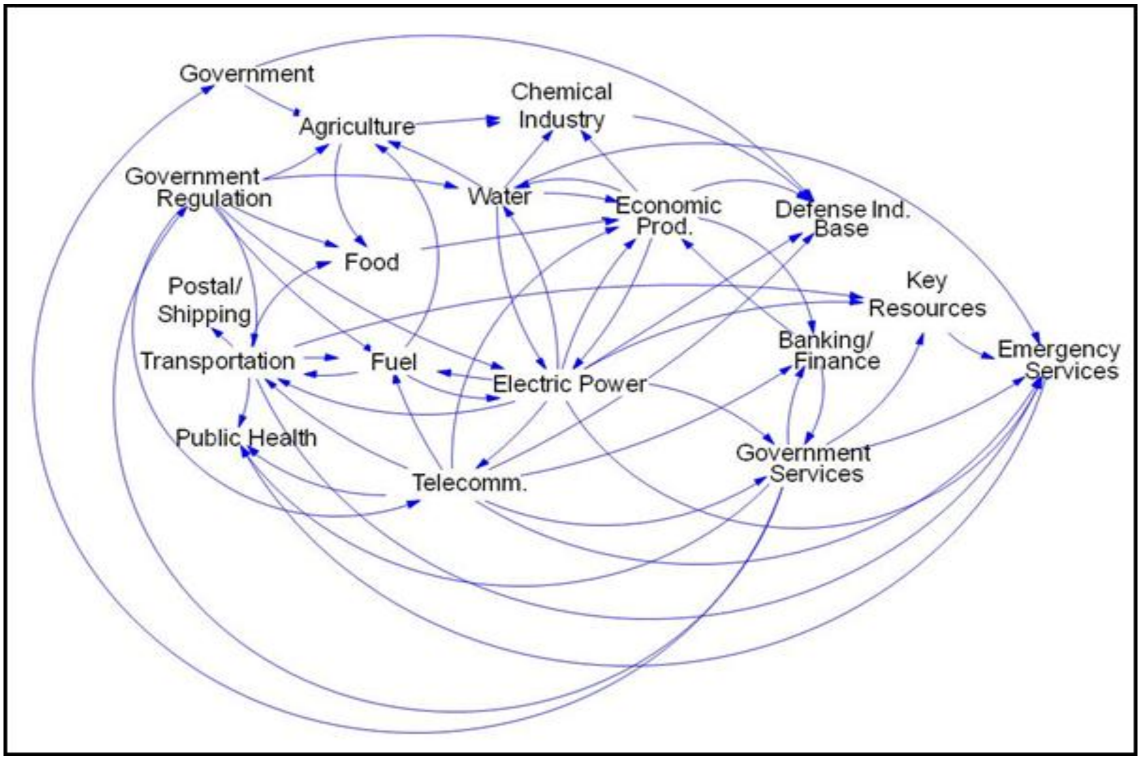


Figure 5.4: Infrastructure Interactions

In the context of risk-assessment temporal requirements, a generic infrastructure conceptualization needs to include the progression from short-term climate and economic impacts, through long-term infrastructure evolution and structural changes in the economy. Figure 5.5 displays the basic, short-term, infrastructure logic where, in this discussion, the ―failure rate" of production facilities is associated with climatic events.

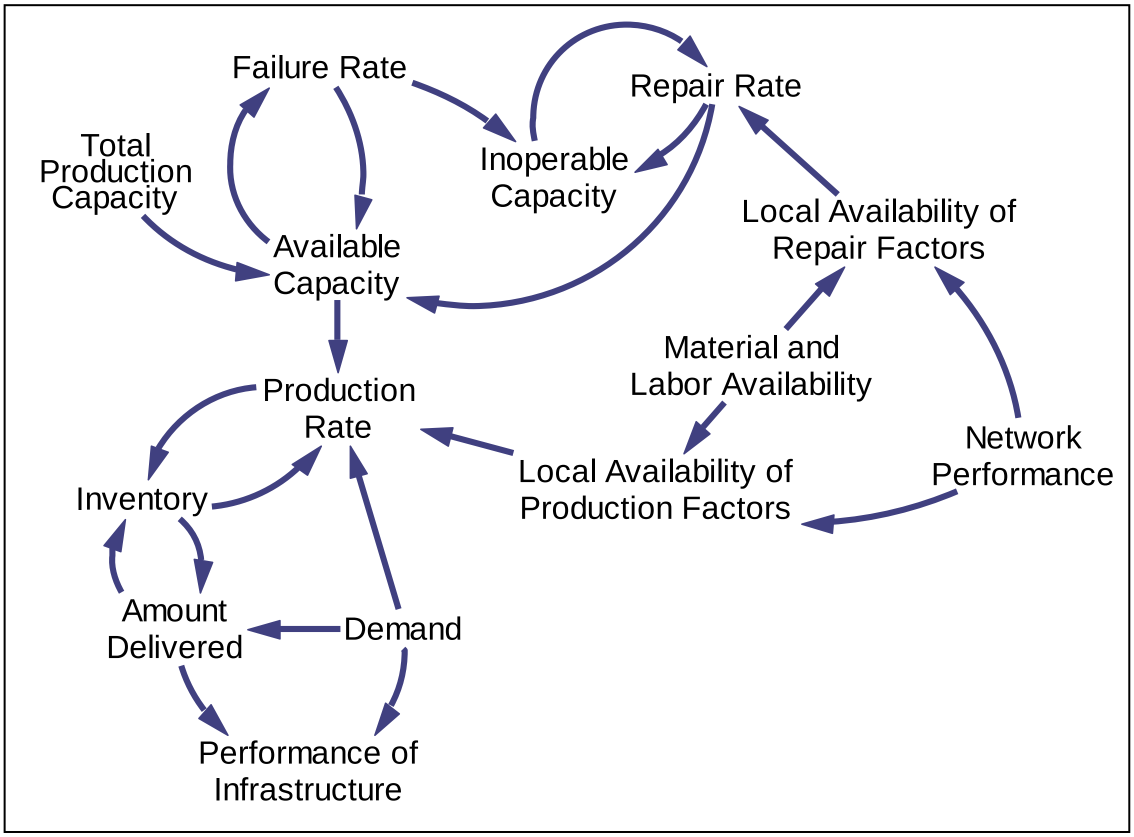


Figure 5.5: Short-term Infrastructure Logic

Such a representation can capture:

- Post-event cleanup expenses and the pulse in demand for repair-related goods and services.
- Rebuild investment – Does not add to productive capital, can crowd out other investments and increase market demand for products in short supply.
- Cost of temporary loss of production capacity (or of having to make use of alternative capacity from other sectors or other regions)
- Adaptive investment (Policy) – Does not add to productive capital but does add resilience and limits future damage. It can crowd-out other investments.

In the longer term, continued climatic impacts change the cost of doing business in a region and lead to structure changes in the economy. Locally, businesses must change processes and equipment to adapt to the new climatic conditions. Internationally, businesses and population move to where the climatic impacts have a lesser effect on cost or actually provide new economic opportunities. The changes in economic organization mean not only changes in investments for new and adapted infrastructure, but also in the interrelationships and dependencies among and within the infrastructure systems. Figure 5.6, shows how climate and the consequent economic changes add long-term dynamics to the short-term logic of Figure 5.5.

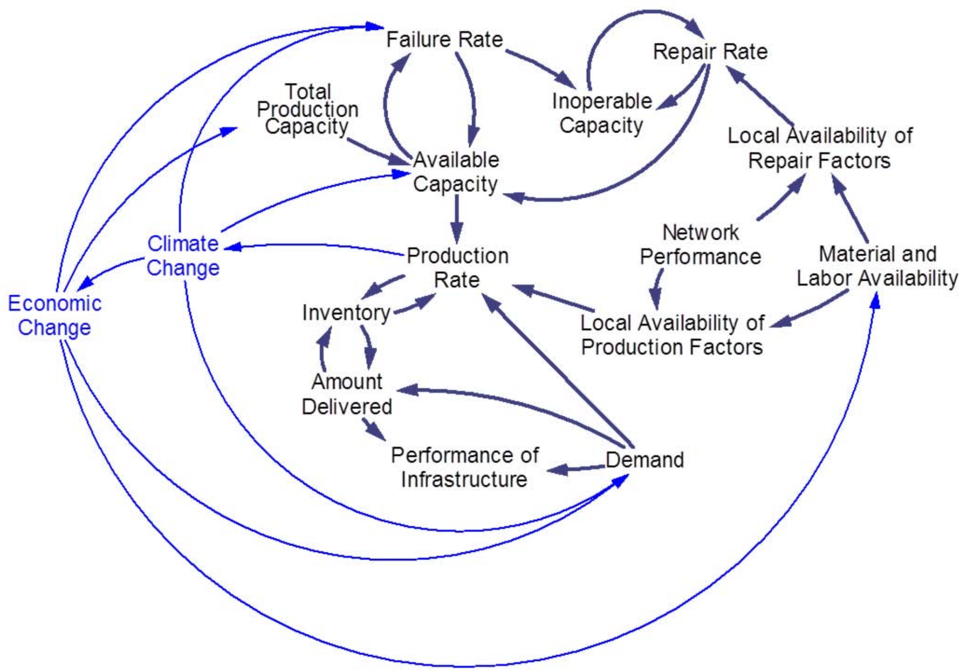


Figure 5.6: Long-term Infrastructure Response

Initial analyses, used as a vehicle to develop an integrated climate risk assessment capability, would considered energy and water interactions in response to climate change. Available generation capacity is affected by water availability and water temperature, as well as failure rates due to extreme events such as from flood, storm surge, wind, snow, and, cold snaps, and heat waves. Power transmission is also affected by extreme events as well as long-term phenomena in addition to increased ambient air temperature. Oil production, refining, pipelines are as affected by water availability and extreme conditions, as is natural gas production (e.g. fracking) and gas pipelines. Non-energy water demand is affected by agricultural prices (leading to changes in planting, irrigation and land-use), and economic activity (e.g., industrial use of water for cooling and consumption, along with municipalities for household uses). The supply of water is affected by precipitation, temperature, and extreme weather (storms may cause pollution and toxicity). Ground water-use can augment surface water availability, but recharge rates may be too low to allow increased or sustained use, or similarly, reduced surface water may decrease recharge rates.

Increased temperatures would increase the demand for summer peak electric power, and reduce the demand for natural gas in winter months. Extreme events, in addition to damaging the energy systems, may damage production capacity in others sectors, thereby temporally or permanently reducing energy demand. Migration of businesses and population due to climate change would require new capacity in the areas with immigration and cause stranded-capacity in the areas of emigration. In turn, the change in load/demand and generation/supply centers would require changes in the transmission or pipeline system -- that if not made would add to the fragility of the energy system to future climatic events.

Different U.S. and global regions have different imbalances of supply and demand, thereby causing import and export interdependencies. Thus, reconciling differences in peak demands, supply capacity, and delivery (transmission) connectivity across regions could be critical to understanding cascading infrastructure impacts. In an energy-water analysis, hydropower, with its sensitivity to climatic conditions, may make an inordinate contribution to the how climate change affects electrical supply and demand.

Any analysis that considers the effect of climate change on infrastructure must underscore uncertainty because (typically smoothly changing) best-estimates of climatic conditions do not set the design basis for infrastructure nor capture the economic risks of climate change. Indeed, the uncertainty also means that projected supply or demand for energy will often be different from the actual supply or demand, thereby affecting investments decisions, operational costs, and system reliability (resilience). It is the uncertainty, in both the events and consequence, that determine the economic risk. A risk assessment approach can identify effective risk mitigations and adaptive responses. Conversely, it can prioritize vulnerabilities and the adaptations to limit the risks from those vulnerabilities. Although it cannot be predicative in determining the timing and realization disruptive technologies (such as appears to be occurring due to new fracking methods for oil and gas), an infrastructure-centric analysis can determine how disruptive technologies could affect future responses and risks from climate change.

5.2 Combined Hydrological and Macroeconomic Analyses

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.

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.

The Parks et al. (2010) work addressed 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 work was at the conceptual model validity-testing stage. Parks et al. address several issues of climate risk modeling:

- Validation
  - Conceptual Model Validation
  - Climate Risk Validation Strategy
- Vulnerability
  - Climate Vulnerability Models .
  - National or Regional Population-Based Climate Vulnerability Model
- Response Capacity
  - Economic Capacity .
  - Infrastructure Capacity .
  - Social Capital
  - Global Economic Capacity
  - Infrastructure Capacity
  - Social Capital Initial Indicators
- Uncertainty

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 is 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 the Park's study addressed 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 included:

- 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.

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 models 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).

5.3 Risk over Varied Temporal and Spatial Resolutions

A prototype model was developed to demonstrate how infrastructure modeling could contribute to the macroeconomic modeling commonly used for climate assessments.[1]

The prototype considered a simplistic national economy affected by local extreme events (flooding/storm-surge) on a single transportation infrastructure (port) over 40 years:

- Single infrastructure (e.g. flooding one of seven major Ports)
    - Use Semantic Graph logic to specify sub region/industry
    - Threshold impact: normal weather variation has no impact
- Cobb-Douglas Macroeconomic Production function
    - Endogenous Consumption, Investment, Capital, GDP
    - Exogenous Population/Tech Growth
- Climatic “Weather” and Volatility
    - Slow mean growth over time, faster variance growth
    - Events modeled as a local (week resolution) event.
- Dual 5-year and weekly time periods
    - Simulation years: 2010-2050
    - Explicit recovery and accumulation from damage:
      Local => National

[1] See http://globalchange.mit.edu/research/IGSM and http://www.globalchange.umd.edu/models/gcam/

It included the aforementioned impact components of:

- Post-event Cleanup expense
- Rebuild investment: Does not add to productive capital, can crowd out other investments.
- Consumption costs: Added cost of using alternative ports and transportation, or allocating temporary shortage.
- Temporary loss of production capacity
- Adaptive investment (Policy): Does not add to productive capital. Does add resilience and limits future damage. Can crowd-out other investments.

In the spirit of Figure 5.6, the model simulates changes in productive capacity due to economic growth, and also the effect of lost capacity by modeling the fractional damage or percentage reduction in production over time. Infrastructure grows in proportion to economy. After the damage from an extreme event, the model employs a 12 week recovery time. To illustrate how to maintain logic compatibility with other modeling methods), the model a uses CGE (Computable General Equilibrium) convention by updating economy-wide stocks at the beginning of each (5-year) period. A Cobb-Douglas formulation for the economy with simple elasticities for demand were was used in this simple prototype, but a Constant Elasticity of Substitution (CES) and Constant Elasticity of Transformation (CET) for demand formulation could also be used to make the logic fully compatible with optimizing CES/CET macroeconomic models.

Figure 5.7 illustrates the prototype model calibrated for the U.S. national GDP and a local ―impact area.” The impact area is equivalent to connectively with the national economy and in value comparable with that of Los Angeles. The purple curve is a representative stochastic set of climatic extreme-events (with one week resolution) causing direct damage to port infrastructure. These events temporarily reduce port activity, with consequent changes in the local and national economy. Because macroeconomic models do not have weekly resolution, the infrastructure results are ―rolled up” to produce the annual or even decadal impact for the macroeconomic model to incorporate, consistent with the macroeconomic model‘s design and assumptions. The frequency and intensity over time increase, as indicated by climate models simulations. The direct damage costs of the purple curve are represented as positive values .The remaining curves represents the difference in the GDP relative to the base case. There is a blue line that represents the base case, and it definitionally stays at 0.0. The red curve show the costs if the economy simply repair the damaged structures after each event. The green adaptive curve replaces the structure but, through increased investments/costs that make the new infrastructure capable of accommodating the past events with a 20% addition contingency. Note that the total cost over time is greatly reduced. Figure 5.8 shows the same results, but as a percentage of GDP. Note that Figure 5.7 and 5.8 are just one stochastic instantiation of extreme events. Different timing and intensify would produce somewhat different quantitative results, but comparable qualitative results. Note also that, in this instantiation, the adaptive costs are more expensive as a % of GDP in the early years, but the costs is dramatically less expensive that the myopic case over the longer term. The curves vary in shape between the figures because the economy continues to grow over time.

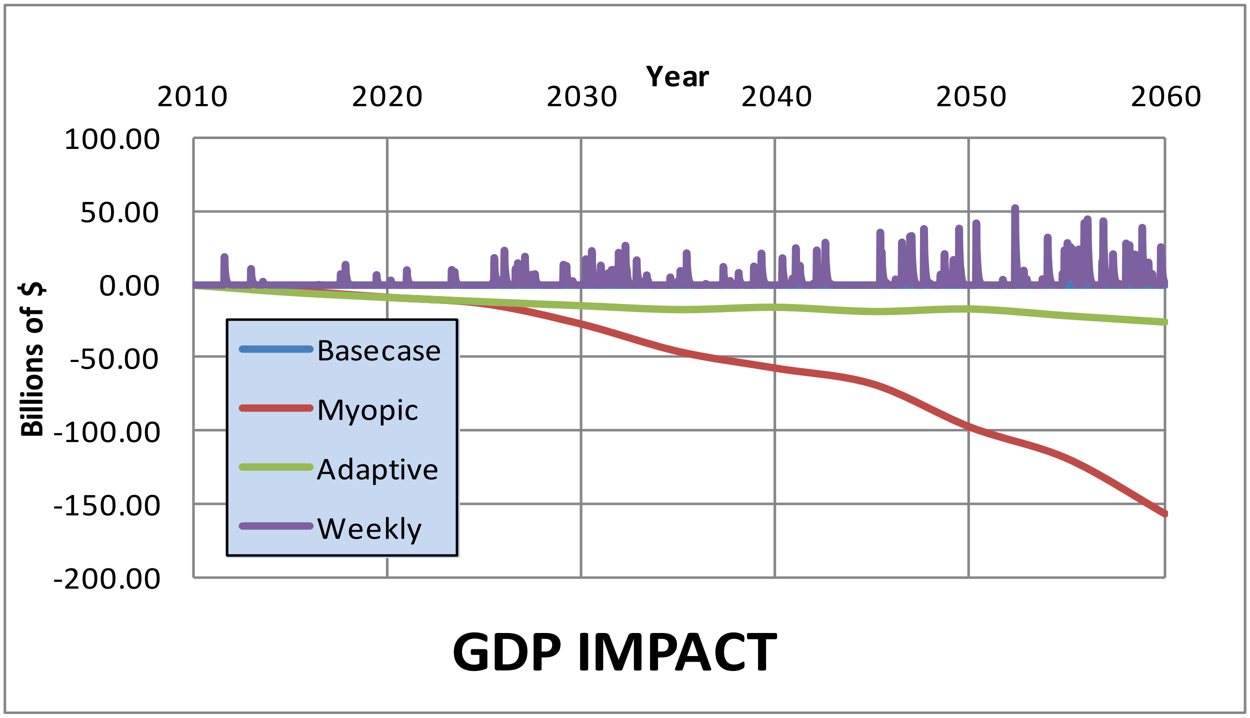


Figure 5.7: Climate Impact on GDP (B$)

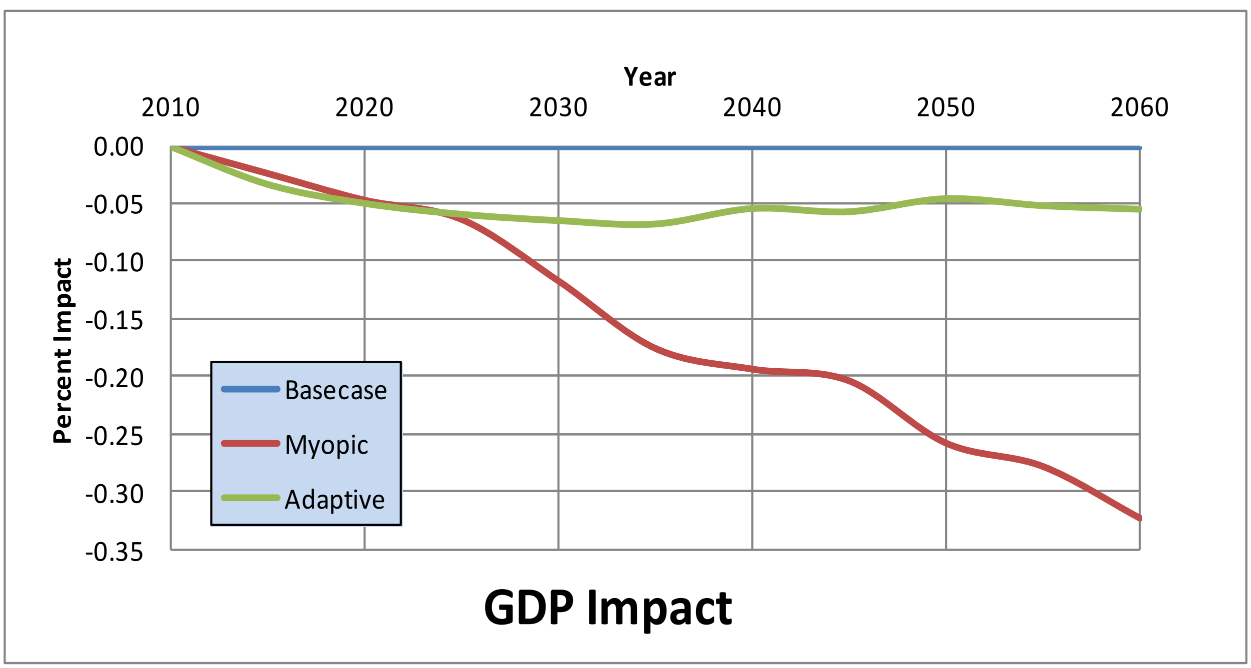


Figure 5.8: Climate Impact on GDP (%)

6. EMERGENT ATMOSPHERIC PHENOMENA (ARCTIC)

Two tasks addressed the consequence of climate change on the Arctic. The first task considered the physical impacts of climate change and the emergent behaviors that could have impacts on the rest of the globe. The second task considered the geopolitical and economic consequences of the climate change within the Arctic. In both tasks, the concern is with tail events. Tail events are have a lower probability than the best estimate of future conditions, but due to climate volatility, it is highly likely that the tail conditions will occur within the 2010 to 2100 timeframe. These tail events represent much larger risks than the best estimate conditions.

6.1 Physical phenomena associated with Arctic sea ice loss

As part of our risk assessment of climate systems for national security, we have identified the Arctic region as the most likely to change rapidly in a way that cascades into the rest of the northern hemisphere. Arctic climate is significantly more sensitive to radiative forcing that the global average, and is a critical component in the Earth's energy distribution system. It also is a powerful driver of the rest of the system. The cause of ―Arctic amplification" is attributed primarily to ice-albedo feedback. Ice and snow are much more reflective than the underlying surface or seawater. In a warming Earth, ice and snow begin to retreat at higher latitudes and altitudes, exposing the darker surface, reducing the albedo and increasing the fraction of sunlight that is absorbed. The strong positive feedback led to the prediction that as the Earth warmed, the effect would be more pronounced in the Arctic, where rapid temperature increases should be accompanied by loss of ice and snow. Other positive feedbacks, such as higher humidity, also contribute to Arctic amplification.

We extended our existing climate capabilities to perform preliminary regional analysis in an attempt to identify emergent and signpost phenomena of climate change, along with sensitivity fingerprints. Our Arctic "emergent condition" work suggests that once the Arctic Ocean becomes ice free, it will have a high probability of being ice-free every summer thereafter. Moreover, an ice-free Arctic will change the boundary conditions for weather that will propagate not only through the northern hemisphere, but globally.
We conducted a series of numerical experiments to test this idea of a significant short-term atmospheric response to a very different ocean configuration that would affect climate on a 5-year time scale. We concluded that a fully-coupled (ocean-atmosphere-cryosphere) model would be overkill for these purposes. Major ocean circulation cannot change fast, but sea surface temperatures can, and the atmospheric hydrological cycle will respond quickly to that. For the purpose of testing a scientific prediction, 20 years is much too long. Our goal was to focus on a significant and measurable effect that has a significant likelihood of happening soon.

We were initially concerned with the following questions:

1) If natural variability causes complete melting of summer Arctic sea ice, will the ice recover in the absence of additional radiative forcing from anthropogenic CO2?
2) Will there be different transient weather effects for ice-free (diagnostic) vs. recovering (active) Arctic sea ice?
3) Will sea ice recover when subjected to 2x or 3x CO2 levels?

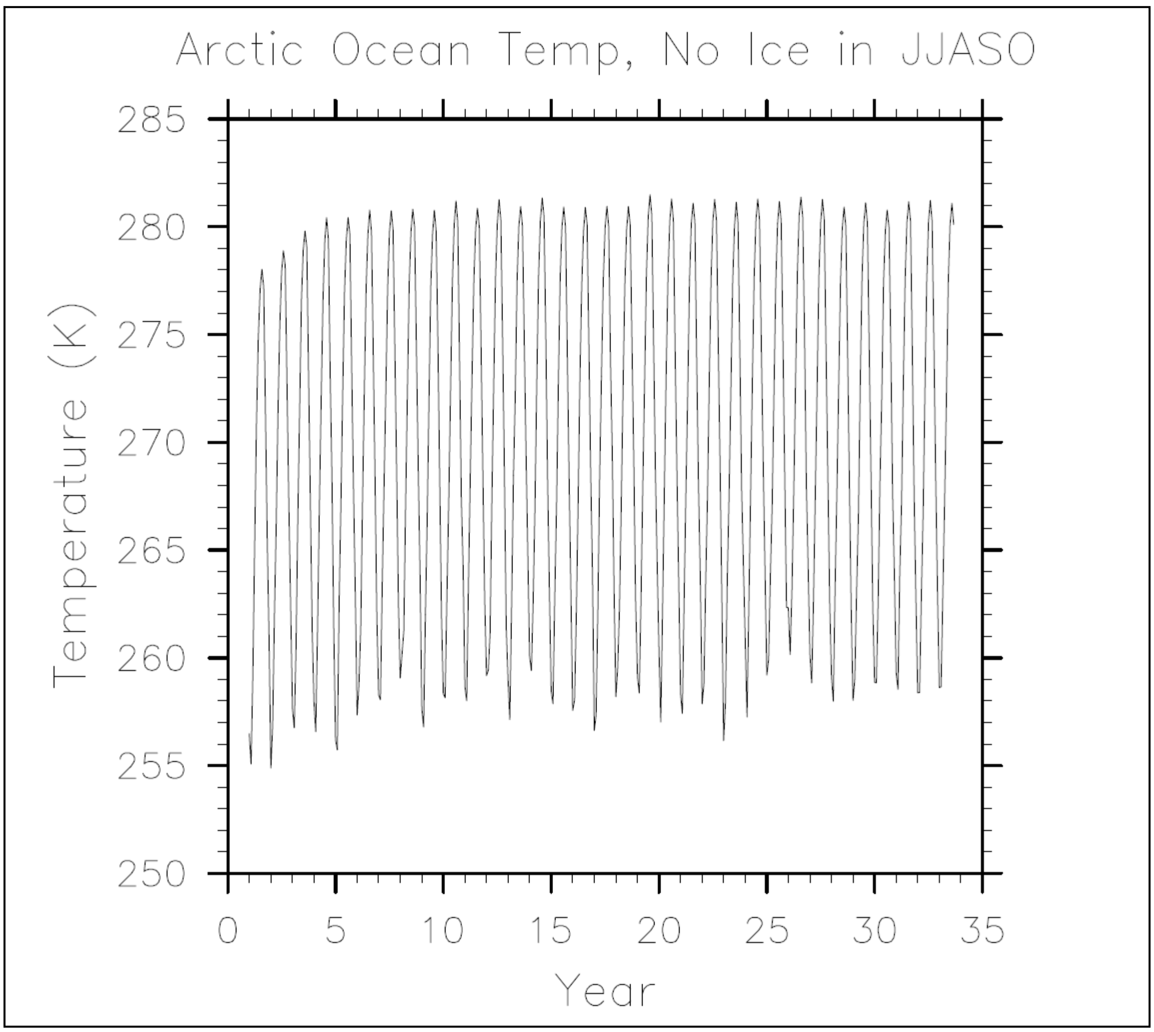


Figure 6.1: Arctic sea surface temperature in an ice-free Arctic

To test this idea, we generated the equilibrium global sea surface temperature (SST) distribution that would emerge after a 32-year period of prescribed Arctic sea ice in which there is a five month period during which it is complete melted (June 1 through October 31). We rotated sea ice masks from other months into the winter months for this experiment. We made an extreme assumption for our test case as a ―bounding problem" in which we would expect large effects (Boslough et al. 2010). Figure 6.1 shows the resulting history of Arctic ocean SST. It shows the history of Arctic sea surface temperature (SST) resulting from prescribed ice-free Arctic during June-October (JJASO) and reduced ice in the remaining months, but with radiative forcing consistent with year-2000 levels of greenhouse gases. The large transient in the first few years exceeds the subsequent natural variability. Annual average sea surface temperatures (Figure 6.2) suggest that approximate equilibrium is achieved within about a decade.

Next, we performed two runs using a coupled cryosphere model, initialized on Sept. 30 of a year with an ice-free Arctic in which Arctic sea ice was allowed to re-form in two different ways: 1) starting with default prescribed SST values for the year 2000, and 2) starting with ocean/atmosphere/land data from the "warm ocean" case (the older prescribed ice with no northern ice extent June - Oct run. The default initialization is labeled –diagIce” and the warm equilibrium initialization is labeled –activeIce0” in the subsequent plots.

After six years of simulation time, surface temperatures in the warm case dropped back to the "equilibrium" levels of the cool case, so it doesn‘t appear that there is significant hysteresis. The ice extent is still showing a slightly bigger drop in the summer, but has otherwise seemingly recovered. Permanent loss of sea ice, in this model, cannot be sustained without a change in radiative forcing.

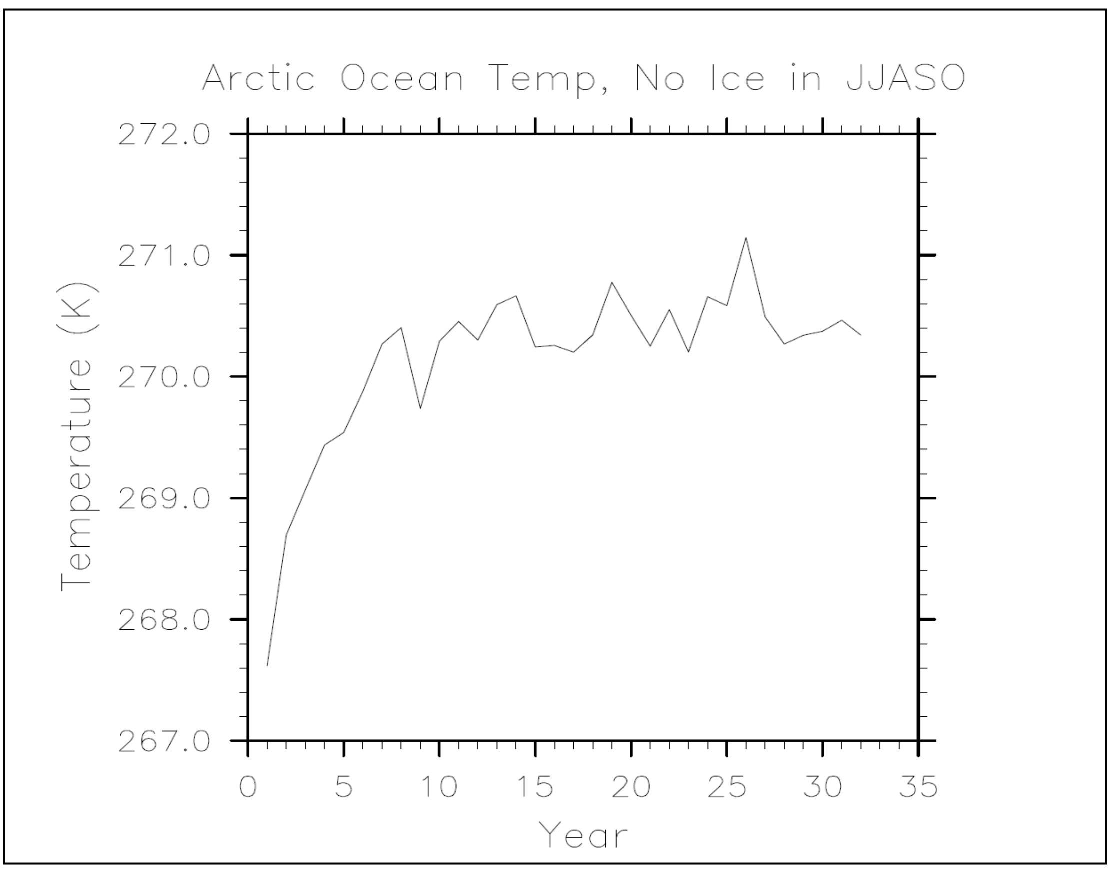


Figure 6.2: Annual average history of Arctic sea surface temperature (SST).

We also found major changes in hydrological cycle as well as heat transport that have the potential of effecting global weather, even in the tropics and southern hemisphere. The following plots and maps (Figures 6.3-6.5) show these differences.

Figure 6.3 shows the global JJA surface temperature for slab-ocean world having Arctic with active ice, which is allowed to grow back (top), prescribed ice-free summer (JJASO) Arctic (center) and the difference (bottom). There are major temperature differences in the polar regions of both hemispheres, as well as significant mid-latitude continental anomalies that are both positive and negative. This suggests that the presence or absence of Arctic sea ice has a significant effect on global climate, even in the opposite hemisphere.

Figure 6.4 shows the global DJF precipitation for slab-ocean world having Arctic with active ice, which is allowed to grow back (top), prescribed ice-free summer (JJASO) Arctic (center) and the difference (bottom). Precipitation patterns are radically altered by the reduction in Arctic sea ice, and is most pronounced in the tropical Pacific. Some equatorial tropical rainforests (e.g. Brazil) and mid-latitude agricultural regions (e.g. the US southern plains) exhibit significant reductions in precipitation.

Figure 6.5 depicts the global JJA global zonal average of cloud fraction. The ice-free Arctic case (diagnostic ice, upper right) exhibits a significant reduction of low clouds in the summer Arctic, and an increase in high clouds in the winter Antarctic.

Figure 6.6 show that with radiative forcing (CO2 concentrations at 3X preindustrial levels) that once the Arctic becomes ice-free, it will likely remain ice-free until the radiative forcing returns to levels that can maintain ice cover in the summer months.

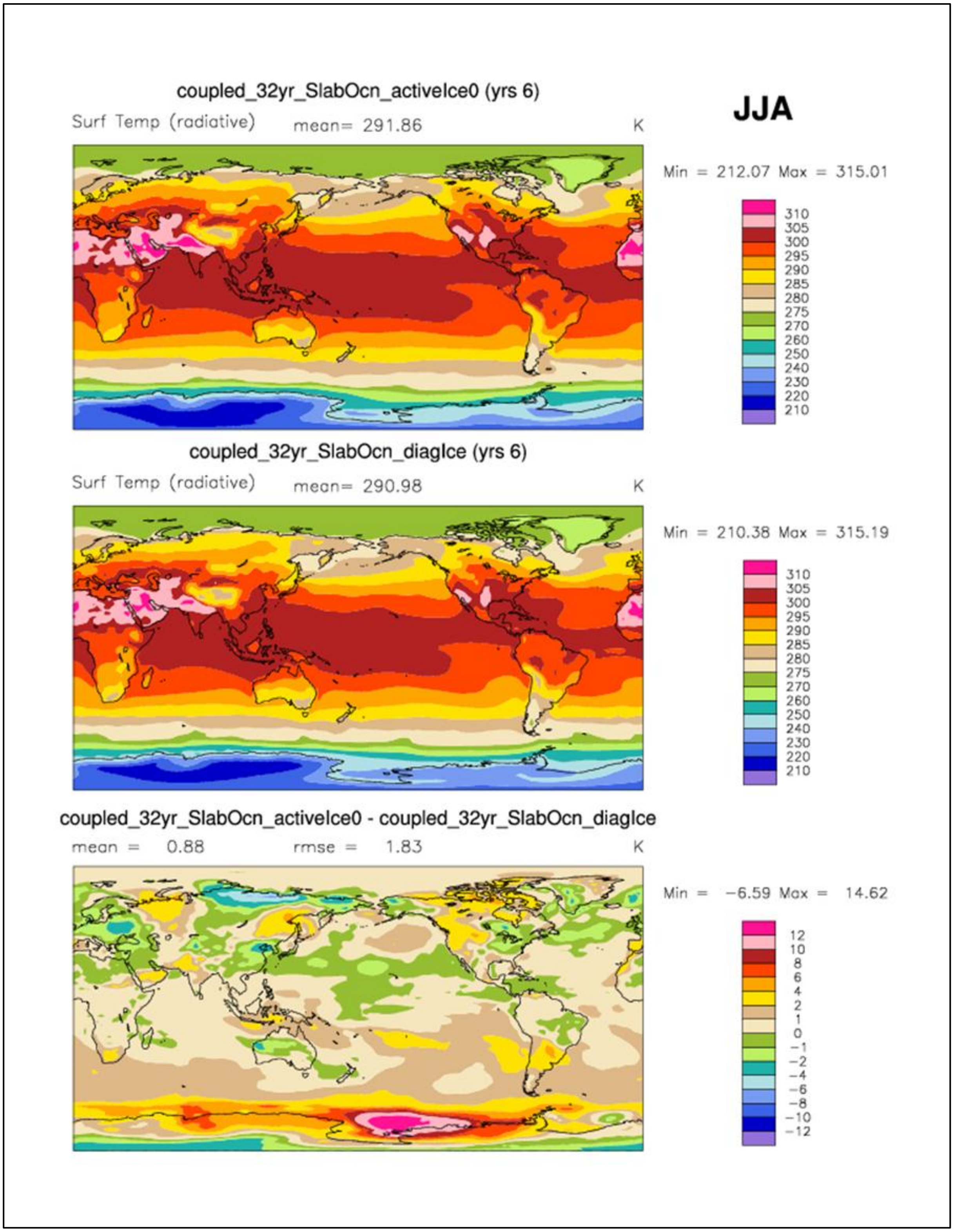


Figure 6.3: Arctic JJA surface temperature for a slab-ocean world with active ice

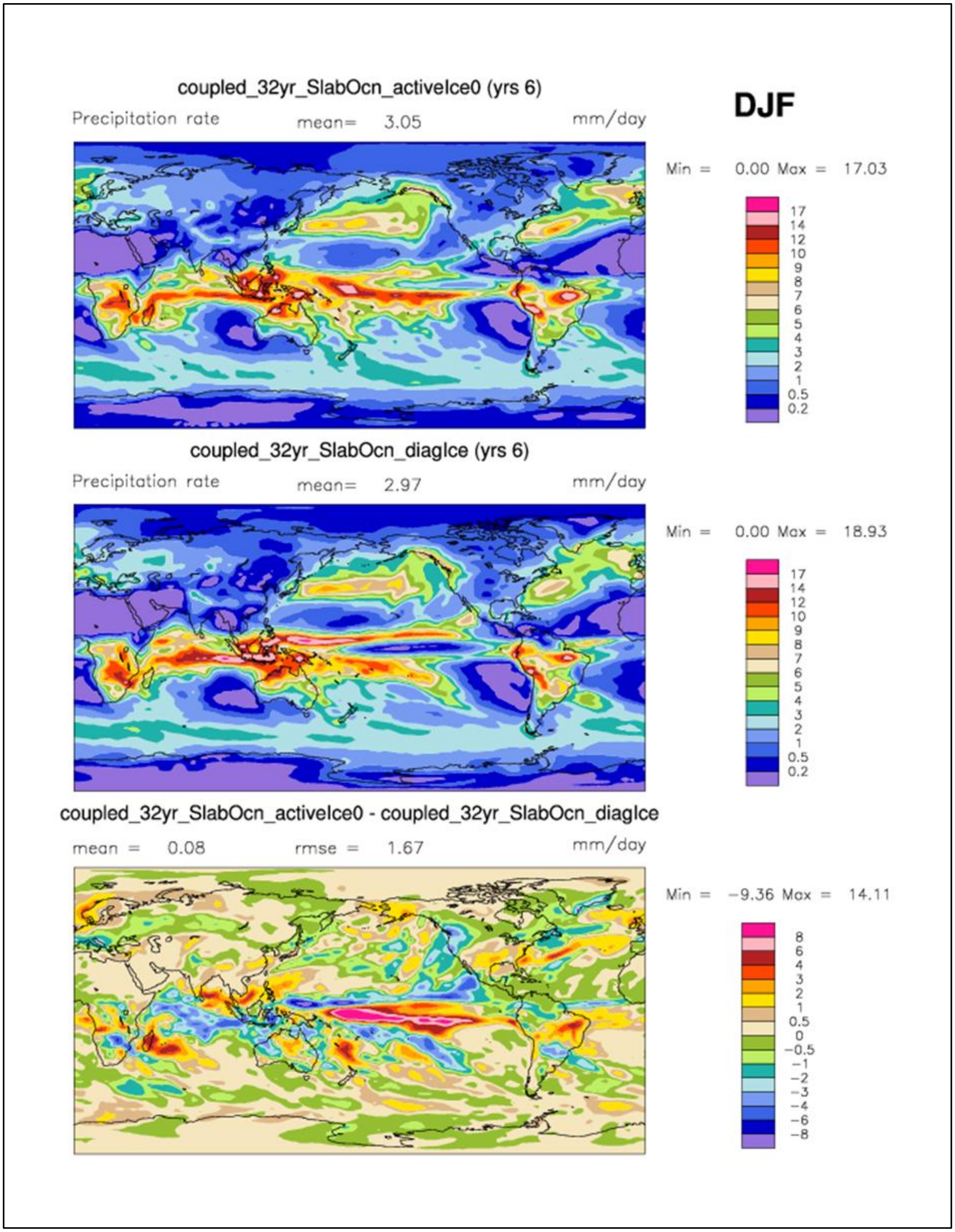


Figure 6.4: Arctic DJF precipitation for slab-ocean world with active ice

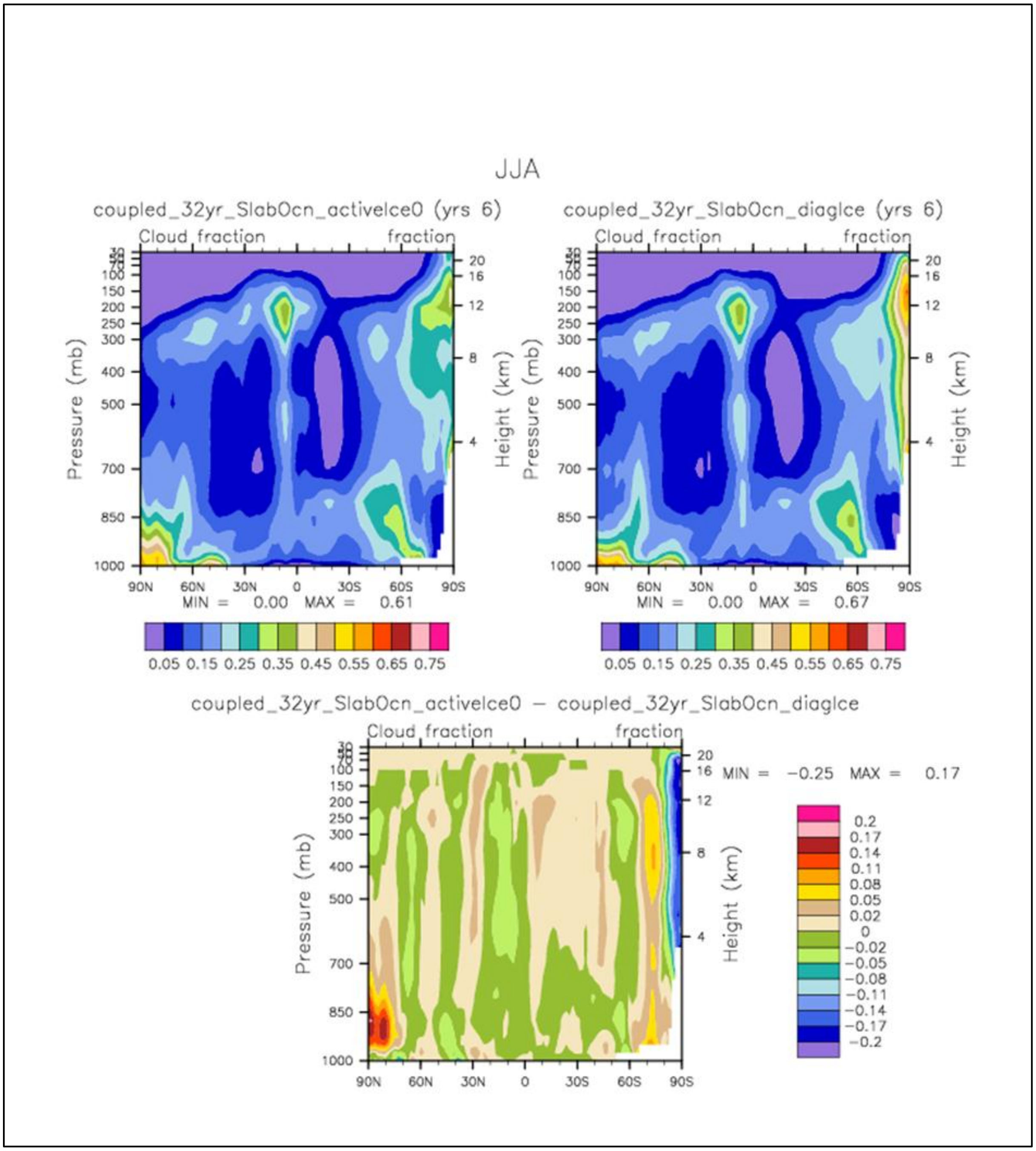


Figure 6.5: JJA zonal average of cloud fraction.

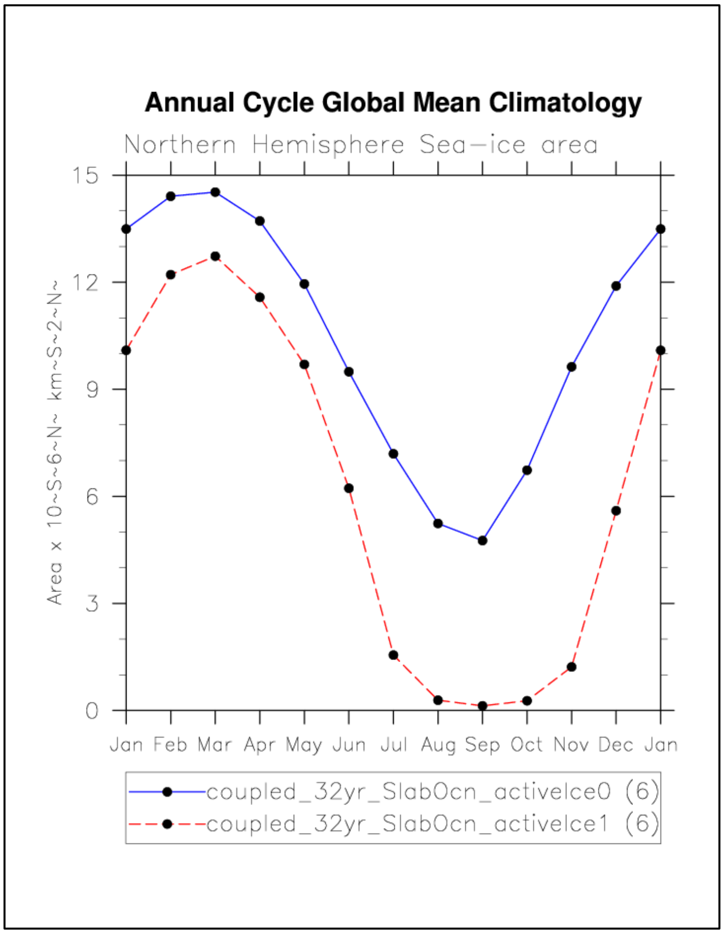


Figure 6.6: Enduring Ice-free Arctic

6.2 Arctic Risk Due to Physical changes

Existing assessments of Arctic security hinge on the expected value of the ice-extent. However, the expected ice-extent is an inadequate metric to evaluate the timing and nature of Arctic access. Specifically, the uncertainty associated with future Arctic conditions are not reflected in the —best estimates" of predicted physical or economic futures, which means that largest contributors to understanding of security risks are absent. The volatility of climate change has a very high probability of transiently bringing future climatic conditions into the short-term present. Climatic volatility, in-turn, affects expectations of economic access to the Arctic. It is these expectations that can trigger rapid expansion of activity within the Arctic, even if physical conditions remain impediments. Perceptions of economic access will determine the growth of economic activity and security risks in the Arctic. The growth in these economic activities governs the intensity and timing of climate-linked security issues – humanitarian and adversarial.

Each activity spawns added new and different economic activities, such as support industries. The combination of a diversifying human presence and a changing physical environment demonstrate that the security missions and the resources needed to serve the missions will have to be much different and more fluid than currently anticipated. By using Uncertainty Quantification (UQ) methods, it is possible to delineate the confidence it has in security assessment results, truly realizable threats that most contribute to the risk profile, and subsequent strategic/tactical decisions. Lastly, because the uncertainty changes over time, its quantification can be used to determine the minimal-cost path of resource acquisition needed for mission surety.

Key Points:

- **All existing Arctic-security assessments use only "best estimates" and disregard the uncertainty in climate futures that can show which threats most contribute to the security risk profile.**
- **Activities in the Arctic requiring security responses are actually driven by perceptions of economic access and expectations of first-mover advantage much more than by the physical conditions in the Arctic.**
- **The minimized set of resources and operational-logistic needed to maintain Arctic security at required levels can be established through progressive hedging methods that determine the minimal sequence of actions as uncertainty varies over time.**
- **Uncertainty quantification and integrated systems analysis methods that Sandia National Laboratories has developed for its Nuclear Weapons Stewardship have been shown to be directly applicable to the Risk Assessments in the Arctic.**

6.2.1 Interdependent-Risk Assessments

Current assessments of the future Arctic environment focus on its physical condition (DOD 2011, Navy 2011). That work is almost exclusively based on the best-estimate or ensemble-averages from climate models that have been shown to dramatically underestimate Arctic ice levels. Additionally, the metric used for inferring the timing of Arctic security threats is based on a threshold for the entire Arctic becoming ―ice-free" (NAS 2011b). Perhaps most problematic is the consideration of future Arctic activity based on the extrapolation of recent historical conditions or a myopic portrayal of infrastructure, technology options, and economic/geopolitical perceptions and motivations. Human activity in the Arctic will stem from an interdependent mixture of pressures -- economic, geopolitical, behavioral, and physical. It is meaningless to use one physical measure to assess security risks in the Arctic.

In contrast to current methods, an interdependent risk assessment would reflect the combination of probability and consequence of security concerns over time and across the interacting elements that include critical supply chains, nation-state interests, non-state actors, multinational corporations, economic responses, military operational logistics, socioeconomics, hydrology, land-sea usability, and human behavior.

Sandia National Laboratories (SNL) is responsible for assuring the safety and reliability of the U.S. arsenal of nuclear weapons. In this duty, it has developed a highly sophisticated capability in integrated system analysis and uncertainty quantification (UQ). The integrated analysis ensures the inclusion of all relevant system responses. UQ ensures that all risks are recognized, thereby enabling appropriate mitigation of any risks.

To illustrate the critical importance of uncertainty, we include Figure 6.7, which presents the accumulation of risk as global temperatures increase (Backus et al. 2010). We observe that even a small change in uncertainty can produce a large change in risk. The two diagrams below illustrate this reality. The green line is a simplistic representation of consequence, here measured in dollars, although it could be represented in other units of security risk. The consequence is asymmetric in that it increases (in this illustration) only as the global average temperature increases. The red distribution has less uncertainty than the blue curve. Both have the same ―expected” temperature of 3 degrees.

The diagram on the right side of Figure 6.6 illustrates the accumulation of risk (probability times consequence), increasing as the calculation includes more of the range of temperature possibilities. The red curve (less uncertainty) flattens out early as the probability declines quickly at relatively low temperatures. The risk associated with the blue curve (more uncertainty) would grow by another factor of three before it flattens out to its final value. The risk associated with the ―best estimate" (3 degrees) is small compared to that contribution associated with the middle of the right side tail of the distribution. Note that the long right side tail of the climate change distribution means that over 50% of the probability, and therefore the lion's share of the risk, is to the right of the best estimate.[2]

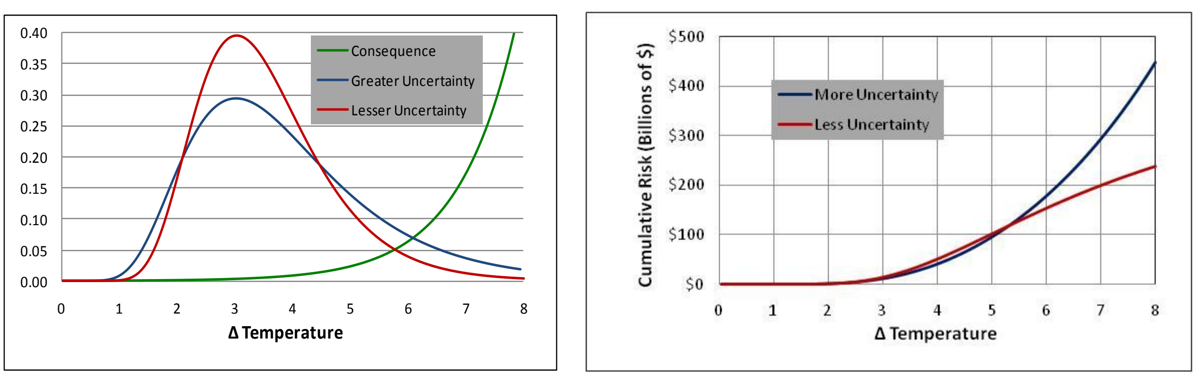


Figure 6.7: Uncertainty and Risk

Integrated systems modeling and UQ enable strategic consequence analysis and strategic prioritization. The result provides a rigorous justification of strategic initiatives and planning recommendations. Notably, in tightly coupled systems such as climate change and economic activity in the Arctic, the design of security responses must consider

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[2] The mode of the distribution is being used to represent the ―bst estimate” or ―expected value” in this discussion. In all cases associated with climate change risk, the ―average" or mean value is inappropriate to describe the ―best estimate” or ―expected value.”

multiple (highly correlated/probable) simultaneous events/conditions rather than just single "worst case" events.

SNL could provide the next level of risk assessment by extending the “best-estimate-only” National Security Implications of Climate Change for U.S. Naval Forces (NAS 2011b) to a complete UQ risk assessment that captures interdependencies and geopolitical activity due to expectations and uncertainty. While even new (still “best-estimate”) research shows that logistical support for economic activity in the Arctic will have to be largely sea-based rather than land-based (due to growing soil instability), the amplified naval mission will require enhanced under-sea, airborne, land, and space-borne situational-awareness capabilities. The risk assessment effort would not only delineate vulnerabilities, it would establish minimal modifications to installation and platform design-requirements that ensure resiliency in a continually evolving mission space. Climate change connects new Arctic requirements with other geopolitical destabilization pressures. Events in the Arctic can have repercussions far beyond the Arctic. Climate conditions in other parts of the world can affect Arctic security risks and vice versa (Zellen 2009).

A risk analysis that simply highlights possibilities is relatively ineffective for supporting risk-resilient decision making. It is important to determine the actual realizability of the risk. This can be done through the use of fingerprinting. Fingerprints are those existing precursor (measurable) conditions/events that establish whether a future event is realizable or not. These fingerprints then allow the determination of the minimum cost (minimum asset/resource/acquisition requirements) to deal with the risks as they evolve (become more certain) over time. Understanding the fingerprinting over the short-term can avoid costly false-positive responses to perceived threats.

6.2.2 Climatic Conditions

The ice extent in the year 2011 is statistically tied with the lowest recorded year of 2007. However 2012 was even lower than the 2007 record as shown in in Figure 6.8 (NSIDC 2012). The best estimate for the occurrence of (summer extent) ice-free Arctic based on climate models is around the year 2035, but the date varies between 2016 and 2080 across studies. A recent study indicates the cyclical phenomena may actually cause a modest return of the ice extent over the next decade, despite a continuing long-term downward trend (Kay 2011). Nonetheless, the 20l1 ice thickness and volume set another new record for diminished ice in 20ll with no signs of abatement. Thickness is much more relevant than ice extent for Arctic access, and current climate models understate that trend by a factor of four (Rampal 2011). All the climate models used by the UN Intergovernmental Panel on Climate Change (IPCC) have grossly overestimated the recent history of ice extent (Winton 2011). And future estimates of Arctic warming are based on IPCC Greenhouse-Gas estimates that only have a 10% chance of being realized (Webster 2008). The uncertainty within the next generation of Arctic climate models remains high, indicating that use of the “best estimate” grossly misstates the risk.

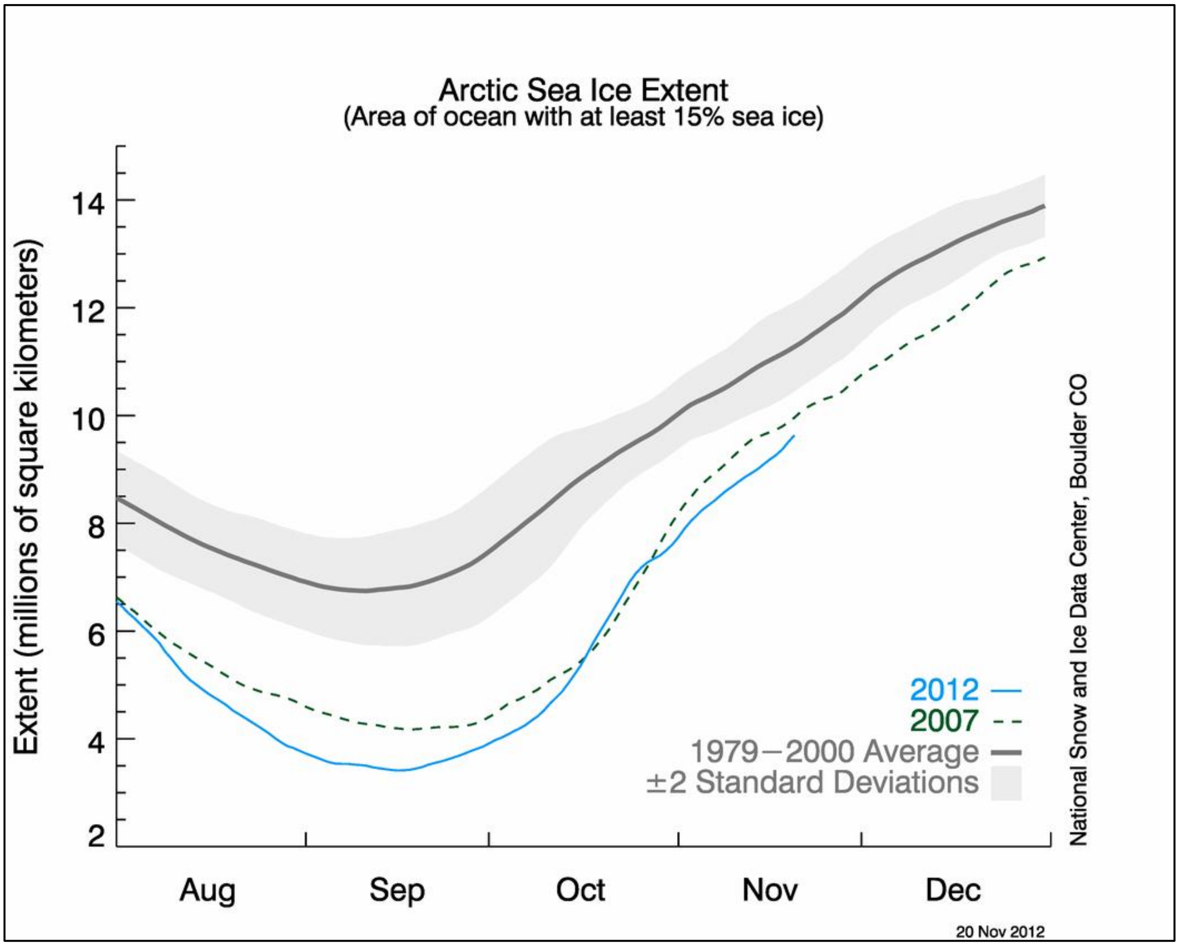


Figure 6.8 2012 Sea-Ice Extent (NSIDC 2012)

New analyses for the IPCC, as shown in Figure 6.9 indicates that an ice-free Arctic could occur within the next decade (Kattsov 2011). Figure 6.10 show an update of Stroeve (2007) to contain the 2012 conditions. It shows the best estimates at that time are dramatically differ from recent observations and are a the extremes of the uncertainty. The rapid ice loss events (RILE) shown in Figure 6.11, based uncertainty analyses using CESM, indicate that the ice extent can change much more quickly that what might be implied from the best-estimate curve of Figure 6.12 (Vavrus 2012).

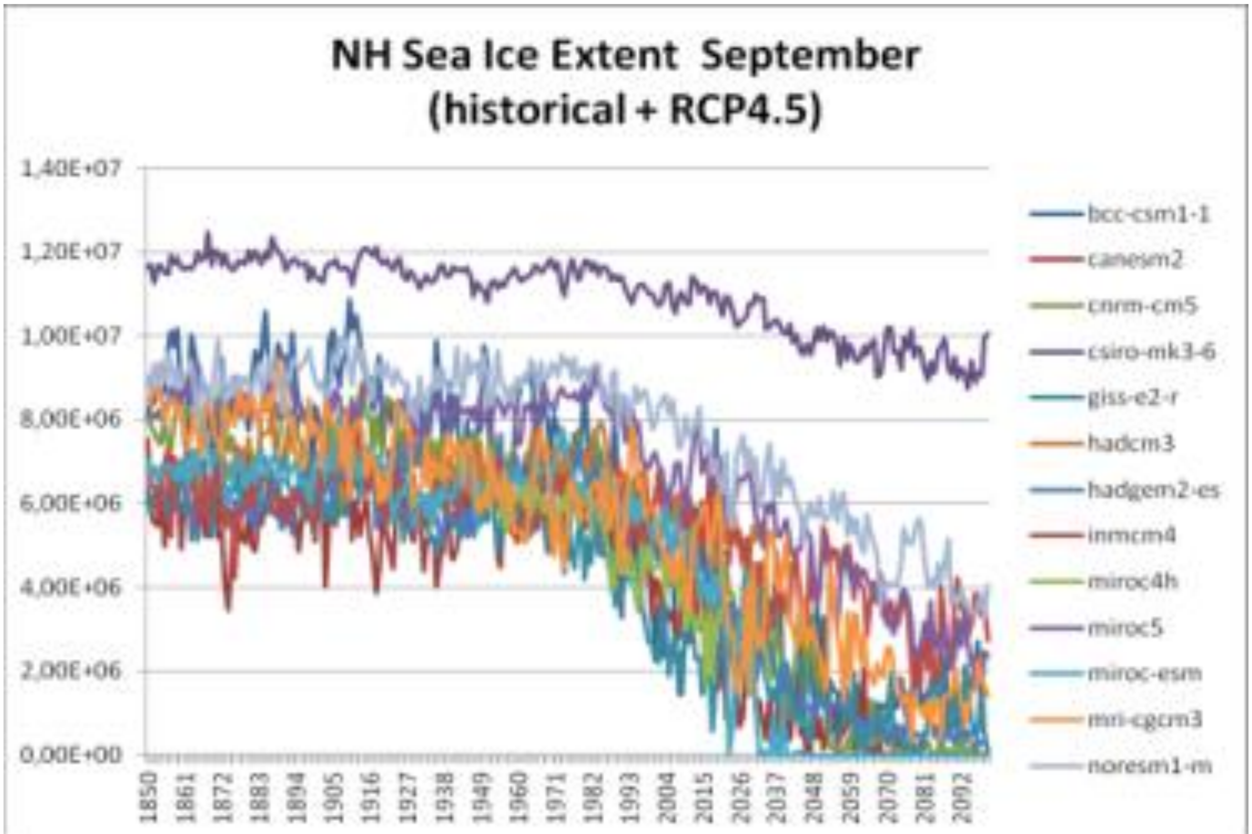


Figure 6.9: Northern Hemisphere Ice Extent Ensemble (Kattsov 2011)

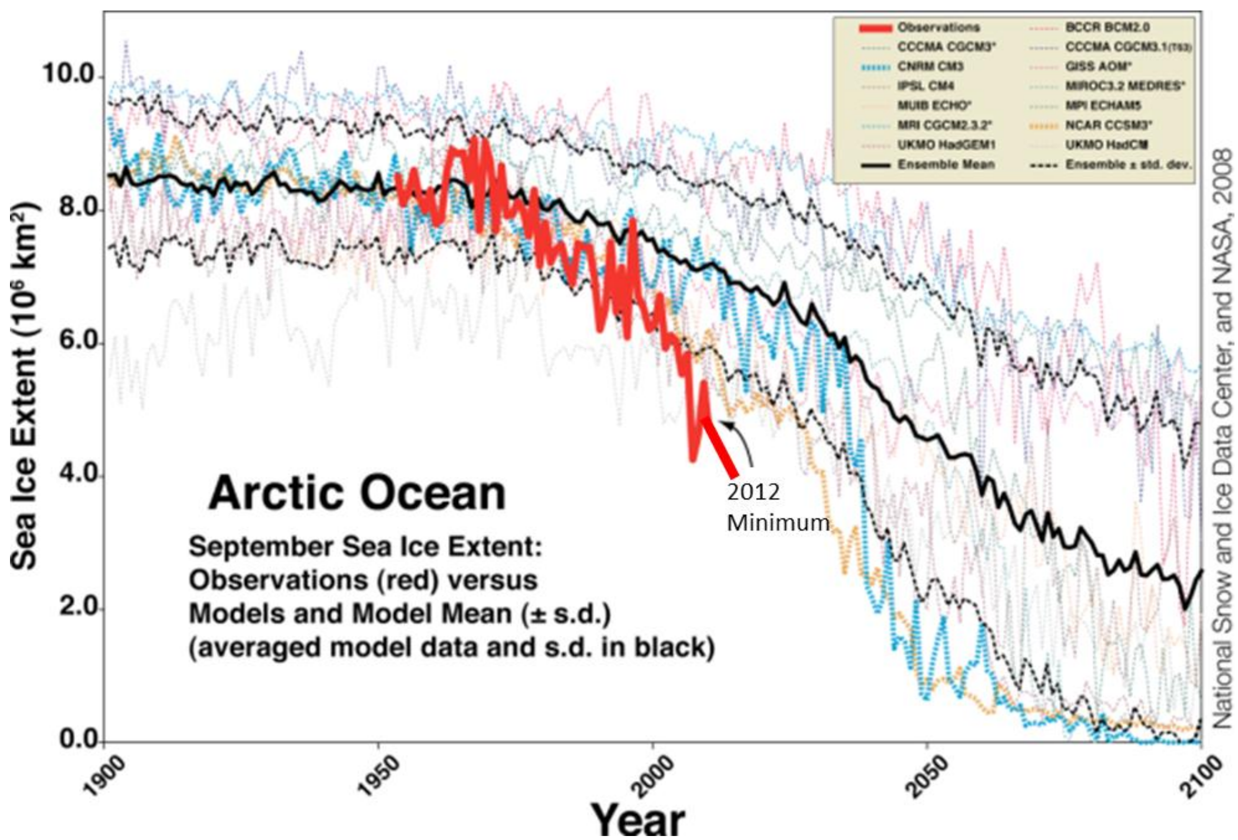


Figure 6.10: Best-Estimate Versus Observed Arctic Sea-Ice Extent

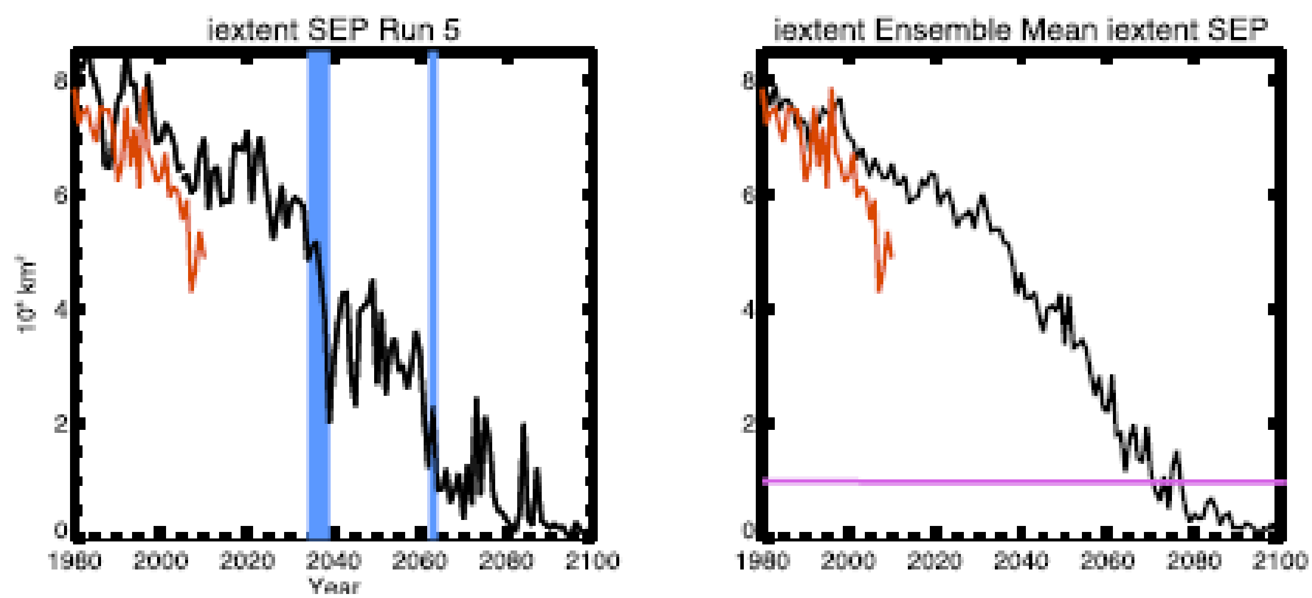


Figure 6.11: Rapid Ice Loss Events (Vavrus 2012)

The ice extent does relate to the open-water gap between the ice sheet and the shore. This open water greatly increases shore erosion, and in the near term the differential temperature between the water, ice and shore, strengthens storm intensity and further erosion. The ice free extent of the Russian portion of the Arctic has advanced to a greater degree than the Canadian and U.S. portions. Storm conditions subside as the continued melting reduces the temperature differential between the land areas and the Arctic Ocean. The result will be more storm surge and erosion in Alaska than in the Russian areas. The increased melting additionally reduces the amount of multi-year ice, and the reduced storm activity then acts to reduce the amount of ice ridging. These features, in combination with the reduced thickness, can cause a dramatic decline in navigation hazards and the need for ice-breaker support (Stephenson 2011). Nonetheless, the Arctic conditions will remain volatile on a year to year basis. Although this could imply added threats to shipping, the volatility can include years of effectively ice-free summer conditions. Positive feedback processes in atmospheric and ocean heating can then temporarily limit (and in some case eliminate) refreezing, even in the winter (NAS 2010, Backus 2011). While melting sea-ice does not have a significant effect on sea level, land ice does. New reports indicate that 1°C change in global temperatures correspond to an eventual 20 foot increase in sea-level (Hansen 2011), with meter-plus levels possible by the end of the century. Other studies indicate the increasing rate of land ice melt in the northern latitudes is drastically underestimated (Tedesco 2011).

An understanding of the near term risks affecting security-mission requirements needs to be based on the uncertainty distribution for physical access to Arctic (as opposed to just the "ice-free" threshold of ice-extent). In addition to summarizing available literature in the context of security concerns, SNL can perform independent analysis, for example, of soil stability (subsidence and erosion) for logistic and installation viability, sea ice flow, cracking and rift dynamics (month to 20 year forecast with uncertainty and based on observation), future wind, surge and storm domains, and shore-side freshwater dynamics (thermokarsts, transient ponding, fresh water availability, waterlogging, and flooding).

6.2.3. Physical Implications

On one hand, the physical conditions in the Arctic affect the construction, maintenance, and logistical-support for bases and missions within it. On the other hand, it affects the economic activity that is the source of security events. Although, initially, Arctic commercial activities will be dominated by mining, shipping, and oil & gas exploration/-production, the development of infrastructure for support industries will soon follow with subsequent ―ease of access” for drug smuggling and human trafficking.” Tourism may dominate the preparedness activities of Search and Rescue (SAR), but energy production and shipping will most likely constitute the greatest challenges. Even under ―best estimate” assumptions that overestimate the ice extent and underestimate the amount of Arctic heating, studies predict reduced ice thickness will allow shipping 8 months of the year by the 2040s using only Type-A class vessels. (Stephenson 2011). Other studies consider ―routine” North Pole transport by 2025 (Navy 2010, DNV 2011) These same studies show a dramatic degradation of land travel in the Arctic, implying that support for economic activity will be more sea-based than conventionally assumed, adding to U.S.

security responsibilities. Permafrost deterioration will severely limit access to fresh water for serving economic and base-of-operation needs. Combined near-shore soil instability and increased at-shore storm-surge and erosion conditions (especially in northern Alaska) will change the strategy of logistical support for commercial activity, including more dependence on (physically stable) Russian-side logistical support – which again could increase Northern Alaska shipping traffic. With the recent ExxonMobil-Rosneft agreement, joint Russian-American ventures in U.S and Canadian waters are likely. Additional Chinese support of Canadian energy expansion, concurrent with Chinese shipping arrangements with Russia, could further increase trans-Bering Strait (as opposed to through-Bering Strait) traffic.

In addition to expanding their ice-breaker fleets, the Russians are proposing to de-mothball their military submarines for commercial uses. The Russians are successfully testing new ice resistant oil & gas production platforms with planned implementation in 2017. Foreign oil companies and ship-builders have already lined-up to serve Russian ambitions. Russian and Chinese expectations of a melting Arctic, almost independent of actual physical change, drive economic expansion in the Arctic.

With reduced maneuverability and infrastructure options, and intensifying (at least in the near term) weather variability, the ability to use conventional means for rapid, but long-range, response to SAR events in the Arctic becomes more complicated. The use of UAVs as first responders (and situational awareness platforms) can limit the northern Alaska footprint and dramatically improve reliability (NAS 2011b). SNL is currently testing the use of UAVs under extreme conditions as part of its management of the DOE Atmospheric Radiation Measurement program at Barrow, AK (www.arm.gov/about). SNL's experience with sensing high-latitude systems can support efforts to develop situational awareness with the Arctic region. SNL's Critical Infrastructure Protection, through its National infrastructure Simulation and Analysis Center[3] (NISAC) can evaluate vulnerability, recovery, and resiliency for both security-mission and commercial infrastructure. A key consideration is the changing installation, equipment, platform requirements in a transforming physical Arctic environment. Any facility designed for the present conditions could be obsolete within the decade.

In addition, amplified shipping, from even modest economic activity, will significantly increase the amount of soot on the ice, with strongly positive effects on ice melting and negative effects on the ice structural integrity (Jacobson 2010). These reinforcing impacts can then further facilitate shipping growth. Lastly, the loss of land ice is causing significant upward land movement in several Arctic areas (including Alaska). Scientists believe this uplift (and resulting thermal expansion) will increase the number and intensity of earthquakes, and possibly volcanic activity where it already exists (McGuire 2012). It is currently unclear whether these events will have a noticeable effect on SAR missions.

6.2.4. Economic Triggers

[3] http://www.sandia.gov/mission/homeland/programs/critical/nisac.html

The economic dynamics will make future physical changes in the Arctic simply amplify the on timing and intensity of security-related events. Contrary to uncertainty driving political skepticism about climate change, climate change uncertainty for the commercial sector implies the potential for dramatic and rapid climate change. These perceptions of faster climate change and the opportunities it will provide, drives commercial activity, especially in the Arctic (DOD 2011). If there are perceived profits, engineers will find a way to overcome physical constraints. Economic changes in the Arctic could have the largest negative effects on the southern hemisphere. A geopolitical (socioeconomic) assessment can consider the eco-terrorism and conventional NGO terrorism risks from populations affected by the economic shifts. Several authors believe threats of Arctic development on local Arctic and southern hemisphere livelihoods yield a realistic prospect for terrorist activity in the Arctic (Zellen 2008). Certainly having Rosneft and Chinese facilities in Canadian waters, with ExxonMobil in Russian waters, convolutes who has response responsibilities in the Arctic. SNL can probabilistically quantify (and document) the expected number and likelihood of missions (policing/environmental/-rescue) under what physical conditions. SNL has already assessed that there may be many more situations than currently expected, sooner than expected (Backus 2011,2012).

For Russia, the Arctic is critical to economic and political stability. The energy resources alone in the Arctic represent a doubling of Russian resources. These are resources Russia will need to accommodate increased gas demand from Europe as Europe reduces its dependence on nuclear power and as Europe's use of renewable energy face technical and institutional hurdles. Conversely, the corporations who gain from economic access to the Arctic are some of the world's largest multinational corporations, whose security and safety are of national security interest to nations in which they are incorporated. Thus U.S., French, English, Chinese, and Russian security activities may be dominated by the protection of corporate interests.[4] A key limitation of current assessments of economic activity and shipping expansion has been an assumption of evolutionary or static technological approaches to operations. Historical analyses indicate that modified technological approaches will have a reinforcing effect to further reduce costs and economic risks. Early commercial ventures do not have to be individually profitable if they establish a commercial foothold and portend large "learning by doing" advantages (cost reductions). Any significant oil & gas or mining operations will promote the development of support industries. The natural infrastructure produced by primary and support industry relationships will further reduce entry costs for other industries and stimulate further economic activity. At some point such reinforced expansion reaches the criteria of being part of a critical supply chain that again affects the mission priorities of U.S. security providers (e.g., PACOM, NORTHCOM, and the USCG).

Russia‘s diplomatic negotiations for Arctic sovereignty are largely seen to be at Canada's expense. China states that it should be part of the Arctic negotiations because the Arctic is as critical to its long term economic and geopolitical interests as it is to Russia and

[4] Samsung Heavy Industry continues to have a large order backlog for ice-reinforced ships and claims a 3-year delivery on standardized vessels. At even current growth rates, an extrapolation of shipping expansion in the Arctic through the year 2030 corresponds to tonnage equal to 20% of current Chinese exports.

Canada. As such, a partnering of China and Canada seems likely (Jakobson 2010, Lasserre 2010).

The key point is that economic perceptions more than physical realities will determine the type, timing, frequency, and intensity of future security missions in the Arctic. There are several relevant quotes from the U.S. Arctic Research Commission (ARC 2007): “Commercial maritime activity in the Arctic will be driven by economics much more than diminishing ice.” Arctic “marine [and commercial] activity is not based on diminishing ice – it is based on economics and technological capability” “Resource extraction is going to take place regardless of ice – global economics are the key driver.”

Again, all the above noted appraisal are again based on the “best estimates” that are far below observed trends. The understated risks need to recognize the large uncertainty. If the dominating threat is recognized through probabilistic uncertainty analysis, SNL can use fingerprinting to determine those measurable conditions that determine its realization, and thus its prioritization for security planning. A large component of the uncertainty in event-occurrence is human behavior, and a large component of the event-consequence, at any given time, depends on the engineered infrastructure that then exists. SNL has two Cognitive Science departments that simulate expectation-formation and the triggering of behaviors that could have security implications. The Critical Infrastructure Protection group noted earlier can determine and analyze Critical Infrastructure and Key Resources for evolving Arctic economic conditions.

SNL's international, geopolitical modeling can quantify the emerging and uncertain economic development across all the industries and countries over time.

6.2.5. Minimizing Mission Resources

The mission needs in the Arctic could vary substantially over time. And the critical needs will unfold with an uncertainty that stretches possibly over decades -- from the very near-term future to the end of the century. For example, the Arctic Marine Shipping Assessment (AMSA 2009) considers summer versus winter shipping constraints in the context of existing technologies and expected conditions. With expectations of a more accessible Arctic or the potential for quick profits, the first-mover advantage would make the pursuit of currently uneconomic options a rational decision. Conversely, a sequence of extreme weather or severe accidents could impede on Arctic development for decades.

As the future unfolds, the uncertainty naturally lessens. Two approaches help maximize preparedness and minimize resource needs over this period. First, commercial entities may have more "on demand" options available than readily recognized (such as Iridium Communications Inc.), multinational corporation and inter-country cooperation can enable existing equipment to serve multiple purposes, and (relatively low cost) autonomous vehicles can act as reliable first responders under surprisingly harsh conditions. Secondly, progressive hedging analysis can determine the sequence of minimal acquisitions or equipment modifications that will fulfill risk mitigation requirements, ensure resiliency to credible threats, and minimize information-gathering resource needs. Progressive hedging can also help minimize the use of resources or maximize reliability with existing resources for specific missions, such as long-range SAR. In all instances, the solution resides in a flexible portfolio rather than in significant numbers of long-lived vessels (NAS 2011a, DOD 2011, NAVY 2011). Uncertainty quantification and the use of progressive hedging analyses can also determine what research priorities would most limit costs and reduce efforts to serve Arctic security needs.

In addition to preparing for future missions in the Arctic, as U.S. security providers considers a permanent presence in the Arctic, it will need to recognize that Environmental Impact Assessments need to be based on future, not the current, ecosystem. Further, climate change connects new Arctic requirements with other geo-political destabilization pressures elsewhere on the globe. A perspective confined to immediate events local to the Arctic could be counterproductive to minimizing the effort to maintain Arctic security. Lastly, the design criteria for Arctic security strategies need to recognize how both weather and economic interact to produce multiple SAR events simultaneously, possibly even cascading events.

SNL could help in characterizing the shifting foci for preparedness in security operations within the Arctic region and developing operational and strategic options that minimize the impacts of uncertainty.

6.2.6. Summary Points

All current assessments of Arctic risks use "best estimates" exclusively focused on the timing and extent of physical conditions to ascertain security-mission needs. There is a high degree of uncertainty associated with future Arctic conditions and lower probability situations contribute more to the risk profile than the best estimates. Moreover, perceptions of an economically accessible Arctic are now more important than the physical changes in climate. These economic drivers can quickly produce significant security issues requiring attention and response. Volatility with the Arctic can also trigger a high frequency of mission events followed by years of minimal activity. The SNL risk assessment methodology is able to determine the dominant mission areas in an uncertain Arctic future. SNL can simulate emergent physical and economic phenomena in the Arctic and quantify the risk of evolving consequences from climate change on national security and on security missions. Integrated systems analysis, that include hydrology (erosion and soil stability), climate modeling (ice and open water conditions, storm surge), economic (multinational corporation and geopolitical dynamics), and statistics (uncertainty), can quantity unfolding (cascading) dynamics and prevent the blind siding from unanticipated security events. Most importantly the risk assessment determines those threats (different from best estimate) that most affect the security-risk profile. Progressive hedging can then determine the minimal resource requirements that ensure the desired level of preparedness despite uncertainty.

7. GLOBAL LAND AND HYDROLOGY DYNAMICS

Water is the vector through which most of the impacts from climate derive. The Arctic is an area where climate change not only brings about rapid physical transformation, but also raises geopolitical security issues, as noted in the previous section. Because of the sweeping changes within the Arctic due to climate change, it is a prime location to study the modeling of land and hydrological dynamics. An initial task considered the elements of modeling required for assessing the risk due to climate change. A follow-on task tested the primary land and hydrology model used by U.S. researchers for global land and hydrology dynamics (CLM 4.0 Community Land Model of the Community Earth Systems Model). That analysis showed the primary limitations of neglecting the human use of water, human decisions that affect the availability of waters, and having an infinite (close to the surface) groundwater supply. It concluded that CLM had limited usefulness for human-impact risk assessments. A third task then modified an alternative water model from IFPRI (International Food Policy Research Institute) to simulate water use (including industry and agriculture), water supply, and water availability, as affected by climate change. That work now provides a worldwide ability to simulate water impacts at a local level.

7.1 Arctic Landsurface Modeling

The first task scoped the issues of a hydrological assessment and addressed the Arctic region as the case-study area.

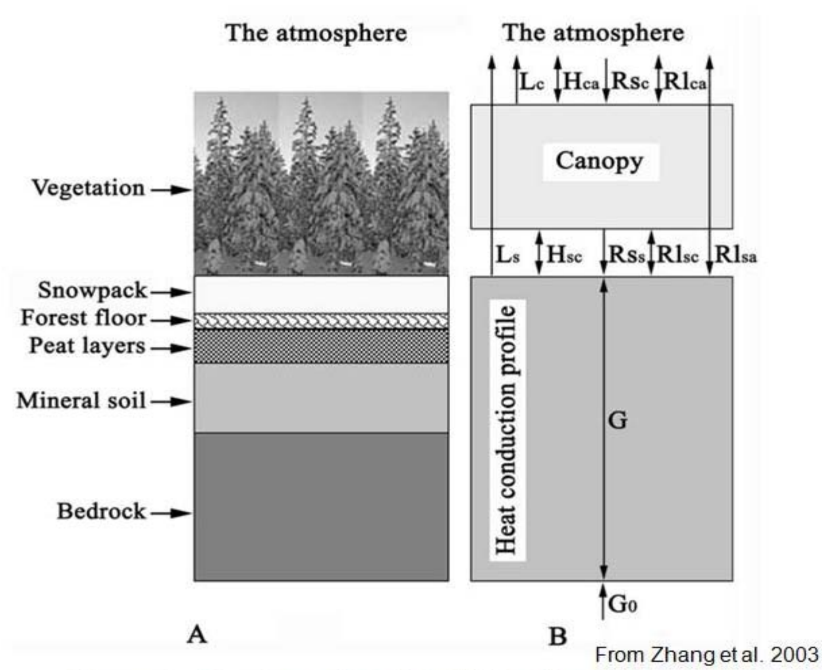
7.1.1 Introduction

A recent synthesis of evidence from marine, terrestrial and atmospheric studies shows that the climate of the Arctic has warmed significantly in the last 30 years (Serreze et al., 2000). This is of particular concern as it is broadly acknowledged that arctic regions play an important role in Earth's climate dynamics (Alley, 1995). Specifically, changing climate could induce biological and physical changes in the arctic that could in turn augment or retard global climate change (Rouse et al., 1997). However, projecting such change is complicated by the fact that arctic biological, climatologic, hydrologic subsystems and their thermal regimes are fully coupled and cannot be completely understood or isolated individually (e.g., Figure 7.1). For example, plant cover is integral to soil moisture and permafrost dynamics, while the ecosystem provides feedback to both the local climate and the hydrology. No single piece of the system is independent, and to fully understand even a part of the system, we need to understand the whole (Hinzman et al. 2005).

A unique feature of arctic regions is the existence of permafrost, defined as ground that remains at or below 0ºC for two or more years. Permafrost varies spatially and temporally with climate and local conditions. Several important features of northern ecosystems are closely related with soil thermal dynamics including: thawing and freezing annually in the top layers underlain by frozen layers, unfrozen layers, or a combination of frozen and unfrozen layers; snowpack dynamics; organic materials on top of the mineral soils;

excess ice in permafrost layers and ground subsidence when excess ice melts (Zhang et al, 2003).

Permafrost plays an important role in defining key hydrologic and ecologic function in the Arctic. The inability of soil moisture to percolate to deeper groundwater zones due to ice-rich permafrost maintains wet surficial soils in arctic regions. However, in the slightly warmer regions of the subarctic, the permafrost is thinner or discontinuous. In permafrost free areas, surface soils can be quite dry as vertical percolation is not restricted, impacting ecosystem dynamics, fire frequency and latent and sensible heat fluxes. Other hydrologic processes impacted by degrading permafrost include increased winter stream flows (Yang *et al*., 2002), decreased summer peak flows (Bolton *et al*., 2000), changes in stream water chemistry (Petrone *et al*., 2000), drying of thermokarst ponds, increased active layer thickness, increasing importance of groundwater in the local water balance and differences in the surface energy balance (Carr, 2003). In response to some imposed disturbance, such as a tundra fire or climatic warming, ice-rich permafrost may differentially thaw, creating irregular surface topography. Depressions forming on the surface soon form ponds, accelerating subsurface thaw through lower albedo and additional heat advected into the pond through runoff. In time, a thaw bulb or talik (a layer of unfrozen soil above the permafrost and below the pond) may form as the depth of water becomes greater than the amount that can freeze during the winter. If the talik grows to a size that completely penetrates the underlying soil or connects to a subsurface layer that allows continued drainage, the pond may then begin to drain (Yoshikawa, 2003).



From Zhang et al. 2003

Components of the system considered in the NEST model and (b) energy fluxes between soil, vegetation, and the atmosphere. L, H, Rs, Rl and G are the latent heat flux, sensible heat flux, solar radiation, long-wave radiation, and conductive heat flux, respectively. The subscripts are to identify these fluxes between different components (s, c and a for ground surface, canopy, and the atmosphere, respectively). G_0 is the geothermal flux.

Figure 7.1: Elements of the Hydrological System

Terrestrial ecosystems of the Arctic and adjacent boreal regions are expected to be highly sensitive to directional climate change and to play a significant role in biospheric feedbacks to global climate (Foley et al. 1994; Bonan et al. 1995; Ciais et al. 1995; Betts et al. 1997; Cramer 1997; Claussen 1998; Ganopolski et al. 1998; Levis et al. 1999). Their sensitivity arises from complex interactions (including threshold relationships) among ecosystem structure and function, soil and permafrost processes, and regional climate. In turn, biophysical and biogeochemical dynamics of these landscapes play a strong role in the global climate system through control over surface-atmosphere exchange of energy, carbon, and radiatively active trace gases (Bonan et al. 1995; Barry 1967; Reeburgh& Whalen 1992; Pielke & Vidale 1995; Randerson et al. 1999; Eugster et al. 2000; McGuire et al. 2000; and see other papers in this issue). Biophysical feedbacks are illustrated by spring albedo differences between tundra and boreal forest which strongly influence the energy absorbed at the surface at high latitudes, which in turn affects regional and global atmospheric circulation. As a result, potential future large-scale changes in boreal forest extent are expected not only to influence regional temperatures in the Arctic, but also to have climatic effects extending to the tropics (Bonan et al. 1992; Thomas & Rowntree 1992). Because arctic and boreal systems are characterized by large carbon stocks, altered vegetation dynamics, including changes in disturbance rates, additionally have potentially large biogeochemical feedbacks to the climate system through loading of global atmospheric pools of biogenic radiatively active gases (e.g. CO_2, CH_4).

The purpose of this research is to understand the potential impacts of climate change on the Arctic and in turn the Arctic‘s effect on climate change will require treatment of the coupled climate, hydrologic, ecologic system. While numerous Arctic models exist, none fully address all the couplings that are potentially important. The limitation largely stems from the computational intensity of this very complex, non-linear set of physical processes operating at timescales of minutes to hours but over timeframes of hundreds of years. Availability of data also represents a significant limiting factor for many of the processes and couplings. Thus, development of a single global or even regional ―super model" that captures all the potentially important couplings is infeasible.

Relatively few of the overwhelming range of physical processes, couplings and feedbacks active in the Arctic will lead to measureable impacts on model fidelity. Modeling efficiency could be greatly improved where such insights are realized prior to investment in costly model enhancement exercises. The objective of this work is to develop a screening tool to identify those processes and couplings most important to modeling climate change in the arctic. Subsequently, those processes and couplings showing the greatest merit will be coded into current global and regional climate models. Although tailored to the arctic, this generic platform could be used to investigate other climate zones.

7.1.2 Approach

In order to make the screening efforts tractable a couple of simplifying assumptions are required. First we assumed that the climate system can be decoupled from the land surface, that is, there is no feedback from changes in the land surface back to the climate. While this is obviously not the case, for purposes of screening we are simply interested in identifying model scenarios (i.e., models with enhanced physics packages or couplings) that lead to significant deviations in output relative to a base case, thus this coupling can be relaxed. Second, we assume that energy, mass and momentum fluxes are limited to one-dimension (vertical). Certainly, the principle dynamics function vertically through the soil, snow, atmospheric column, as evidenced with most Global Climate Models (GCMs), which adopt a 1-D treatment for most land surface processes.

A general modular architecture was considered for the screening tool. That is, we designed a platform that would allow easy swapping of alternative physical process modules. Each module will quantify a particular physical process (e.g., heat transport, unsaturated flow of water, thawing in the active zone) and involve a defined set of inputs and outputs from/to other modules (i.e., couplings). Modeling began with a defined set of process modules, which we will call the base case. This base case was be constructed so as to replicate the most current version of the Community Land Model (CLM) of the Community Climate System Model (Oleson et al. 2004). Screening exercises would simply involve swapping a module from the base case with an enhanced formulation of that physical process, likely involving additional inputs/outputs or coupling across systems. In effect, each screening analysis would involve running a particular test case with the base case model and then again with some package of enhanced process modules. These screening analyses would systematically investigate a broad range of enhanced process models and couplings.

Each of the screening scenarios (different combinations of process modules and couplings) would be exercised for a range of forcings, initial conditions, and parameterizations. Forcings on the model are essentially climatic conditions, temperature, solar radiation, precipitation, etc. The adopted forcings were be based on the climate-model ensembles from the Intergovernmental Panel on Climate Change‘s (IPCC) Fourth Assessment Report 4 (AR4). Likewise, we want to run the 1-D models for a broad range of conditions representative of that found around the globe in arctic to subarctic regions. Initial conditions and parameterizations will be varied to account for differences in soil conditions, permafrost thickness, elevation, latitude, vegetation cover, etc. Distributions for these model inputs were developed from the database supporting the CLM. Some original data development will be required for those parameters and initial conditions not currently represented in the CLM. Care was given to maintain proper correlation across the forcings, initial conditions and parameterizations (to avoid unphysical combinations).

The screening analysis would involve simulation of a range of scenarios (sets of different combinations of physical processes and couplings) with the 1-D model for a range of test cases (forcings, initial conditions, and parameterizations). Each scenario would be compared directly to the base case model exercised under the same set of test cases. Comparison will be used to identify those scenarios and test cases where significant differences exist. Comparisons would be drawn on the basis of 1-D model output such as thinning of permafrost, average days of snow cover, CO_2 emissions from the soil, etc. Importance of the enhancement would be assessed on the basis of the degree of divergence between the base and enhanced model as well as how wide-spread such effects are (by relating the test case to the global extent that it represents). The intent was to subsequently integrate those processes and couplings identified as most important into the CLM.

The Community Climate System Model (CCSM) has evolved in complexity and scope since development began at the National Center for Atmospheric Research (NCAR) in 1983. With the advent and ready availability of computers powerful enough to run it, the model has become widely used in the global climate research community. The version we are using (CCSM4.0) was released in April of 2010 and is composed of 4 separate models running simultaneously to simulate earth‘s atmosphere, land, oceans, and sea ice. Each sub-model can provide input, or feedback, to the other sub-models. The 4 sub-models are coordinated with a coupler which allows each sub-model to run either in combination or as a stand-alone model, with static data input. At this time we are running the CLM coupled with the Community Atmosphere Model (CAM).

CLM4, the main code of interest in this research, went through substantial upgrades prior to the April 2010 release. The model was extended with a carbon-nitrogen (CN) cycle model that is prognostic in carbon and nitrogen as well as vegetation phenology. A transient landcover change capability, including wood harvest, was introduced and an urban model (CLMU) was added that contributes urban ―heat-island" effects. The hydrology scheme was updated with a TOPMODEL-based runoff model, a simple groundwater model, a new frozen soil scheme, a new soil evaporation parameterization, and a corrected numerical solution of the Richards equation. The snow model incorporates SNICAR - which includes aerosol deposition, grain-size dependent snow ageing, and vertically resolved snowpack heating - as well as new snow cover fraction and snow burial fraction parameterizations. CLM4 also includes a new canopy integration scheme, new canopy interception scaling, and a representation of organic soil thermal and hydraulic properties. The ground column was extended to ~50-m depth by adding 5 bedrock layers (15 total layers).

Linking the CLM with CAM provides necessary input in the form of precipitation, solar radiation, temperature, and atmospheric pressure. CAM at this time supports 1 and 2 degree finite volume simulations which is an increase in resolution of 2 orders of magnitude from traditional scaling. This allows climate prediction at a regional scale of 10-25 kilometers.

CCSM4.0 appears to be the final version of a model with this name as NCAR is now moving toward the Community Earth System Model (CESM), with still finer grid resolution. This should bring prediction capabilities to the scale of less than 10 km.

7.1.3 Results

Results of a 1-D CLM modeling run are obviously dependent on the location, and will include effects of precipitation, elevation, humidity, average temperature, soil type, soil depth, geomorphology, as well as others. Looking for representative locales with available data led to the SCANNET sites. SCANNET is a network of terrestrial field sites located around the arctic including northern Europe, Greenland, Canada, Alaska, and Siberia. These sites provide long-term data on soil, plants, and climate at key points and climate transition zones in the Arctic. For example the Abisoko site in Sweden has been studied for years as the driest area in Scandinavia with mixed permafrost. The site in the Faroe Islands is noted for being extremely set. Being able to compare results of the CLM with data from specific climate zones will be very useful in the future, particularly in cases where there are observed changes in temperature and precipitation. This may allow us to ask questions regarding plant migration or melting of permafrost. We selected The Alaska site as will be discussed in the next section on the follow-on task.

The CLM has been compiled and tested in fully coupled, decoupled full-earth, and decoupled single-column modes. To run the model in the decoupled modes, atmospheric data must be provided to act as forcing conditions on the model. The Qian forcing data sets (Qian et al. 2006) were used as initial data for testing the decoupled models. However, because these data sets are only available for dates from 1948 to 2004, another method must be used to do predictive modeling. This forcing data comes from the output of running the fully coupled CCSM model. Unfortunately, the high-resolution timing required by the CLM decoupled model is not available from IPCC or other sites, and so it must be generated locally. Generating data that corresponds to the IPCC analyses is only possible using supercomputing resources and large disk arrays.

The single-column mode of the CLM has been compiled and tested, with additional scripts written to automatically set up a CLM run from a single latitude/longitude (lat/lon) measurement. The standard input data must be pre-processed, and the cell nearest to the measurement selected. The single-column mode runs very quickly compared to the full-earth and fully-coupled models, and this will allow for more variability in experimental design compared to using the fully coupled model. The output from the single-column model has undergone initial analysis to find the important data streams among the output database files.

Projections of future climate change from Global Climate Models (GCMs) suggest significant impacts on the hydrological cycle (Bates et al., 2008). However, the range in the projections is in some cases very large, in particular at the regional and local scales relevant for the analysis of impacts and adaptation options in the face of climate change. These differences arise from several sources of uncertainty within GCM simulations, including radiative forcing, initial conditions, model formulation (including resolution) and model inadequacy (Stainforth et al., 2007). The analysis of multi-GCM ensembles such as those available from the Fourth Assessment Report of the Intergovernmental panel on Climate Change of the Coupled Model Intercomparison Project (CMIP3) archives is one approach that provides information on GCM uncertainties (Solomon et al., 2007). In these analysis, little effort has been made to determine why these models differ so much, that is, what is the genesis of these differences. Another key point is that these types of studies focus very little on the land surface component of the GCM.

As we researched this concept of model intercomparison, another approach was identified. This alternative philosophy makes use of perturbed physics ensembles (PPEs), which are specifically aimed at evaluating uncertainty in GCM formulation (Collins 2010; Murphy et al., 2007, 2004; Stainforth et al., 2005). These ensembles usually comprise a large number of runs of a state of the art climate model, where each individual run uses a version of the model with parameters representing various physical processes set to different values within their acceptable range, as defined by the experts in each particular area of physics parameterization. For each combination of parameter values an initial condition ensemble is used so that the relative contribution of formulation and initial condition uncertainty can be evaluated.

In efforts to complement the intercomparison of physical processes and couplings, we pursue an analysis consistent with that of the PPE approach, as noted in the next section below. Specifically, key parameters in the land surface model were be identified and appropriate distributions developed. Using a standard Monte Carlo approach, the sensitivity of key climate forcings were investigated relative to their associated mix of parameters. The combined effort helped identify the relative contribution of parameter/data uncertainty and model structure to model sensitivity. In this way, we were able to assess whether model uncertainty/sensitivity is data driven or structurally driven (e.g., formulation of the physical processes and couplings). In this task, we identified these key parameters and their associated distributions.

7.2. Hydrology Model Evaluation

This section describes the sensitivity testing and assessment of the CLM model.

7.2.1 Introduction

The purpose of this study was to identify major parameters and physical processes that have greatest impacts on the near surface energy balance in the Arctic environment. The historical data set for the period of 1948 to 2004 from National Center for Atmospheric Research (NCAR) was used to generate atmospheric forcing data for this analysis. The CLM 4.0 (Community Land Model) was used for land simulations of the point grid cell located near Fairbanks, Alaska. A range of hydrogeologic and thermal soil properties and vegetation characteristics was defined for the vegetation and soil data. The current approach used in CLM was modified to simulate soil moisture to allow for more realistic water table representation. Multiple CLM sensitivity runs were analyzed with regard to their effects on the feedbacks to the atmospheric model. This analysis allowed for identifying major parameters and important physical processes with the potential to impact the climate either in the short or long term.

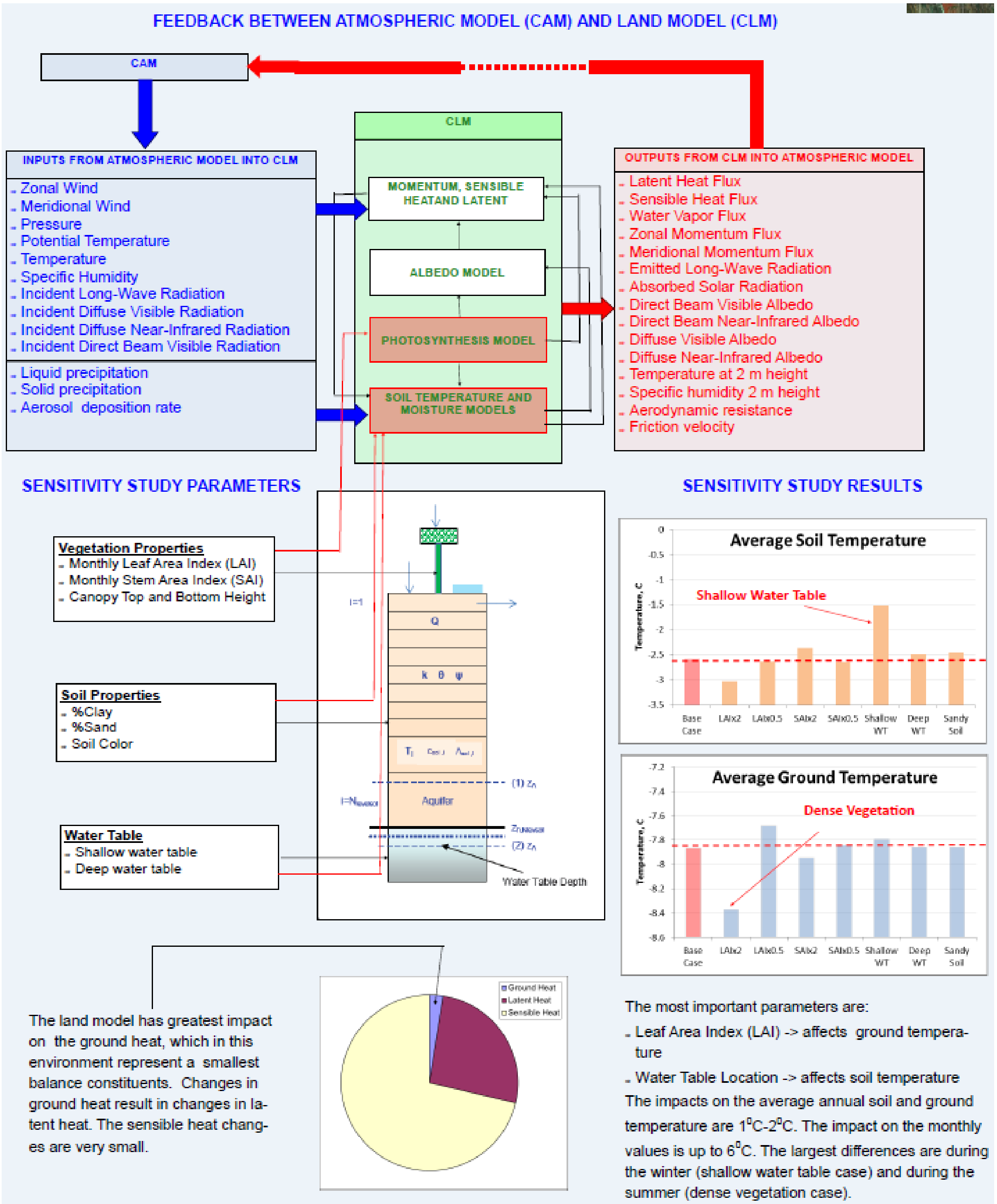


Figure 7.2: CAM and CLM Interconnections

The Community Land Model (CLM version 4.0) is the land sub-model of the Community Earth Systems Model (CESM version 1). CESM is an open-source, FORTRAN language, global climate model maintained by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. It is the product of on-going development, which started with the Community Climate System Model (CCSM) in 1983. The other modules within the CESM are for atmosphere (CAM), sea ice (CICE), oceans (POP2), land ice (Glimmer-CISM), and the ―coupler" which links the modules together. The linkage of the CAM and CLM components for this analysis are depicted in Figure 7.2

CLM approximates the land surface using a grid cell approach. A few different resolutions are available. CLM can be run in a stand-alone mode and in a fully coupled mode. The stand-alone mode can model either single cell or multiple cells (regions). Each grid cell is defined in terms of its land units. The land units are: glacier, wetland, lake, urban, and vegetated. Each land unit is simulated as a one-dimensional column. The vegetated land unit is defined in terms of plant types (this includes bare soil). The vertical profiles of temperature and soil moisture are calculated for each column.

The physical processes simulated by the CLM include the following:

- Absorption, reflection, and transmittance of solar radiation
- Absorption, reflection, and transmittance of longwave radiation
- Momentum, sensible heat, and latent heat
- Heat transfer in soil and snow
- Canopy hydrology
- Snow hydrology
- Soil hydrology
- Photosynthesis
- Lake temperatures and fluxes
- Dust deposition and fluxes
- Runoff from rivers and oceans
- Volatile organic compounds
- Carbon-nitrogen cycling

The summary technical description of these models is provided in Oleson (2010). Additional details concerning the specific models and modeling parameters are spread over many different supporting publications and studies. Each model represents a different area or even a discipline and this multi-disciplinary aspect is the major reason of the CLM complexity.

The models in CLM have very different levels of representation of the underlying physical processes. Some models significantly simplify the physical processes. An example is the canopy model in which simple water balance equations are used. The other models use very detail representations of the physical processes. An example is the soil moisture model that implements non-linear modified Richard's equation (Oleson, 2010). However, all the models are inter-related and they either provide the inputs to a downstream model or use the outputs from an upstream model. Due to this, a few iterations are needed to take into account the feedbacks between the models and to make the necessary adjustments in the calculated state variables during each time step. The diagram in Figure 7.3 shows in a simplified form the relationships between the different models. The Sensible Heat, Latent Heat, and Momentum Flux Models are separate and complex models. They are shown in one box because the focus of this analysis was on the hydrogeologic and vegetation models in CLM.

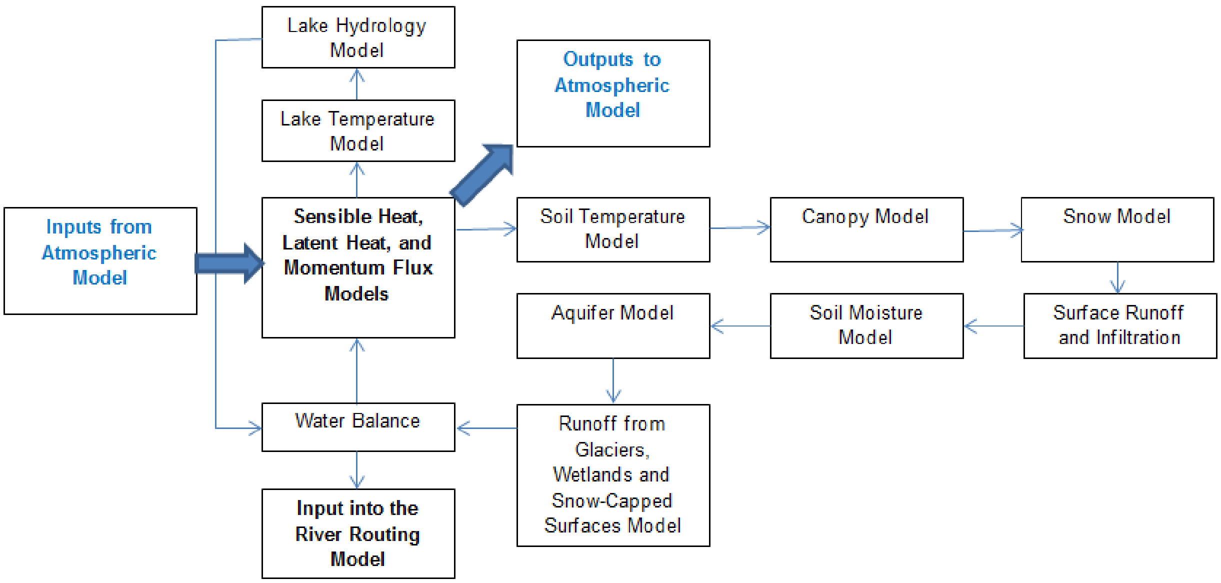


Figure 7.3: Simplified Diagram of Relationships between the CLM Models

Note that Sensible Heat, Latent Heat, and Momentum Flux Models represent direct interface with the atmospheric model. They use the atmospheric model inputs and they generate the atmospheric model outputs. The vegetation and hydrogeologic models indirectly affect the atmospheric model outputs through their feedbacks to the Sensible Heat, Latent Heat, and Momentum Flux Models. The models with noticeable feedbacks may require detailed physical representation. Our goal was to review the vegetation and hydrogeologic models in CLM with this criterion in mind.

7.2.2 Objective

The hydrogeologic and vegetation models in CLM have a number of simplifying assumptions. The soil column depth is 3.54 m in any grid cell in the world. The hydraulic and thermal properties of soils are defined based on their organic matter, sand and clay content, which is an approximation that may or may not be applicable at a site-specific scale. The temperature boundary condition at the bottom of the bedrock is zero flux. The aquifer, as implemented in CLM, has infinite resources. This limits the simulations of water withdrawal effects. The subsurface drainage parameters are the same in every grid cell and the rooting depth parameters are fixed for each vegetation type.

Our objective was to investigate the potential effects related to some of these assumptions, as well as modeling parameters and physical processes. In order to evaluate the importance of these effects, we considered their impacts on the CLM outputs to the atmospheric model.

Because the arctic environment is especially important in the climate studies, we selected a grid block located in the Fairbanks area in Alaska. The scale of a single grid block at that latitude is 62.1 x 36.25 miles. The coordinates of the grid block corners are provided in Table 7.1. The map of this area is shown in Figure 7.4.

Table 7.1: Study Area Coordinates

Grid Block Point	Latitude	Longitude
North East	66.316	213.75
North West	66.316	211.25
South East	64.421	213.75
South West	64.421	211.25
Grid Block Center	65.36	212.5

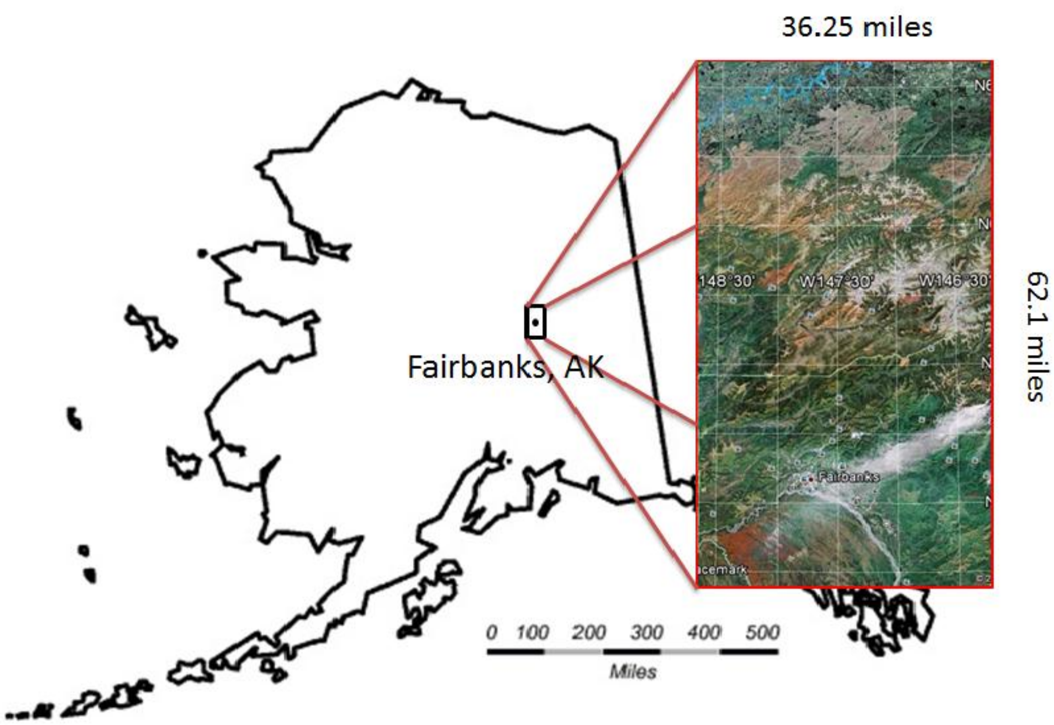


Figure 7.4: Study Area Map

7.2.3 Summary

The Community Land Model (CLM) simulates major physical processes at the land surface and in the shallow subsurface and calculates the parameters (including energy components) that are then used as the inputs into the atmospheric model. One of our goals was to identify the parameters that have greatest impacts on these inputs and thus, the greatest potential to impact the climate. Another goal was to identify the limitations in representing different physical processes and to determine whether these limitations restrict the ability of CLM to predict the distribution of energy at the land surface.

The focus of our analysis was on the vegetation and soil models. We selected a grid cell near Fairbanks, Alaska and defined the ranges for all the applicable surface parameters in this grid cell. This included soil color, soil texture, and vegetation parameters. We modified the root distribution parameters hard-wired in CLM to represent its potential variability.

The major limitations of the CLM include the following:

- The soil depth is the same in any grid cell (3.54 m).
- The subsurface drainage parameters are hard-wired and are the same in any grid cell. These parameters keep water table at a depth of 3 m and does not allow for large water table fluctuations.
- The bottom boundary condition in the soil moisture model does not allow for drying the soil. As a result, the dry soils effects may not be properly evaluated.
- The aquifer is represented as an infinite source. This precludes the simulation of the water withdrawal impacts.
- The bottom boundary condition in the soil temperature model is zero flux. A better representation would be the actual temperature at the bottom of the bedrock.

We selected for the analysis the limitation concerning the water table representation because in the arctic environment the water table is often very close to surface and the soils are saturated. We modified the subsurface drainage parameters to simulate these conditions.

We performed multiple sensitivity runs and analyzed the parameters that represent the direct inputs into the atmospheric model as well as the parameters that have indirect impacts on these inputs. Figure 7.5 shows the quantified sensitivity and correlations (Kalinina et al. 2012a)

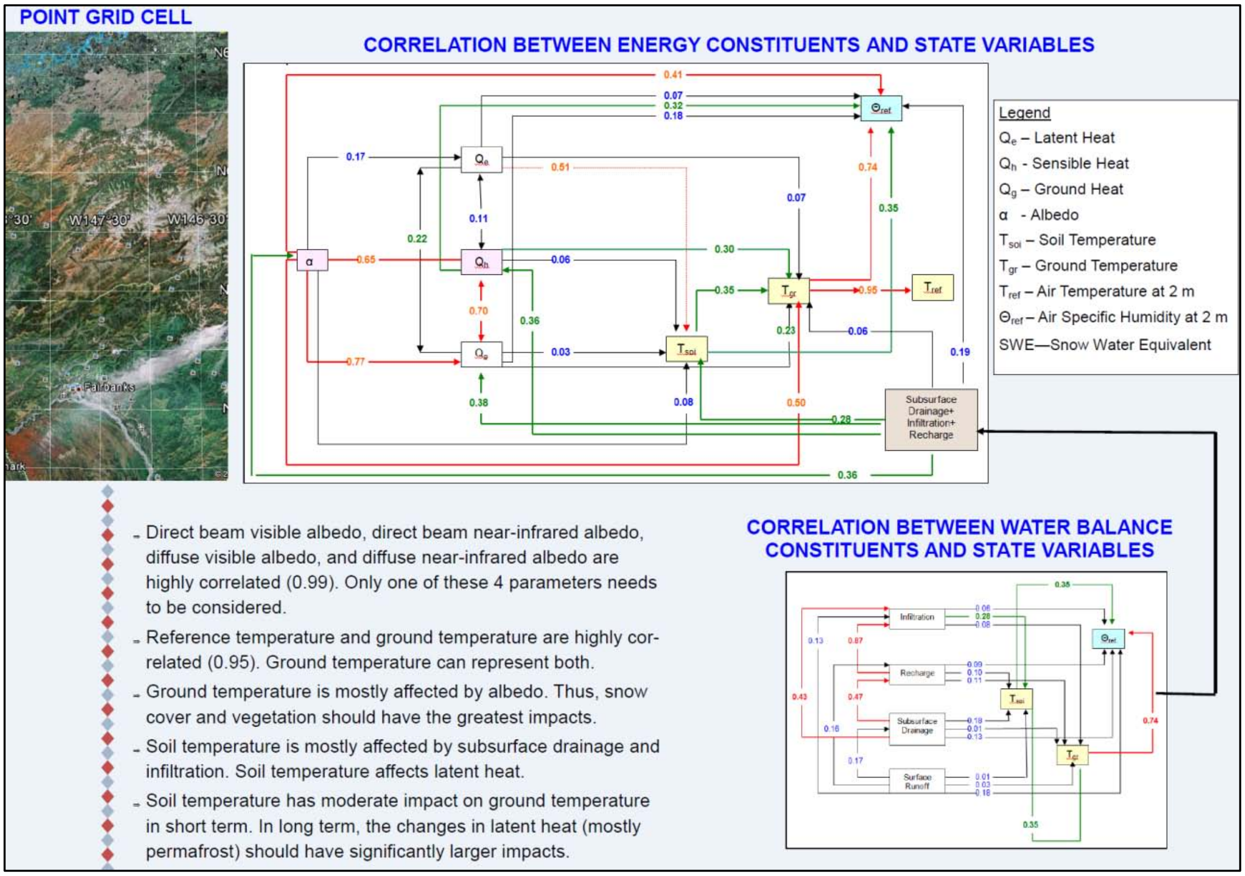


Figure 7.5: CLM Sensitivity

We made the following conclusions based on this analysis:

- The vegetation and soil parameters mostly affect the ground heat component of the energy balance, which in this environment is only about 3%. As a result, these parameters have relatively small impacts on the atmospheric inputs.
- The most important parameters are the Leaf Area Index (LAI) and soil moisture. The other parameters have insignificant impacts on the energy distribution at the land surface.
- The vegetation affects both, soil and ground temperatures, with the most impacts occurring during the summer when the LAI are at their maximum values.
- The vegetation impacts ground temperature, which is highly correlated with the reference (atmospheric temperature). Because of this, the change in vegetation may impact the feedback into the atmospheric model and cause short-term changes in the climate.
- The soil moisture noticeably increases soil temperature during the winter when the evaporation is low and slightly decreases temperature in the summer when evaporation is high.

- Because soil temperature is weekly correlated with the ground temperature, the immediate impacts from the soil moisture are small. However, soil moisture may have significant long-term effects via its impacts on the depth of thawing.
- The combined effects of soil moisture and vegetation are only slightly higher than the corresponding individual effects because the greatest impacts from vegetation are in the summer and greatest impacts from soil moisture are in the winter.

This work is further documented in Kalinina 2012b)

7.3 Food And Water Modeling

This section describes the modification of the IMPACT-WSM model for use in climate risk assessments.

7.3.1 Overview

The consequences of climate change are dominantly mediated by hydrological impacts and changes in water availability (Backus et al, 2010). While the core, unintended-consequences model (UCM – discussed in the Section 8.0) captures the interrelationship of economic impacts across countries and economic sectors, a meaningful risk assessment requires linkage to a global hydrological model, with the detail and components that can address changes in food production and water availability. This requirement is overcome by integrating the Water Simulation Model (WSM) (Cai and Rosegrant 2002a, 2002b) and the supply portion of the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Cai and Rosegrant,2002b).

WSM calculates water demand for domestic, livestock, industrial, and irrigation sources and then calculates water supply based on precipitation data and water flow through two hundred eighty-one food production units (FPU‘s) as seen in Figure 7.6**Error! Reference ource not found.**. The FPU‘s are derived from the intersection of one hundred seventeen political regions and one hundred twenty six river basins. WSM uses a constrained optimization to determine water releases which maximize an objective function which includes the water supply to demand ratio, the minimum water supply to demand ratio, and environmental water requirement ratios for each FPU on a monthly basis. This optimization serves the purpose of providing a method to determine a basin scale aggregate of local reservoir and river operations for which world wide data is often unavailable or is difficult to assemble. A system dynamics model has been formulated in place of the optimization to make UCM‘s and WSM‘s algorithms internally consistent[5].

[5] Updated versions of WSM and IMPACT have been moved from their original coding language GAMS™ to Matlab™ in order to make integration into UCM seamless. Both translations have been thoroughly verified to produce the same answers as the original code.

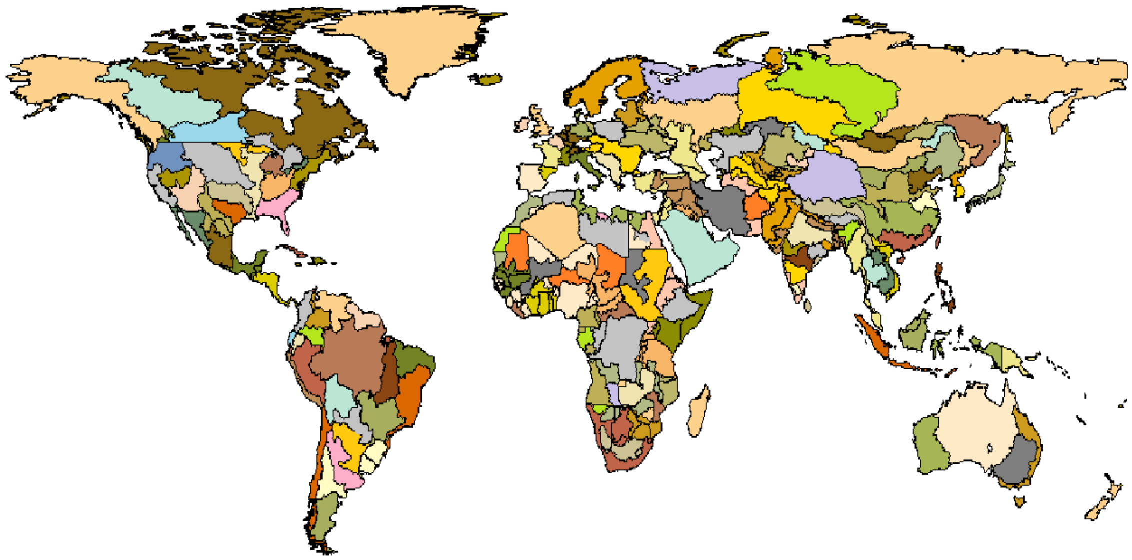


Figure 7.6: FPU boundaries[6]

UCM and IMPACT accomplish the same purpose of balancing resources based on prices, supply, and demand. Unlike UCM, IMPACT is a partial equilibrium model which assumes price is a free variable to equilibrate supply and demand. In this analysis the IMPACT supply equations and data have been used because of their higher resolution quantification of world-wide food production given water constraints. UCM handles demand and price. For the UCM-IMPACT-WSM model, UCM provides the price of its agriculture commodity per geographic region, as shown in Figure 7.7. This price is split into producer, intermediate, and consumer prices for WSM's thirty-five livestock, fish, and crop commodities[7]. This output and water data is fed into IMPACT to produce the amount of area planted for each crop and livestock quantities to slaughter. The crop areas and livestock quantities are then used as an input to WSM to recalculate water supply based on the resulting demands. IMPACT can then be rerun with the new water balances and the actual crop and livestock productions can be aggregated and fed back into UCM as supply terms to its water and agriculture commodities[8].

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[6] This figure was obtained and altered from Zhang and Cai 2011. Full access to an ArcMap database of the FPU boundary data has been obtained by the authors of this paper which makes generation of this figure possible.

[7] Currently this is accomplished through historical price ratios and marketing margins contained in WSM's data. A more thorough regression analysis of the margins and ratios against a couple of key variables in UCM framework would create a more flexible transformation. The fish commodities and some of the crop commodities such as tropical fruits do not have all of the data needed to resolve the calculations. The final list of commodities tracked is seventeen but the code contains all of the generalizations needed to do as many commodities as needed.

[8] Currently these tools are not tightly coupled so that each tool runs each time step. Instead, each tool runs to completion and the output is used as an input to the next tool. The results can be rerun until the outputs have equilibrated. A second run of IMPACT is therefore not necessary for the scheme to converge but has been included to demonstrate that the system dynamics permit decision making to be imperfect based on projected water balances rather than perfect knowledge of the future.

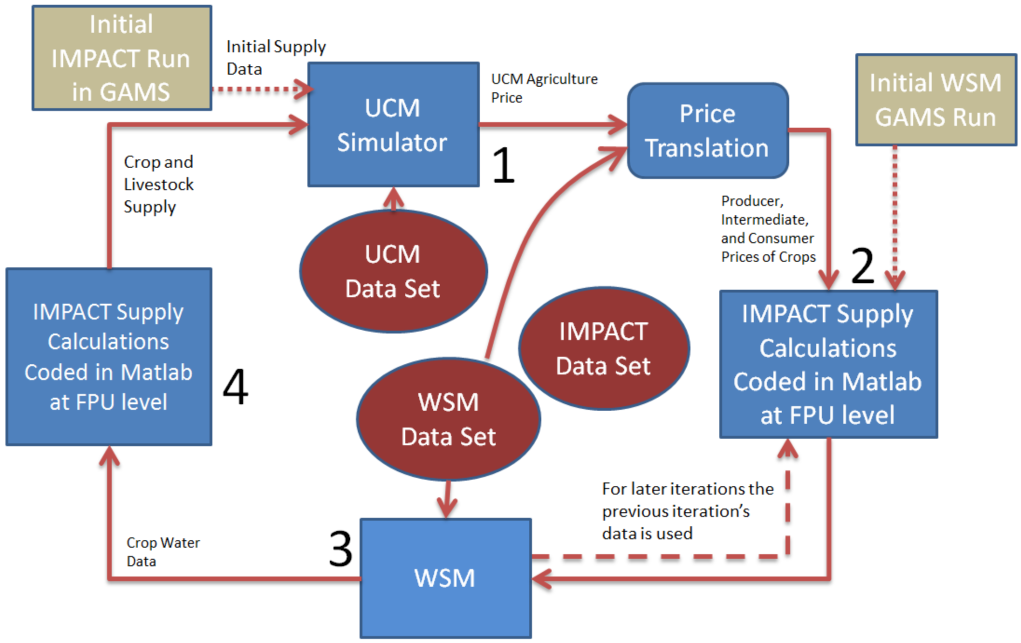

Figure 7.7: High level view of coupling UCM, IMPACT, and WSM

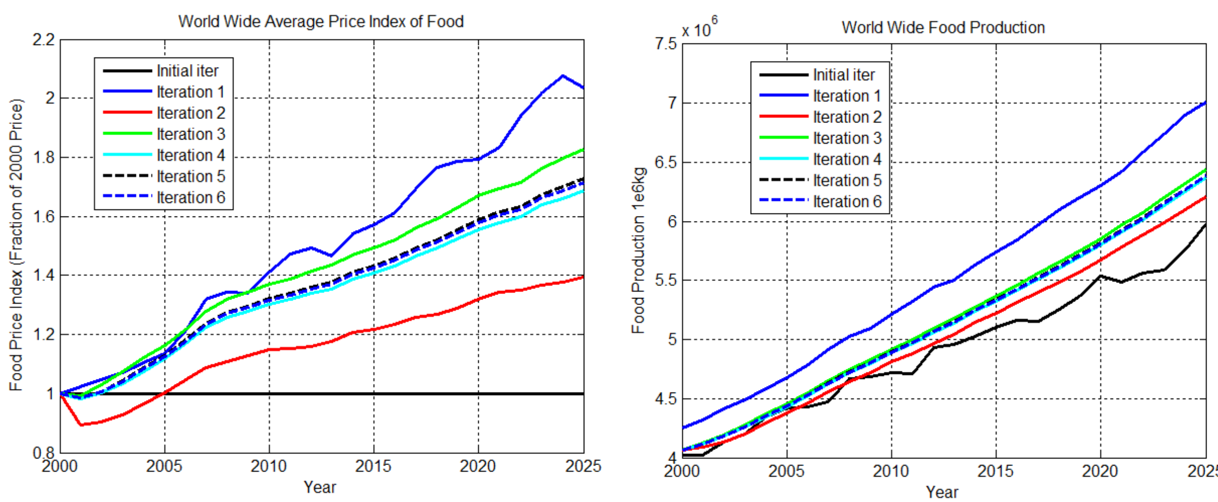

Figure 7.8: Convergence of the loosely coupled UCM-simulator-IMPACT-WSM.

The integrated system is not yet complete. For the purpose of getting the other components connected, the UCM model is simulated using a simple world agriculture algorithm similar to that used by UCM but without any connection to governance, economics, conflict, and other commodities which are included in UCM. If UCM reaches a mature enough state, the entire suite of tools will be integrated into a single code.

The current tools have been tested and the resulting loop converges with a percent change tolerance of 0.01% in six iterations after running for two hundred ten seconds as seen in

Figure 7.8. The dataset used in this analysis needs to still be adjusted to baseline and various climate and use scenarios for the results to be meaningful.

7.3.2. Climate Effects

IMPACT's yield equations are log-linear functions whose canonical form provides a straightforward method for including climate effects. The complexity and uncertainty involved in modeling anthropogenic, biophysical, and climactic effects simultaneously has led to an abundance of methods to approximately couple climate to other effects or provide quality climate inputs (McCarl et al 2008, Moore et al. 2012, Field et al. 2010, Parry et al. 2004). For IMPACT, any of these methods can be introduced as a means of introducing a factor, θ, which adjusts yields based on climate. θ is equal to the average yield for the current climactic conditions divided by the average yield at the baseline conditions. One of the simplest models for doing this is shown in equation 7.1.

$$\boldsymbol{\theta_{u,i,t}} = \prod_{c} \left(\frac{\boldsymbol{CL_{c,u,t}}}{\boldsymbol{CL_{0_{c,u}}}} \right)^{\boldsymbol{\kappa_{c,u,i}}} \qquad 7.1$$

Where CL is a multidimensional array of several types of climate data projections coming from one or several climate models, CL_0 is an array of the baseline conditions for which commodity yield is assessed, and κ is a multidimensional array of exponents estimated by multivariate regression of historical climate data versus crop yield data. The index u represents the range of FPU's, t the time step, i the 35 WSM commodities, and c is the set of climate indicators. For example, c could be the set of indicators used by McCarl et. al. (2008) which are the Palmer Drought Severity Index, temperature, standard deviation of temperature, and intensity of precipitation.

7.3.3 Data Transformation

The WSM, UCM and IMPACT models all have different levels of spatial and commodity aggregation. Bridging the gaps between the different regions is an activity which has been accomplished using linear transformations of one or two variables which are derived from known data. The work accomplished thus far provides static transformation based on historical data. There is plenty of room for continued improvement and further analysis of the relationships between the variables being passed between the models. The resulting matrices are sparse matrices.

IMPACT's thirty-six regions (CTY) and sixty-nine watersheds (WSHD) are no longer needed once FPU level data can be assembled for the required inputs. The transformation from these regions is accomplished using two separate transforms. The first, called the distribution transform, takes values which do not represent quantities. For example, commodity prices or price elasticities use this transform. The nonzero entries of both matrices are the same as seen in **Error! Reference source not found.**9. he second, called the area transform, concerns physical quantities of commodities or population. Both transforms are derived through a geospatial analysis of the intersecting areas of the various regions with respect to each other as seen in **Error! Reference ource not found.** for the United States. Each coefficient in the resulting matrix is the area of a given FPU divided by the sum of the corresponding areas of every region which touches the FPU for the IMPACT region or watershed.

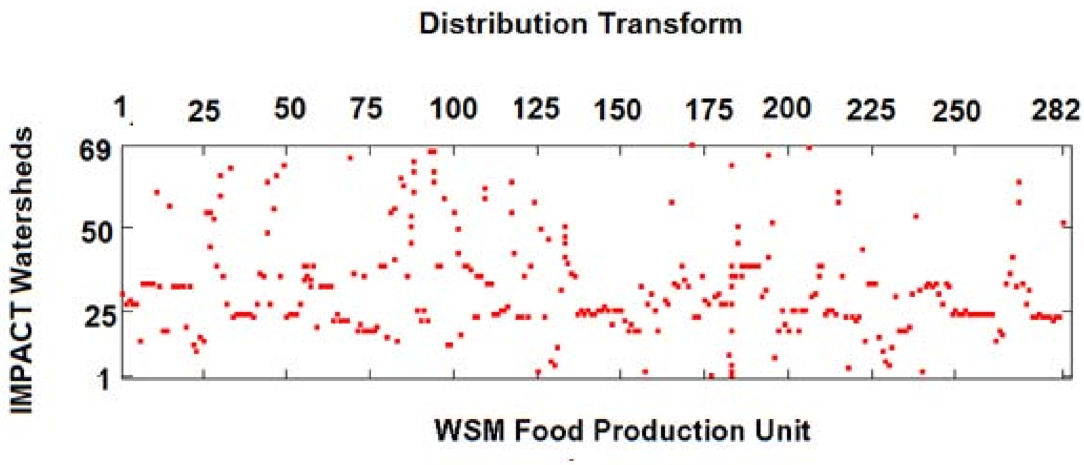

Figure 7.9: The distribution transform non-zero entries.

The transformation between the 230 United Nations UCM regions and FPU‘s is endogenous to the simulation. It was accomplished by creating a population weighted linear transform between a vector of known population in the UCM regions and a vector of known population in the the 281 FPU‘s. Most of the boundaries between regions were shared in common but a couple regions such as those pointed out in Figure 7.10 contained multiple borders which led to conflicting constraints[9]. In Figure 7.10, red borders are watersheds; dark red is an area. Green are slivers due to boundary differences. The blue arrows point towards regions which do not share common borders. The least squares solution to all of the conflicting constraints was used to minimize the conflicts. Figure 7.6 shows the FPU boundaries for the entire world.

The single commodity in UCM –agriculture” has to be split into the seventeen livestock and crop commodities in IMPACT. This has been accomplished by assuming that the ratios of commodity quantities for the base case year of 2000 in WSM stay constant throughout the simulation.

7.3.4 Water Simulation Model

The water simulation model (WSM) created by Cai and Rosegrant (2002a, 2002b) is a global hydrology model which divides regions along both political and water basin levels. It is coded in an optimization program called the General Algebraic Modeling

[9] Even though **Error! Reference source not found.** is for the IMPACT-WSM transformation, the issue is he same between UCM and WSM with the unfortunate except that the UCM border data was not available for a more detailed area based transform analysis.

System (GAMS™)[10]. WSM is not nearly as detailed as gridded, world-wide, water resources models such as the WaterGAP Global Hydrology Model (Döll et al. 2003, 2012), but strikes the right balance between computational cost and the need for hydrological considerations in this effort. In this discussion, only the aspects of WSM which have been altered with respect to the original version provided by Cai are discussed. WSM has been used in a number of studies with IMPACT to assess global food and water issues given future policy and climate scenarios (Strzepek et al. 2010, Zhang and Cai 2011, Rosegrant et al. 2009, 2002).

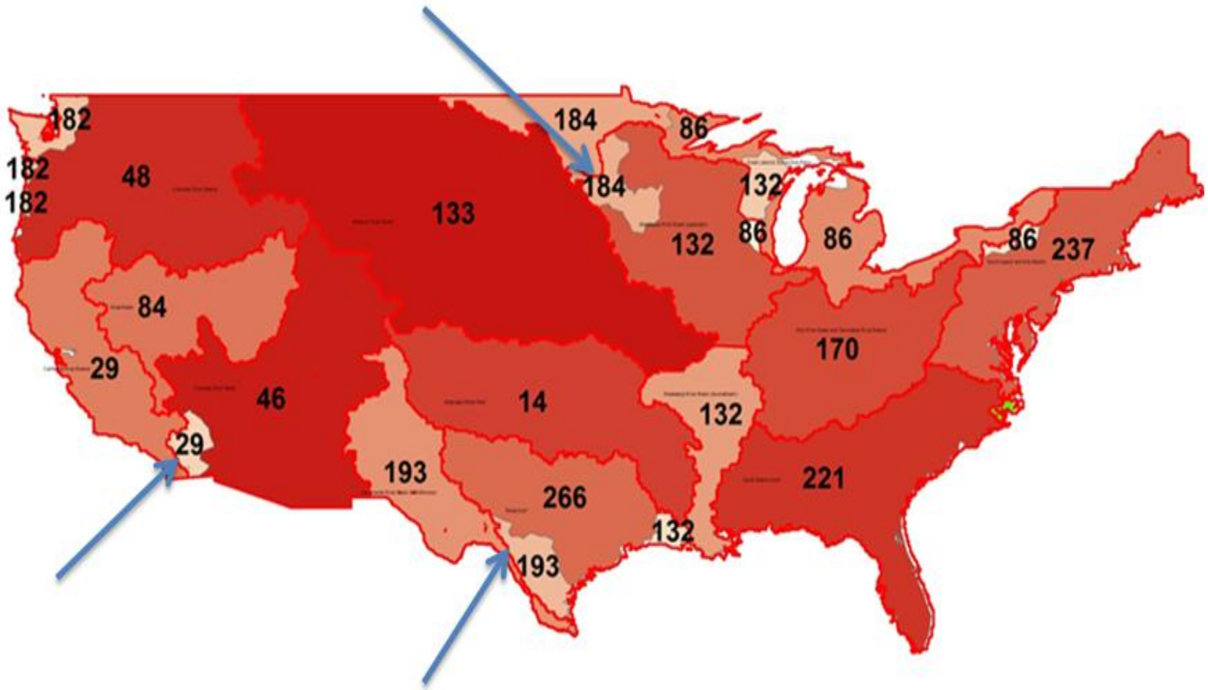

Figure 7.10: WSM FPU's intersected with IMPACT watersheds.

WSM divides the world into two hundred eighty-one food production units (FPU). The divisions are described in detail by Cai and Rosegrant (2002a) along with a description of how data was collected and how the model was verified in previous uses (Cai and Rosegrant, 2002b). WSM requires input from detailed climate and water runoff models to characterize effective precipitation for crops.

The use of optimization to resolve water balances can conflict with the system dynamics architecture of UCM. The optimization could easily outperform the real world. Two water prioritization algorithms were developed to address this problem. The first uses a proportional integral derivative (PID) type controller (Richie et al. 1986). The PID controller algorithm simultaneously seeks to keep surface water balance equal to a monthly rule curve and groundwater balance to a corresponding groundwater balance

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[10] See http://www.gams.com/ for details.

rule curve[11]. It also seeks to meet monthly environmental flow requirements and provide the requested amount of water to crops, livestock, domestic, and industrial demands. The algorithm serves its purpose but calibration of its behavior through applying weighting factors to the four signal errors is fairly involved without a very good phenomenological justification. One of the most interesting examples of one of the FPU's performance for the year 2000 is shown in Figure 7.11. A preliminary set of rule curves were not followed very well. Most of the FPU's follow patterns of moving from one side of the constraint boundaries to the other side at the monthly time step level.

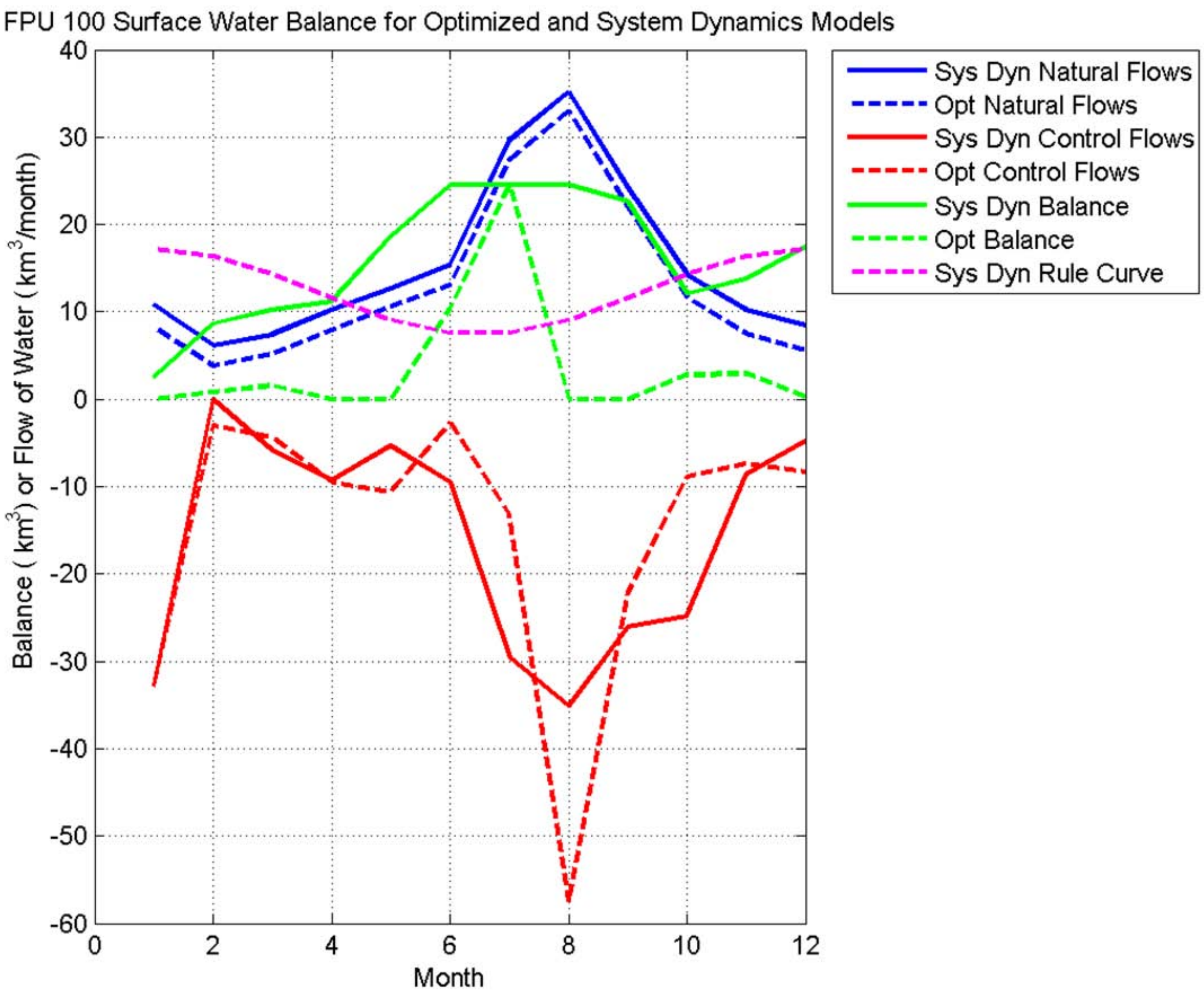

Figure 7.11: Example PID controller optimization (India Indus River)

As expected, the optimization scheme performed significantly better at supplying water demands. The overall ratio of water demand to water supply in the optimization was 0.892 whereas the PID controller produced a value of 0.740. The gap might be closed further if better methods were used to derive the rule curves but the point to highlight is

[11] The data to create parameters for a groundwater balance rule curve either does not exist or is uncertain for many portions of the world. This was included for completeness but none of the calculations included a significant weight for this term.

that the optimization maximizes water delivery for food output in a coordinated fashion which does not exist in the real world. Using a system dynamics model does a better job of allowing inefficient water use patterns to develop in the simulation.

The PID algorithm was first programmed in GAMS so that translating from Matlab to GAMS would have a one-to-one correspondence. This arrangement aided in the systematic removal of bugs in the translation process until results were very close to each other. Checking was comprehensive across the WSM data set for the year 2000. Figure 7.12 illustrates the type of plot which was automatically output for additional visual verification of select samples of the commodities, months, and variables. The percent difference between all of the results is shown in Figure 7.13.

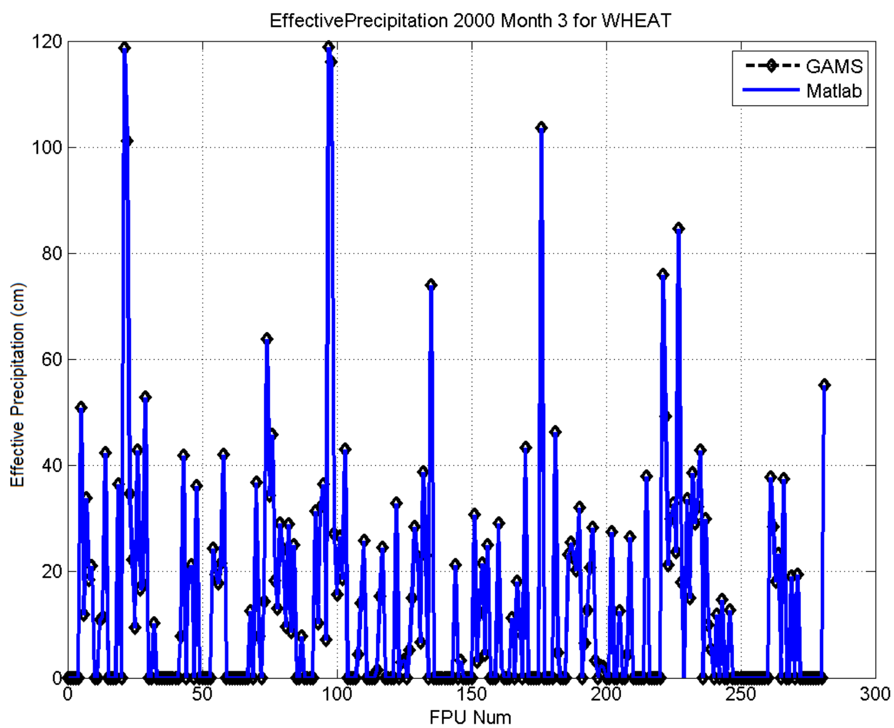

Figure 7.12: Example output of GAMS versus Matlab for effective precipitation.

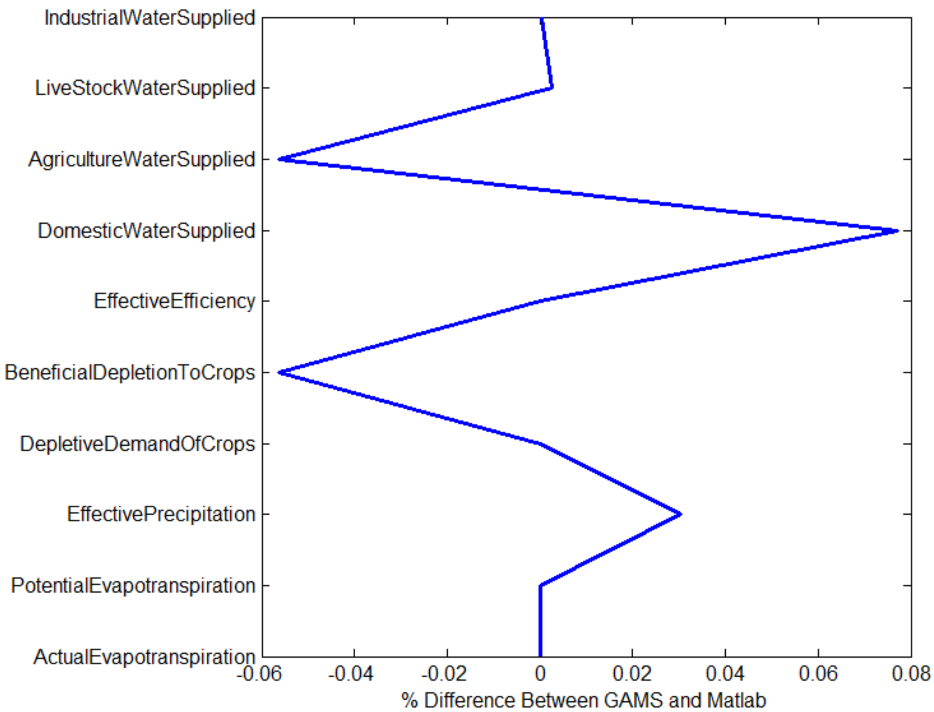

Figure 7.13: Difference between Matlab and GAMS for all FPU's.

The second algorithm developed to handle water distribution has been developed into a general queuing system model which can be applied to the water decision problem needed in WSM. It has been developed without reference to known literature but there is a good possibility that it is not a unique mathematical scheme. It involves listing water demands in order of priority. The list of demands, $\{D_1, D_2 \dots, D_q\}$, has a corresponding list of depletion factors $\{F_1, F_2 \dots, F_q\}$. The depletion factor is the amount of water which is dissipated from the system by its corresponding demand. The remaining fraction, $1 - F$, is available for reuse by other demands after the process completes. Each demand therefore requires D water but only depletes DF, water and releases $D(1 - F)$ for reuse by other demands. This is analogous to a power plant using water as a coolant for its thermodynamic cycle. Some of the water is lost by evaporation and the rest outflows at a higher temperature than the original stream. Each demand is either a ―use" demand $\{D_{u_1}, D_{u_2}, \dots D_{u_r}\}$ or a ―downstream" demand $\{D_{d_1}, D_{d_2}, \dots D_{d_s}\}$[12]. Use demands dissipate water and release it for use by other demands. Downstream demands always have a depletion factor of one since they reserve water for downstream use which is outside of the system. They require a more involved treatment because they can often be met by water that is reused but must be met fully. The following sub-algorithms drive the behavior using recursive models. An additional piece of information needed to derive the model behavior is stated in axiom 1.

[12]The sets $\{u\}$ and $\{d\}$ are monotonically increasing subsets of $\{1,2,\dots,q\}$ $\{D_{u_1}, D_{u_2}, \dots D_{u_r}\} \cup \{D_{d_1}, D_{d_2}, \dots D_{d_s}\} = \{D_1, D_2 \dots, D_q\}$

Sub-Algorithm 1: Each downstream demand D_{d_j} reserves enough water for itself $X\ (0 \leq X \leq D_{d_j})$ such that it is fully met with as much reuse as possible R_P. All potential reuse in lower rank, use demands is redirected to the first downstream demand above themselves until D_{d_j} is fully met and $R_P + X = D_{d_j}$. Any remaining reusable water R_u is fed to the next demand. Once $D_{d_j}$is fully met, Sub-Algorithm 1 exits. If there are no use demands between $D_{d_j}$and $D_{d_{j+1}}$, or $D_{d_j}$is at the end of the list of demands, then D_{d_j}satisfies itself or uses up the remaining balance $R = R_A + R_U$ and the algorithm exits. If $R < D_{d_j}, D_{d_j} = R$. This algorithm outputs the supply $\left\{S_{d_j}, S_{d_j+1}, \dots , S_{d_{i+1}}\right\}$, where $1 \leq i \leq d_{j+1} - 1$ after recursively moving along the list of demands.

Sub-Algorithm 2: When the next demand is not a downstream one, if enough water is available, use demands D_{u_k} deplete $D_{u_k}F_{u_k}$ and release $D_{u_k}\left(1 - F_{u_k}\right)$ to the next demand D_{u_k+1}[13]. Otherwise the rest of the available water, $R_A + R_U$ is applied to D_{u_k} and $(R_A + R_U)\left(1 - F_{u_k}\right)$ is released for reuse by $D_{u_{k+1}}$. Water at the end of the demand list is lost downstream and is not available for any further reuse. This algorithm produces the supply S_{u_j}

Axiom 1: Reusable water is used up first. When no reusable water is left ($R_U = 0$), more water is released from the remaining available reservoir R_A.

Sub-algorithm 2 leads to an intuitively easy recursive model which requires no further derivation. It will always release some water for reuse since the result is an exponential decrease in proportion to the depletion factor. Sub-algorithm 1 requires careful attention on several boundaries and iterating its recursive model to produce a solution. For the purpose of simplifying the indices in the following discussion, for every $d_j \in \{d\}$, the union of $d_j$and every use demand after it before d_{j+1} $\left\{d_j, d_j + 1, \dots d_{j+1} - 1\right\}$ can be mapped to the set $\{1,2, \dots , m\}$, where m is the number of elements in $\left\{d_j, d_j + 1, \dots d_{j+1} - 1\right\}$. If R total water is available for use, the index i $(i \mid 1 \leq i \leq m - 1)$ is needed for which the next demand's (D_{i+1}) reuseable water $D_{i+1}(1 - F_{i+1})$ will exceed the water set aside X $(X \geq 0)$. The flow diagram shown in Figure 7.14 depicts how X can be determined. Summing X and all of the reusable flows, equating them to the downstream demand D_1, and solving the expression for X produces the expression seen in equation 7.2.

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[13]Be careful with the indices! $u_k + 1$ (the number listed in this equation) is the next priority demand which may be a use demand or a downstream demand. u_{k+1} is the next use demand.

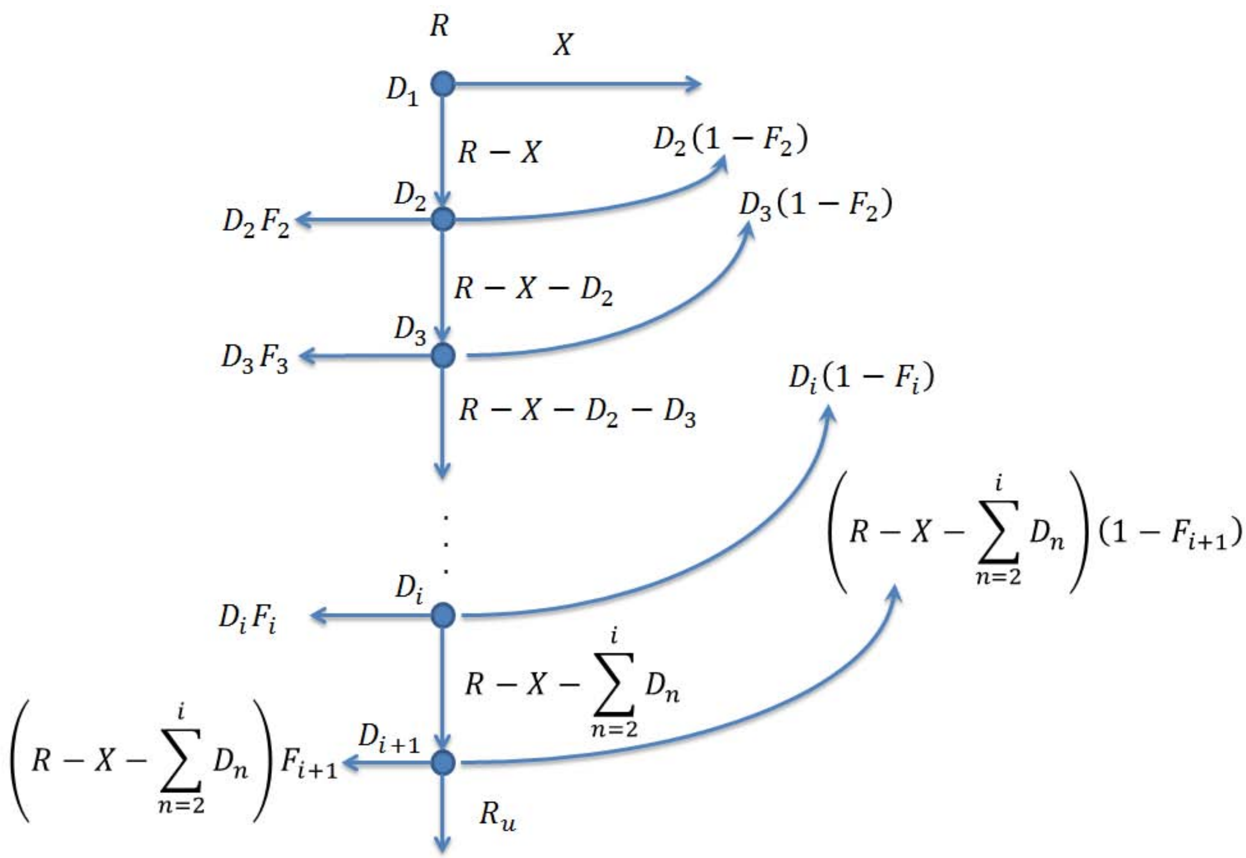

Figure 7.14: Downstream node system

$$\boldsymbol{X} = \frac{\boldsymbol{D_1} - \sum_{n=2}^{i} \boldsymbol{D_n}(\boldsymbol{1} - \boldsymbol{F_n}) - \left(\boldsymbol{R} - \sum_{n=2}^{i} \boldsymbol{D_n}\right)(\boldsymbol{1} - \boldsymbol{F_{i+1}})}{\boldsymbol{F_{i+1}}} \qquad 7.2$$

The method for finding i which allows the correct value of X to be calculated and sub-algorithm 2 to use its recursive algorithm correctly requires a couple of steps.

1. Assume $X = 0$ and apply sub-algorithm 2. Keep in memory the total amount of reuse R_P which occurs.
2. If $R_P = D_1$ (sub-algorithm 2 enforces this) then the assumption $X = 0$ is true and no further steps are needed. All of the supplies from 1 to $i + 1$ have been defined and the next demand is $i + 2$. Otherwise move to step 3.
3. Calculate $\sum_{n=2}^{m} D_n - R_P$. This is the amount of water needed to satisfy all of the demands. If $R > \sum_{n=2}^{m} D_n - R_P$ then the solution is simply that the supplies equal the demands times the depletion factors and $R_u = R - (\sum_{n=2}^{m} D_n - R_P)$. Otherwise move to the next step.
4. Since $R_P < D_1$, $X > 0$ but evaluating equation 7.2 requires that the correct value for i be found. Starting with $v = 1$ evaluate equation 7.2 with v replacing i and check to see that all the flows in Figure 7.14, and X are greater than zero. Continue to evaluate until $v = m - 1$. i is equal to the expression below

$$i = max\left(v \in \{1, 2 \ldots, m-1\} \mid R - X_v - \sum_{n=2}^{v} D_n > 0 \ and \ X_v > 0\right) \quad 7.3$$

5. Once i is known, the correct X can be calculated and sub-algorithm 2 will produce the desired water supplies.

This algorithm was generalized even further by allowing the original demands to be broken up into as many layers as desired. Each layer is considered to be higher priority than the next. For example it allows the modeler to input the amount of domestic water demanded but to then say that 80% of the water is the absolute highest priority and that the remaining 20% can be met after 80% of livestock, industrial, and agricultural demands have been met. Each layer's demands $D_l \ l = \{1,2,\ldots,g\}$ can be calculated using an $g \times q$ matrix of fractions L whose columns sum to one.

$$D_l = LD^T \quad 7.4$$

The output of each layer can be fed into the input of the next layer. If enough water is available, then it outputs how much extra water there is. This extra water may be spilled downstream to follow a rule curve or to simulate overflow of the reservoir. The additional spilled water does not have to be fed through the algorithm.

This scheme was programmed and tested for multiple configurations such that the generalized implementation is believed to be accurately reflected in the programming[14] Testing included verification that no artificial jumps occur in the logic for a broad range of configurations and that the programming successfully conserves mass for all of these configurations. An example case for which the total amount of water available R is varied between zero and three thousand was run. The inputs were as follows below. The patterns developed illustrate how the solutions of supply produced are non-trivial as water reuse between demands occurs (Figure 7.15).

$D = \{120, 83.33, 41.67, 80, 333.33, 16.67, 100\}$,
$L = \{0.5,0.3,0.5,0.5,0.5,0.5,0.5; 0.5,0.7,0.5,0.5,0.5,0.5,0.5\}$
$d = \{2,3,6\}$
$u = \{1,4,5,7\}$
$F = \{0.5,1.0,1.0,0.6,0.6,1,1\}$

[14] Testing has not been so thorough to generate a statistical confidence bound for whether the implementation is fully general but the testing conducted is probably sufficient for use in the WSM application.

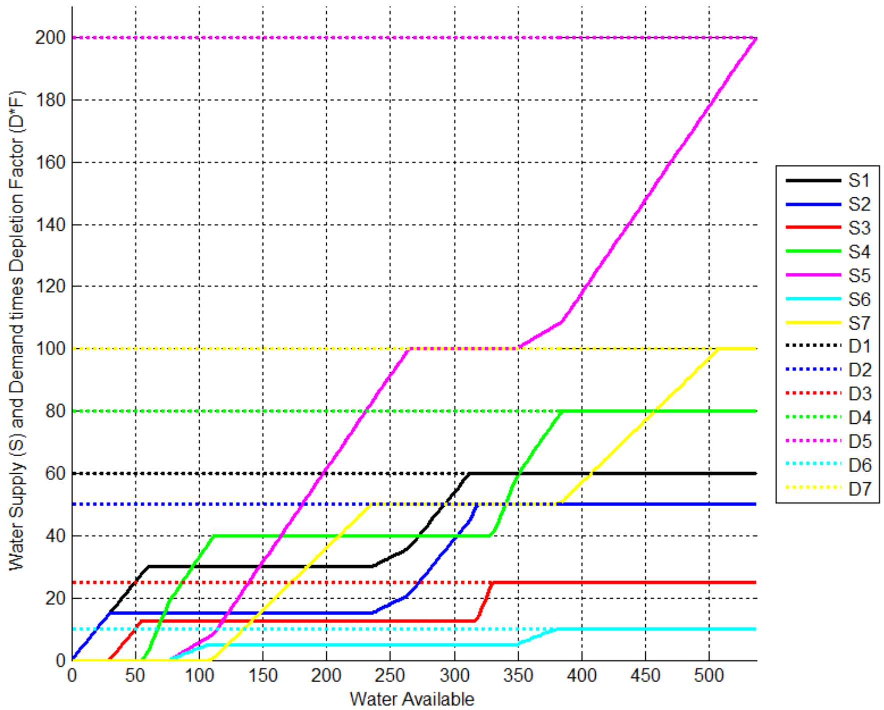

Figure 7.15: Example showing the complexity of water supply solutions.

A comparison of the results obtained by the combined UCM-simulator-IMPACT-WSM code shows that the converged results are insensitive on a global level to the dispatch algorithm used as depicted in Figure 7.16. Further analysis may show that there are significant differences at local levels though. The prioritized demands algorithm runs about 30% faster than the PID controller and it will be used as development progresses. Both algorithms are fully integrated into the UCM-simulator-IMPACT-WSM code.

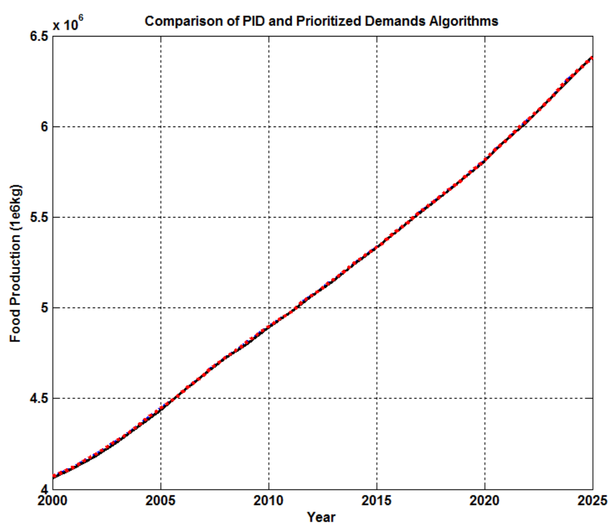

Figure 7.16: PID versus prioritized demands for world food production.

7.3.5 IMPACT Model

The IMPACT model is a partial equilibrium economics model which includes the livestock and crop sectors. It was developed by Mark Rosegrant of the International Food Policy Research Institute (IFPRI)(Rosegrant et al. 2008).[15] It has been coupled in much the same way that UCM is being coupled to WSM in order to provide detailed inputs to its area and yield reduction functions which require potential evapotranspiration, potential beneficial water consumption and effective precipitation as inputs. This coupling is described by Rosegrant et. al (2008). Like WSM, IMPACT is not a high resolution food production model like growth and development process models such as CERES (Rosegrant et all 2002). It balances food production by price, water, and average values for crop coefficients. The crop coefficients used reflect underlying assumptions about the climate and soil that the user must be aware of. The climate effects in this modeling effort are described in section 7.3.2 and crop coefficients which are synchronized with the underlying assumptions of the climate effects terms are needed to produce consistent analysis. IMPACT and WSM have been coupled into a composite IMPACT-WATER model which has been the basis for several studies (scenarios (Strzepek et al. 2010, Zhang and Cai 2011, Rosegrant et al. 2009, 2002).

Like WSM, IMPACT was originally coded in GAMS and needed to be ported over to Matlab to interface with the UCM-IMPACT-WSM code. Only the supply equations of the IMPACT code were used since UCM-simulator calculates the demand and price index for agriculture. The isolation of the supply side is possible since price is fixed by UCM-simulator. Price is usually the independent variable to meet supply-demand equilibrium requirement in IMPACT. With a fixed price, the equations work to produce a corresponding supply.

The Matlab version of IMPACT was changed from 36 regions and 69 watersheds to WSM's 281 FPU's. This causes the comparisons between the codes to have error since the equations in IMPACT are not linear. For a GAMS IMPACT run, the watershed (WSHD) level data run through IMPACT and then transformed to the FPU's. In Matlab the data is transformed to the FPU level and the equations are then applied. The statement in equation 7.5 illustrates the operation for a simple exponential function.

$$\boldsymbol{T(I_{WSHD})^{\alpha} \neq I_{FPU}{}^{\alpha} = (TI_{WSHD})^{\alpha}} \qquad 7.5$$

T is one of the 281×69 transform matrices described in section 7.3.3, I is a vector of data which is being raised to the power α. Raising to the power α is analogous to application of the IMPACT equations to I. Despite this imperfection, the transformations, T, have many terms which have one-to-one correspondence. This allowed specific instances of the equations to be directly verified to produce the same results. The comparison process was therefore successful at isolating multiple bugs between the codes and the differences in results were acceptable. Considerable errors were generated between the Rest of World (ROW) watershed in IMPACT and the FPU's that intersect it. This is expected since the IMPACT ROW is an extensive list of

[15] See http://www.ifpri.org/staffprofile/mark-rosegrant

countries in different locations throughout the world. Figure 7.17 gives an example case where it is clearly observed that most of the data is very close between the two versions but a couple of points have significant error for small dense FPU's.

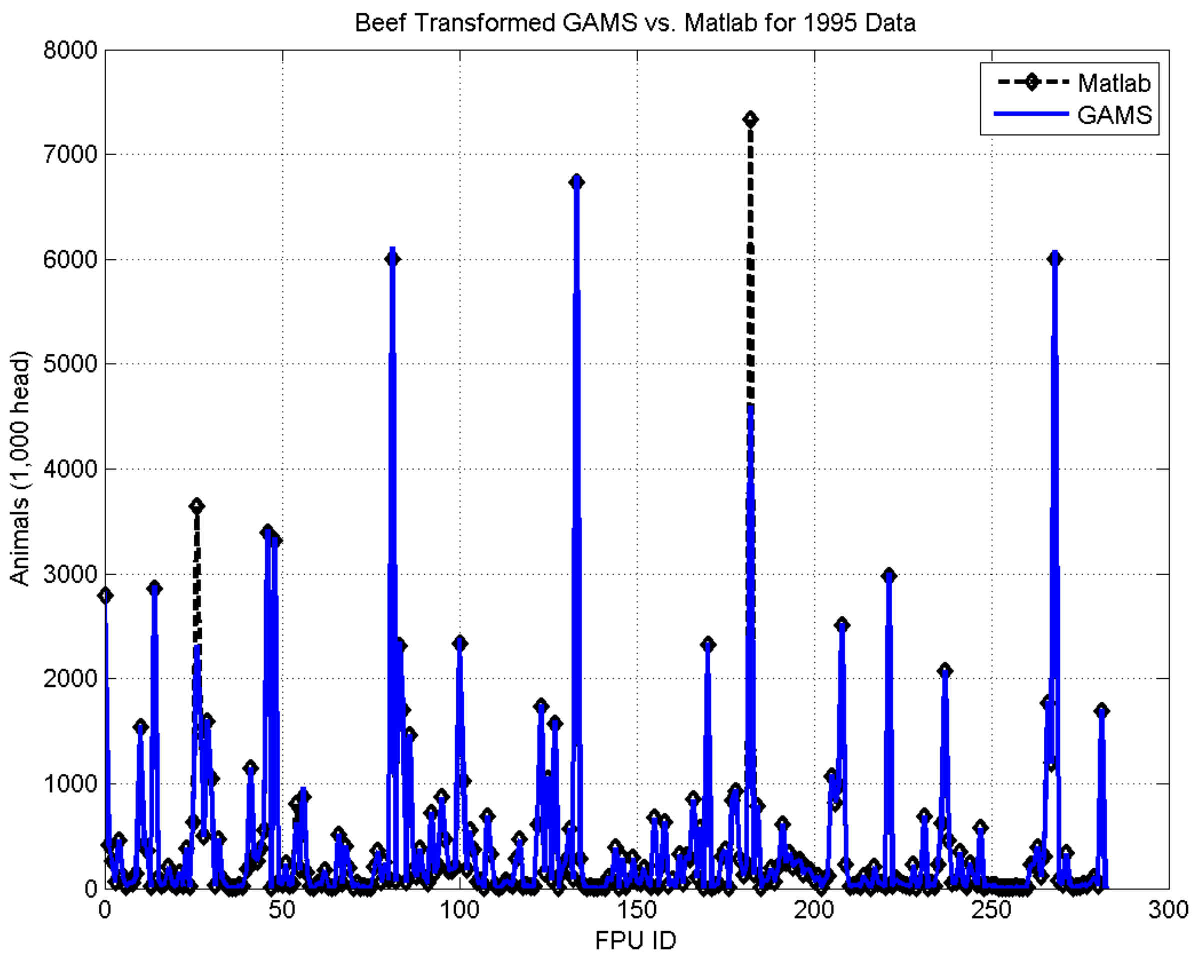

Figure 7.17: Example comparison of GAMS and Matlab IMPACT versions.

Path Forward

The hydrological and food issues framework developed is ready for integration to UCM. The code has been tested sufficiently to warrant confidence in its functionality. The transformations used to connect the codes and datasets used by the codes are functional but static and are expected to be enhanced. The following activities are the code's path forward.

1. Updating UCM-simulator so that it replicates UCM's interfaces exactly. This will also require changes to the price and commodity transformation routines.
2. Implement a depletion factor algorithm based on data already in the model.
3. Construction of a baseline dataset which has a more recent start year than 2000 and extends to 2100. Rearrangement of the data to a central source will greatly enhance configuration control of the scenario.

4. Identify and calibrate parameters inside the models such that the models are consistent with historical data. This has been done by the original authors of IMPACT and WSM individually but not for the entire coupled code. Extract hard coded constants and parameters in the code and place them within the input structure.
5. Create variations to the baseline scenario which represent different policies and climate futures, run the model, and publish the conclusions drawn from the results.

The coding constructed, like every code, has a very large list of enhancements which can be added as the opportunity arises. A description of how to get started with the code is contained in Appendix A: Getting Started with the UCM-WSM-IMPACT code.

8. INTERNATIONAL CONSEQUENCE SIMULATION

In a globalized world, dramatic changes within any one nation causes ripple or even tsunamic effects within neighbor nations and nations geographically far removed. Multi-national interventions to prevent or mitigate detrimental changes can easily cause secondary unintended consequences more detrimental and enduring than the feared change instigating the intervention. This LDRD research developed the foundations for a flexible geopolitical and socioeconomic simulation capability that focuses on the dynamic national security implications of natural and man-made trauma for a nation-state and the states linked to it through trade or treaty. The developed Unintended Consequence Model (UCM) contains a database for simulating all 230 recognized nation-states and sovereignties with the detail of 30 economic sectors including consumers and natural resources. The model is designed to explicitly simulate the interactions among the countries and their governments. Decisions among governments and populations is based on expectation formation. In the simulation model, failed expectations are used as a key metric for tension across states, among ethnic groups, and between population factions. UCM considers the uncertainty across nations and the impact, through world trade, on the U.S. (and on other nations). It is designed to simulate the impacts of the extreme events from climate change on migration and changes in governmental capacity, as well as on the economies. UCM does not calculate optimal solutions, but rather simulates the evolving, causal impacts from climate change.

The global connectivity of the modern world has brought many opposing forces into enduring conflict. Inevitable economic disruptions, resource shortages, and nature disasters lead to fragile societal conditions that are ever more sensitive and whose failure now quickly cascades across many borders. For example, pandemics and the destabilizing governmental power-voids they produce could be facts within a few years. Soon, national and international security organizations will require tools to anticipate, assess, analyze, and mitigate extreme-event conditions. Military interventions and advanced technology utilization need to incorporate societal dynamics to ensure desired outcomes. The return to stability and the avoidance of unintended consequences depends on understanding and managing the intertwined economic, societal, cultural, and political dynamics within a region. The US defense and intelligence community needs the capability to anticipate and plan for remote, destabilizing events that threaten US and global security. These same communities depend on SNL for support in making the right decisions. SNL has an urgent need to develop the basic capabilities to evaluate socio-economic dynamics and behavioral responses prior to intervention. While macroeconomic models of essentially all countries in the world exist, they are universally devoid of security considerations and conflict dynamics. Past attempts at assessing conflict initiation and evolution have depended on quantifying static conditions, such as poverty or ethnic majorities -- with minimal success. New methods described in this report address the behavioral dynamics and expectation formation that appear to show much promise. Enhancing macroeconomic models to include endogenous security metrics and adding behavioral dynamics should produce a reliable tool set that SNL and the nation can use to address emerging and evolving threats. Such an approach could simulate the impending dynamics, delineate the complex social-behavioral phenomena, and determine intrinsically secure engagements that alleviate the cascading, unintended consequences that cause enduring global destabilization.

A large body of empirical evidence shows that humans, even a group of experts, have a minimal ability to mentally unravel the feedback dynamics in real systems. These limitations cause incomplete decisions process whose consequence is avoidable blind-siding. Simulation models formalize, document, and benchmark the best knowledge available. They can elucidate the dynamics and support reliable decision-making. Further, they allow the comparison of model results to reality and promote continued improvement. Through such models, SNL can apply engineering methods to add the behavioral element to the ―engineering of national security.”

Complex, social-behavioral interactions, for which no nation yet has adequate proficiency, will dominate future security activities. If SNL is ―the primary national security laboratory that federal agencies call on to help solve the nation‘s most difficult problems,” it must ensure it can address the approaching threats. Any misunderstanding of international societal dynamics hampers the ability to mitigate WMD-proliferation conditions. Further, SNL is routinely asked by the defense and intelligence community whether it can provide support for influence and info-ops, and societal assessment of both terrorist activities and the consequences of allied intervention strategies (including attempts at nation building). The purpose of this effort is to develop intrinsic security processes within the region and the ability to evaluate tradeoffs of solution cost and graded risk.

There are no existing macroeconomic or societal models that address security dynamics or coordinated kinetic and non-kinetic intervention. The reason for this lack is may be due to academics being adverse to such models (they violate some basic tenets of orthodox ―equilibrium” economics) and the current short-term prioritizations driving the war on terror. Nonetheless, defense and intelligence planners are recently able to step back and see the larger unfolding picture. There are many types of macroeconomics models, but only a few even have the foundation to serve the needed function. The methods developed at REMI (www.remi.com) and Cambridge Econometrics, Ltd. (www.camecon.com) provide the computational machinery to produce a self-consistent model and to work effectively with limited data. The authors worked on the development of both models (Backus 1994, Nabors et. al. 2002) and we apply the relevant components of that work to this work. Methods developed by Backus and Glass (2006) combined with new V&V approaches under development at SNL (McNamara et. all 2008) can provide robust behavioral-response simulations (Backus et. al. 2010). The foundation of these behavioral methods comes from Nobel Prize winning work by Daniel McFadden on Qualitative Choice Theory that accurately portrays human decision making (McFadden 1986,1982,1974) and by Clive Granger on Cointegration that determines those variables which affect decisions with enduring or transient significance(Granger 1981, Engle and Granger 1987,1991). These techniques can integrate disparate perspectives and information, qualitative as well as quantitative, into analysis and decision support systems. The methods are compatible with orthodox macroeconomic assumptions and used for all matter of choices (including those associated with security), but no one has attempted to integrate (security related) behavioral response mechanics within a macroeconomic framework. Other than for accommodating data limitations and more complex statistical methods (to ensure consistency and model stability) we do not expect, nor have so far experienced, any compatibility hurdles.

We have developed a complete database (other than verification) for the entire globe and the model can automatically configure itself to any inter-regional analyses among 230 nation-states. The current configuration we are using for testing is a 6 region-configuration composed of China, Russia, U.S., European Union, Middle East, and Rest-of-World.

Partially related to this work, project staff provided input to the National Intelligence Estimate for the NIC/Whitehouse on the climate change and conflict. We took advantage of additional work by European Union countries on climate change and cascading failures [for example, as based on historical dynamics, e.g., Stewart, & Fitzgerald (2000)] to enhance the dynamics our modeling effort includes on conflict evolution and cross-nation spillover.

The macroeconomic model includes employment and wages by employer (i.e., industrial sectors – including agriculture), investments, consumption, government, prices, technology, and trade. The model is designed to include labor classes with an association to education and ethnic backgrounds. The model logic to explicitly captures the migration of business and people across nations. Nonetheless, thorough testing and validation assessment, not completed before the end of this project, is required before the model results can be used with confidence.

8.1 Project Characterization

This modeling project focused on the economic activity of businesses, government institutions, and the population within and among nation states from the time period of 1960 to 2060. The historical period is used to give context to future conditions.

The model is designed to simulate the interactions among and within the nations over time, capturing delayed feedback response that can produce unintended consequences. The model has capability to consider 250 nations and currently includes the completed data sets for simulating any and all existing 230 nations and their associated (self-governing) territories. The model design focuses on comprehensive integrated assessment. All simulation represent the entire global socioeconomic system and the constraints such self-consistency imposes.

For transparency, when the user selects key nations of interest, the model automatically configures itself for those selected nations, key neighbor/partner nations and with an aggregate (residual) rest-of World (ROW). This process balances overall complexity (understandability) with the detail for the primary concerns of interest.

The model simulates international trade for over 30 commodities (including labor) and the geopolitical tensions associated with changes in economic conditions -- and the population's perception of those changes. The behaviors of governments and population are based on changing expectations and thus capture what was previously considered the paradoxical frequency of violence among relatively better-off populations.

Natural resource endowments and constraints are explicitly simulated in the model, but energy is not given any special status or presented in a differently level of detail than, for instance, land or metal ores. Technological advances are endogenous to the model as a function of innovative capability and the need to innovate. This approach overcomes the paradox of large high-tech investments struggling countries and strategic initiatives with ―advanced-nations" often having a poor correlation with future national conditions.

The model simulates the changing stocks of resources, productive capacity, and financial assets to ensure that the user understands the impacts of the various socioeconomic and geopolitical the time-constants relative to the time constants of any policy interventions.

The model explicitly includes inventory dynamics to capture prices transients (including those in financial markets).

Figure 8.1 depicts the overall structure of the UCM model.

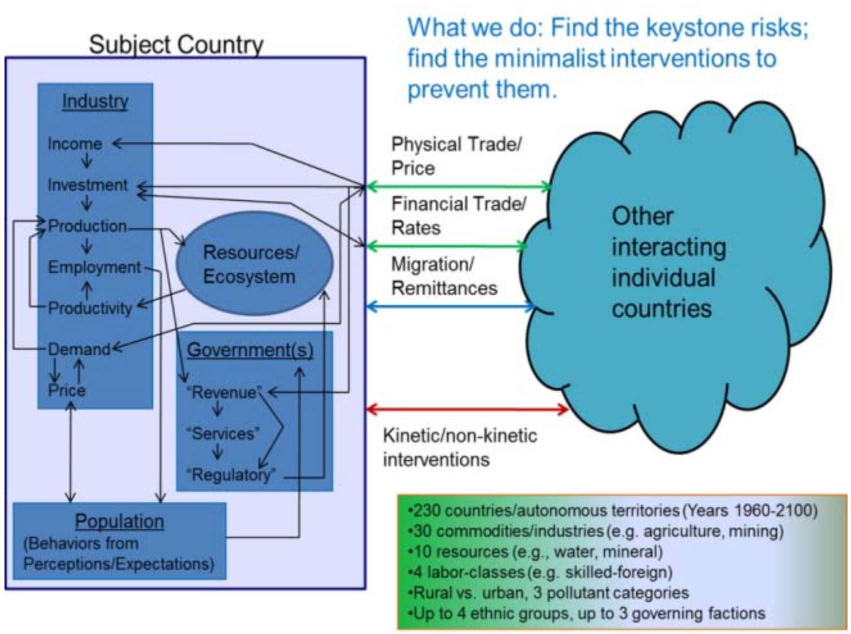

Figure 8.1: International Model Overview

The remainder of this section explores the foundations of the model development and its key elements. The ultimate purpose of the model developed in this effort is to address the unintended consequence of political, economic, and military interventions in response to changes in the socioeconomic or geopolitical status of a foreign country.

8.2 Model Conceptualization And Design

Conventional macroeconomic models, as will be discussed more in the next section, assume optimal equilibrium conditions. This work uses system dynamics to simulate the disequilibrium conditions that are generally experienced during disruptive (national security) events.

The basis for the model is the GTAP (Global Trade Analysis Project) database developed at Purdue University (Hertel 1993, https://www.gtap.agecon.purdue.edu/default.asp). This database contains trade data from 1960 and recognizes 87 commodities across 115 nations/regions. Using World Bank data and other sources (discussed in a later section) we produce a self-consistent data set for 230 nations and 30 commodities. Many of the GTAP commodities focus on detailed agricultural products. We aggregate these into three categories (agriculture, fish, forest) to maintain a focus on overall socioeconomic and geopolitical dynamics. The GTAP model includes investments which we separate out and use to estimate capital stocks and production-to-capacity relationships.

The model structure can distinguish rural versus urban conditions, but we have not yet mapped the data sets with this information into the model parameters. We keep track of inter-nation flows by an accounting approach that explicitly keeps track of the origination and receiving regions for all commodities (goods and services). The model does recognized skilled versus unskilled labor but we have not implemented the algorithms to cause laborers (population segments) to change their status between these two categories. The model allows four arbitrarily defined ethnic groups within any region and the migration of those populations to other regions. We have not yet exercised this capability. The model structure does consider greenhouse and ―other" pollution because they may become source of international tensions, should global treaties dictate compliance requirements. The model currently updates with three-month time-increments and therefore does not include any implicit to explicit time-constant below 6 months. To prevent generating any misperceptions on model resolution, the aging of capital and human stock is divided into three categories (young, middle, and old), rather than by individual year vintages.

The model is conceptualized to allow the separation of industries into a distribution of firms (agent based modeling). Some economists note that the classical use of representative firms or aggregate categories produce both static and dynamics inconsistencies (Keen 2001). Our experiments using McFadden‘s qualitative choice theory (QCT) indicates that QCT results are not overly sensitive to these inconsistencies. Therefore, for testing, we only have one representative firm per commodity per nation. Because the destabilization of large firms within a nation can destabilize a nation‘s economy, the model structure does maintain the capability to include agent-based macroeconomic (Testfatsion 2006, http://www.econ.iastate.edu/tesfatsi/amulmark.htm#Basic) dynamics. Further, a distribution of firms more correctly captures innovation dynamics that affect the ability for nations to accommodate change. Conventional macroeconomic models consider technology as an exogenous conditions. Studies relating economic dynamics to biological evolution (Raup 1991, Vermeij 2004) indicate the dynamic outcome may be significantly different when multiple-path (many firms) versus single path (aggregate industry).

Despite having a complete data set for all 230 nations-states, the model itself can only simulate 6 nation/aggregates at a time. The model automatically configures itself to self-consistently capture the dynamics among the particular nation(s) of interest, the salient neighbors/partners, and a residual (aggregate) Rest-of-World. Having more than 6 interacting regions produces a level of dynamic complexity that masks (or causes distractions to) the dynamics most critical to intervention assessment. For relevancy, the initial testing of the model is configured to represent China, Russia, the Middle East, the United States, Europe, and the ROW.

The tables below show the specificity within the Unintended Consequence (UC) model structure.

Table 8.1: UC Model Resources

Skilled labor	Unskilled labor
Water	Wind
Solar	Minerals
Forest	Land
Ocean	Fish

Table 8.2: UC Model Pollution

Greenhouse Gases	Other Pollutants

Table 8.3: UC Model Labor Levels

Skilled	Unskilled

Table 8.4: UC Model Age Vintages

Youth	Middle	Mature

Table 8.5: UC Model Ethnic Groups

Ethnic1	Ethnic2
Ethnic3	Ethnic4

Table 8.6: UC Model Intra-Regions

Urban	Rural

Table 8.7: Countries Available for Simulation

Arubae	Afghanistan	Angola	Anguilla
Antarctica	Albania	Andorra	Netherlands Antilles
United Arab Emirates	Argentina	Armenia	American Samoa
Antigua And Barbuda	Australia	Austria	Azerbaijan
Burundi	Belgium	Benin	Burkina Faso
Bangladesh	Bulgaria	Bahrain	Bahamas
Bosnia And Herzegowina	Belarus	Belize	Bermuda
Bolivia	Brazil	Barbados	Brunei Darussalam
Bhutan	Botswana	Central African Republic	Canada
Switzerland	Chile	China	Cote D Ivoire
Cameroon	Drc Congo	Congo	Cook Islands
Colombia	Comoros	Cape Verde	Costa Rica
Cuba	Cayman Islands	Cyprus	Czech Republic
Germany	Djibouti	Dominica	Denmark
Dominican Republic	Algeria	Ecuador	Egypt
Eritrea	Spain	Estonia	Ethiopia
Finland	Fiji	Falkland Islands (Malvinas)	France
Faroe Islands	Micronesia	Gabon	United Kingdom
Georgia	Ghana	Gibraltar	Guinea
Guadeloupe	Gambia	Guinea-Bissau	Equatorial Guinea
Greece	Grenada	Greenland	Guatemala
French Guiana	Guam	Guyana	Hong Kong
Honduras	Croatia	Haiti	Hungary
Indonesia	India	Ireland	Iran
Iraq	Iceland	Israel	Italy
Jamaica	Jordan	Japan	Kazakhstan
Kenya	Kyrgyzstan	Cambodia	Kiribati
Saint Kitts And Nevis	S Korea	Kuwait	Laos
Lebanon	Liberia	Libyan Arab Jamahiriya	Saint Lucia
Liechtenstein	Sri Lanka	Lesotho	Lithuania
Luxembourg	Latvia	Macau	Morocco
Monaco	Moldova	Madagascar	Maldives
Mexico	Marshall Islands	Macedonia	Mali
Malta	Myanmar (Burma)	Montenegro	Mongolia
Northern Mariana Islands	Mozambique	Mauritania	Montserrat
Martinique	Mauritius	Malawi	Malaysia
Mayotte	Namibia	New Caledonia	Niger
Norfolk Island	Nigeria	Nicaragua	Niue
Netherlands	Norway	Nepal	Nauru
New Zealand	Oman	Pakistan	Panama
Peru	Philippines	Palau	Papua New Guinea
Poland	Puerto Rico	N Korea	Portugal
Paraguay	French Polynesia	Qatar	Reunion
Romania	Russian Federation	Rwanda	Saudi Arabia
Sudan	Senegal	Singapore	St Helena
Svalbard & Jan Mayen Islands	Solomon Islands	Sierra Leone	El Salvador
San Marino	Somalia	St Pierre And Miquelon	Serbia
Sao Tome And Principe	Suriname	Slovakia	Slovenia
Sweden	Swaziland	Seychelles	Syrian Arab Republic
Turks And Caicos Islands	Chad	Togo	Thailand
Tajikistan	Tokelau	Turkmenistan	East Timor
Tonga	Trinidad And Tobago	Tunisia	Turkey
Tuvalu	Taiwan	Tanzania	Uganda
Ukraine	Uruguay	United States	Uzbekistan
Saint Vincent & Grenadines	Venezuela	Virgin Islands Uk	Virgin Islands Us
Viet Nam	Vanuatu	West Bank & Gaza	Wallis And Futuna Islands
Samoa	Yemen	South Africa	Zambia
Zimbabwe			

Note that per the tables below model can include opposition (rebel) government activities within a nation and its interaction across nations.

Table 8.8: UC Model Commodities

Agriculture	Forest
Fish	Coal
Primary Oil&Gas	Mining
Textiles	Paper
Refining	Chemical
Metal	Non-Metal
Machines	Other Manufacturing
Electricity	Gas Distribution
Water Utilities	Construction
Trade	Transportation
Communications	Finance, insurance, real estate
Govt Services	Govt Consumption
Govt Opposition	Unskilled Labor
Skilled Labor	GHG
Other Pollution	Other/Misc.

8.3 Model Structure

Conventional macroeconomic models have components which typically represent households, firms and governments, or represent savings, consumption, and intermediate goods. In our model, we consider governmental institutions and households to be economic actors in the identical vein as industry. Thus, our model only contains the components of an economic actor and its regulator (which may be a government, but may also be a separate body, such as an external entity). The components of the model are: Accounting, Assets, Capacity, Delivery, Finance, Markets, Monetary, Planning, Pollution, Price, Production, Regulatory, Resources, and Technology. Figure 8.2 shows the connection of these components to one another.

A post-processor can transform model results into the composites often recognized and used for analyses.

In the model, the Regulatory functions determine laws, tariffs and taxes and how they apply to the other commodity sectors. Laws are exogenous, but revenue producing activities are an endogenous function of governmental needs.

The planning component determines the future need for productive capacity, inventory adjustments, and future demand based on the trends of historical conditions. Studies indicate this is much more realistic and accurate than approaches using optimization or modeled clairvoyance. (Sterman 2000)

The production component must serve expected demand and maintain inventory. Production comes from productive capacity. The capacity capability may be limited because of a shortages of production factors, such as materials or labor, or by reductions in resource quality such oil, fishing, or water. Production has fixed operating costs, such maintenance, and variable costs, such as the cost of consumable production factors. It has a stock of production factors and inventory that it must maintain to allow production for serving demand. It also produces its own inventory to ensure it can meet immediate demand, and it determines its future demand for production factors from other sectors.

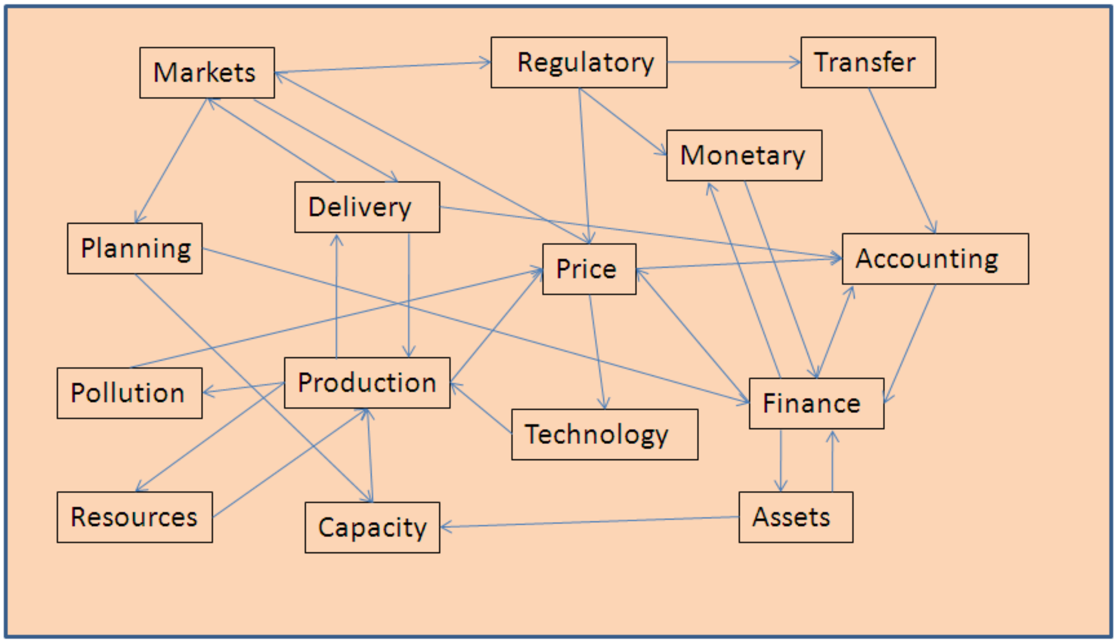

Figure 8.2: UC model Component Connectivity

The monetary sector represents the regulatory function of the central (or international) bank. It sets interest rates and adjust exchange rates to maintain employment or to control inflation.

Price is a composite of fixed and variable costs and profits. Price is determined as a function of supply/ demand conditions and costs. Fixed costs include interest payments and depreciation. Variable costs include the consumable factors of production used to make a product. Transportation costs, taxes, and tariffs increase the delivered cost experienced by the consumer.

The market component determines the demand of each commodity from each nation based on market prices, consumer preferences, and government regulation (e.g. quotas). The demand allocations are based on QCT.

The transfer component can generate transfer payments, such as subsidies and welfare payments across sectors. These may the endogenous consequence of government financial needs or are set exogenously. Income and royalty taxes are also specified in this component. The sector also includes the transfer of dividends across sectors and the payments from foreign national laborers to families abroad.

The Delivery sector allocates the production to the demand specified in the market sectors. It also does the inventory accounting.

The resource sector determines the availability of resources in terms of the effort to extract or obtain them. Land, minerals, commons-goods (fish, air, sun, biomass, water) and labor are all considered resources that may be depletably finite or renewable.

The technology component determines changes in technology and thereby economic productivity,. The primary relationship improves technology based on need (Backus 1996), but technology can also be exogenously specified. Endogenous technology dynamics can use both evolutionary (Nelson and Winter 1985) and induced-change (Ruttan 2000) algorithms. The model keeps track of marginal productivity (investments) and average productivity (embedded in capital stocks).

The capacity component accounts for the delays in investments becoming productive capital, the costs of construction, and capacity retirements.

The asset component keeps track of debt and equity plus gross, tax and net assets. It also does the accounting for retirements and depreciation.

The accounting sector determines profits, income taxes, interest payments other income, total costs, funds for operations, returns on investment, dividends, current assets and current liabilities.

The Finance sector determines debt repayments, fund required, debt limits, equity limits, new debt, new equity, short term investments, redemptions, government loans/repayment, nationalization, financial stocks, and retained earnings.

Lastly, the pollution component simply performs the accounting of greenhouse gas and other (gaseous, liquid and solid) pollution from economic activities.

Figures 8.3 and 8.4 show the basecase output for the UCM when it is configured for the 6 regions (USA-United States, CHN-China, RUS-Russia, EUR-Europe, MDE-Middle East, and ROW-Rest-of-World.) Figure 8.3 uses the foreign exchange rate to compare GDP (Gross Domestic Product) values. In this perspective, the Chinese economy is only half as big as the U.S. economy even by the year 2100. Figure 8.4 uses Purchasing Power Parity (PPP) to compare GDP, and it shows China exceeding the PPP GDP of the United States within the next 20 years, as is commonly noted in the press.

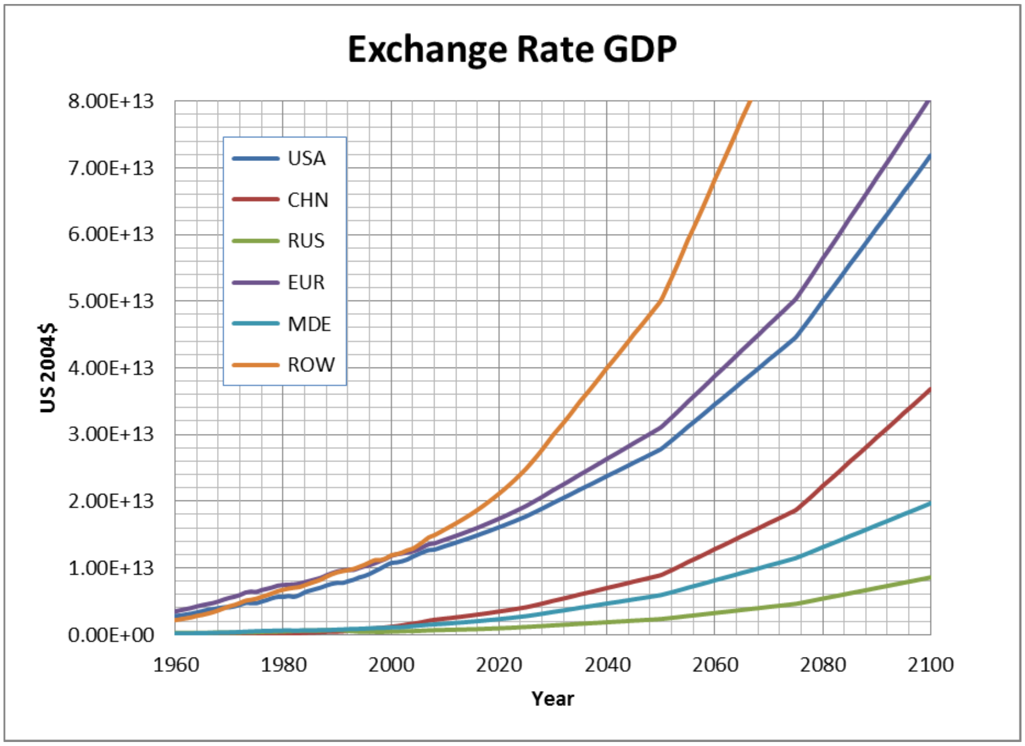

Figure 8.3: Exchange Rate GDP

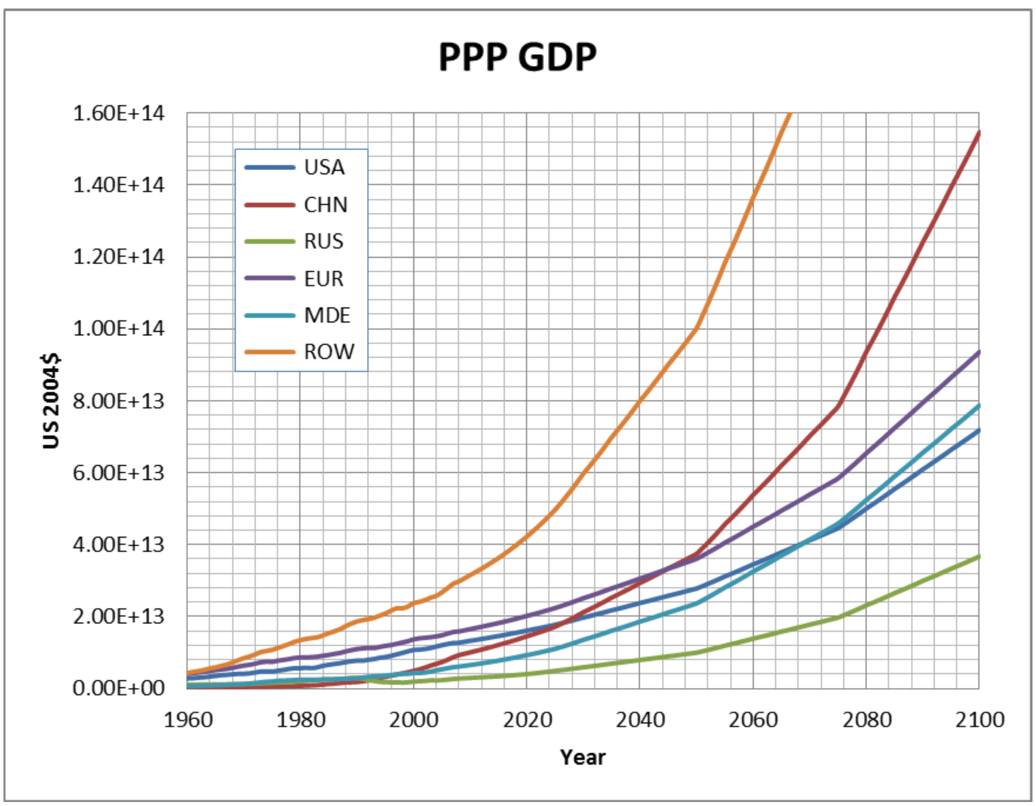

Figure 8.4: PPP GDP

9. ASSESSING THE RISK FROM CLIMATE CHANGE

The research presented here is a follow-on of a late-start LDRD on assessing the U.S. risk to climate change (Backus et al. 2010, 2011a, 2012). That work determined the risk to the economies of interacting U.S. states economy from climate change, as a function of uncertainty and volatility. Figure 9.1 shows the individual state impacts through 2050. Figure 9.2 illustrates, at the national level, how the risk is dominated by the conditions beyond the best-estimate (50% exceedance probability). Figure 9.3 makes the point that volatility can bring the future climate conditions temporarily into the future. The intensity of the 50% exceedance probability event for the year 2047 (in this instantiation of the probabilistic climate) is the same as for the 50% exceedance probability for the year 2026.

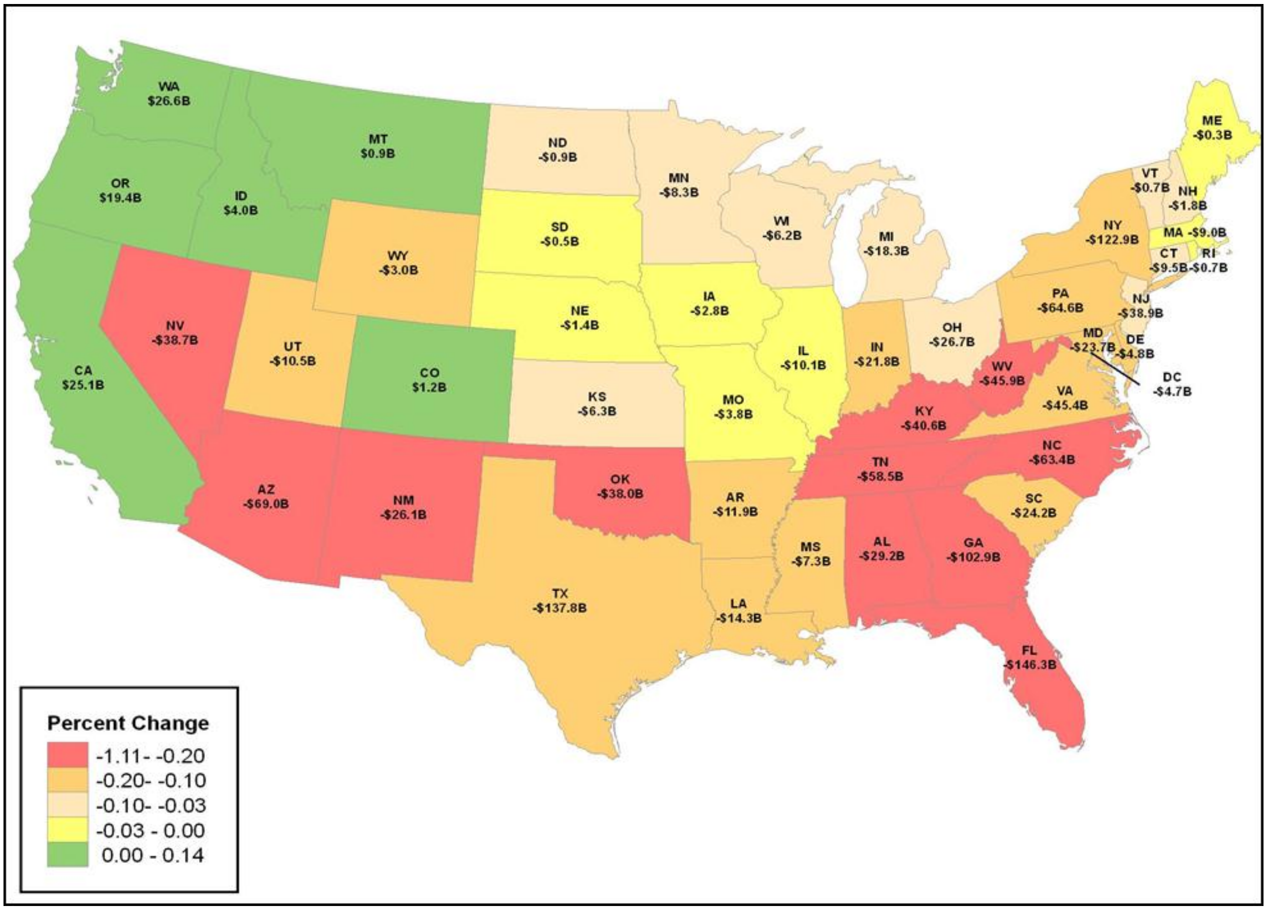

Figure 9.1: U.S. State risk from climate change through 2050 (2008$B)

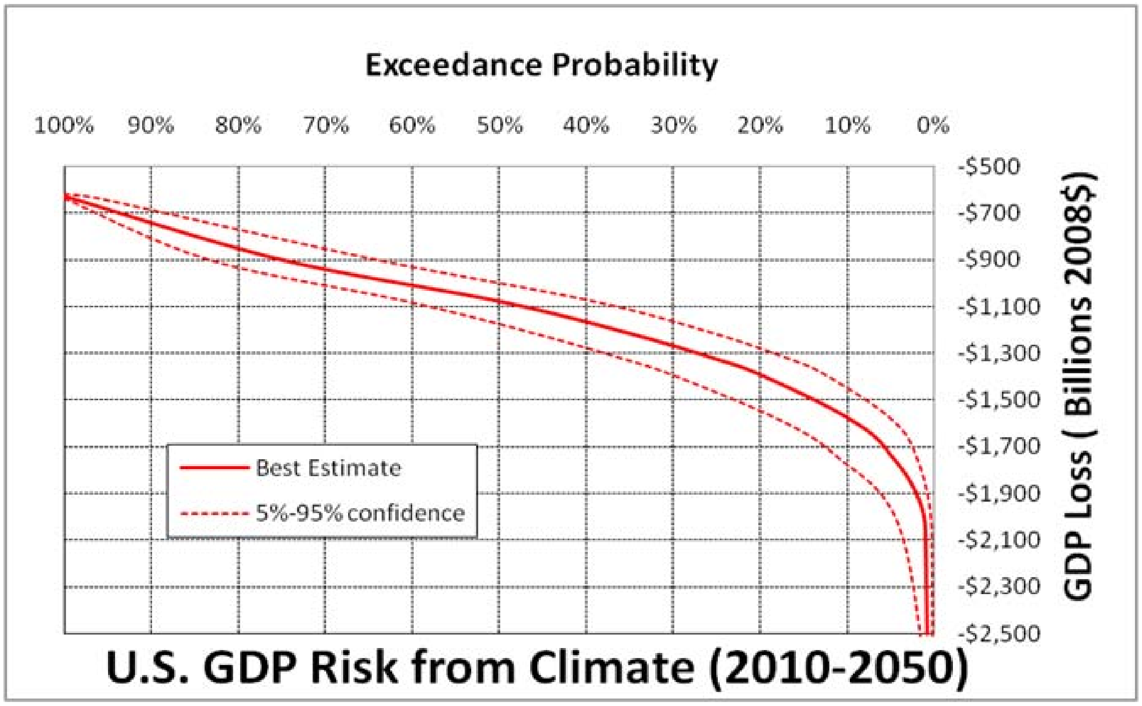

Figure 9.2: The Cost of Climate As A Function Of Exceedance Probability

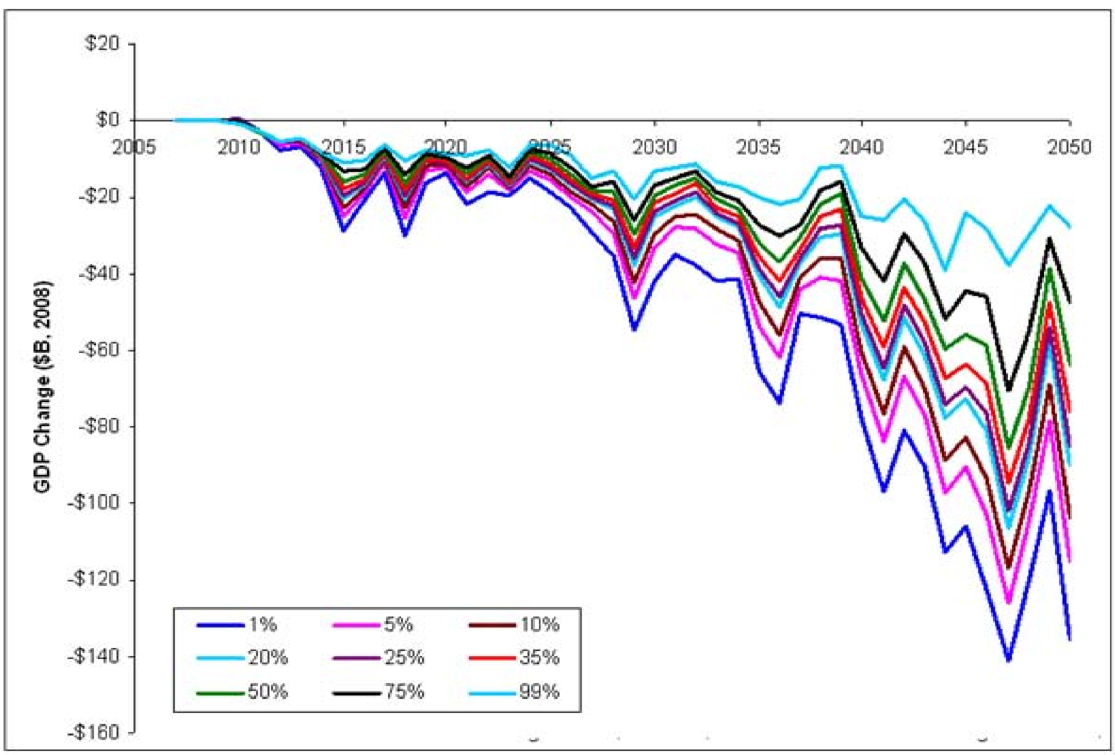

Figure 9.3: Cost and Climate Volatility

The 2010 study showed that it the uncertainty of the climate that justifies the concern for its consequences. Several news and scientific channels recognized the work as being a significant contribution in the quantification of climate impacts, including a book highlighting Sandia's work (Nash 2013, Johnson 2012a).[16] That work, extended by the work reported here, then led to new considerations that were added to the 2013 National Climate Assessment (NCA), directed by the White House. The Sandia contribution (not part of this project) is noted in Wilbanks et al. (2011) and Skaggs et al. (2012).[17]

Additionally, the international work described herein also led to Sandia being invited as an expert reviewer for the Working Group II Contribution to the Fifth Assessment Report Climate Change 2013: Impacts, Adaptation, and Vulnerability 2013 of the United Nations' Intergovernmental Panel on Climate Change (IPCC) in the topics of: uncertainty quantification, quantified resilience, economic impacts, infrastructure, hydrology, adaptation, and emergent risks and for the regions of Arctic, North America, and Open Oceans. The work is also noted in Backus (2011).

The arctic research led to Sandia being the invited to articulate the U.S. perceptive on Arctic security issues with Russian and Canadian experts for the Global Forum on Arctic Policy (Backus 2012b, Morosov 2012, Huebert 2012). The Arctic research is now part of U.S., Russian, Canadian, and Danish Defense planning documents.[18]

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[16] International Business Times: Sandia Climate Change Study Looks At Effects On Economy http://www.ibtimes.com/articles/38023/20100723/sandia-climate-change-study-looks-at-effects-on-economy.htm , Forbes: The Case for Climate-Change Alarmism, William Pentland http://www.forbes.com/sites/williampentland/2011/10/10/the-case-for-climate-change-alarmism/ , ScienceProgress: What We Don't Know Can Hurt Us: Quantifying the Economic Risks of Climate Science Uncertainty http://scienceprogress.org/2011/03/what-we-don%E2%80%99t-know-can-hurt-us/, ThinkProgress: Sandia Labs study: ―It is the uncertainty associated with climate change that validates the need to act protectively and proactively" http://thinkprogress.org/climate/2011/03/08/207634/sandia-labs-study-uncertainty-climate-change/ , Pay Now, Pay Later: A State-by-State Assessment of the Costs of Climate Change (SNL study as reference.) http://americansecurityproject.org/news/2011/report-series-pay-now-pay-later-a-state-by-state-assessment-of-the-costs-of-climate-change/ and http://americansecurityproject.org/issues/climate-energy-and-security/climate-change/pay-now-pay-later/http://americansecurityproject.org/resources/pnpl/ , UN Fellow Robert Repetto's Reports on State-level Climate Change Impacts (SNL study as reference.) http://www.demos.org/publication/climate-change-states and http://www.energyfuturecoalition.org/editorsblog/New-Reports-Economist-Robert-Repetto-Explore-Climate-Change-Impacts-Massachusetts-Florid, Fleck, J, 2011, Global Warming: Risk Huge Despite Uncertainty, Albuquerque Journal, March 22, 2011 http://www.abqjournal.com/upfront/22225216469upfront03-22-11.htm, KOAT TV Interview on U.S. Climate Risk Study: http://www.youtube.com/watch?v=FPv9oiiVBuo

[17] The NCA resulted in a Letter of commendation from John Holdren, Senior Advisor to the President and Director of OSTP - the only one to a NCA team/lead. Sandia had four lead authorships for the NCA.

[18] http://forsvaret.dk/FAK/Nyt%20og%20Presse/Pages/NytResearchPaperClimateSecurityFromAgenda-settingtoPolicy.aspx, http://www.airforce.forces.gc.ca/CFAWC/eLibrary/pubs/Projecting_Power_2019.pdf , http://www.imemo.ru/ru/publ/2011/11011.pdf , www.acq.osd.mil/dsb/reports/ADA552760.pdf

In summary, the key accomplishments of this LDRD were:

- Methods to enable regional risk assessment
- Development of multi-parameter ensembles of CESM runs using DAKOTA for Global, Arctic and Hydrological Uncertainty Quantification.
- New, more efficient and accurate UQ methods for climate models
- Evaluation of current hydrological models and enhancements to allow human-impact risk assessments
- Functioning international model of hydrological and macroeconomic climate impacts
- Methods to assess the impact of climate change on infrastructure risk and evolution
- Methods to perform V&V for combined physical and behavioral models
- Methods to asses Arctic geopolitical/socioeconomic risks and their evolution

In a substantial way, this Sandia climate-risk research has led to the Department of Energy to (DOE) initiate a new program on the impact of climate on infrastructure and on humans. The Department of Defense (DOD) , Department of Homeland Security (DHS), and the U.S. Coast Guard (DHS) now seek Sandia advise on climate risk and Arctic security concerns. Via our National Climate Assessment (NCA) contribution and our climate security reports, we believe we have changed the way the nation looks at climate uncertainty. We currently have the only –accepted" methods/capabilities accepted by DOE. DOD, DHS, and the USCG to perform climate risk assessments. At the beginning of the research, the climate community treated uncertainty as an embarrassment, best avoided. Among Sandia's clientele, uncertainty is now embraced, being converted from an apology to a strength.

The infrastructure work is being continued via DHS and DOE funding. The hydrology efforts are being continued via follow-on LDRD funding and DOE funding. UQ and (physical) Arctic work is continuing via DOE funding. PCMM and Aerosol modeling development was completed, with no additional research expected as a follow-on of this reported LDRD work.

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APPENDIX A: GETTING STARTED WITH THE UCM-WSM-IMPACT CODE

This appendix seeks to provide clues concerning how to use UCM-simulator-WSM-IMPACT. The data and programming has a composite structure between object oriented programming and conventional programming. Three objects contain all of the required input data. The objects have a somewhat self-explanatory structured array architecture which is several layers deep. Eventually these objects can serve as the database for all input to the model through some kind of user interface. For now, coding has been written to read in a large amount of input data from the same sources as used by the original GAMS codes. Seen below is a subset of the WSMObj.Data field.

```
WSMObj.EconomicIMPACT.Elasticities.Demand.Food
WSMObj.EconomicIMPACT.Elasticities.Demand.Feed
WSMObj.EconomicIMPACT.Elasticities.Demand.OtherUses
WSMObj.EconomicIMPACT.Elasticities.Demand.Income
WSMObj.EconomicIMPACT.Elasticities.Demand.IncomeOtherUses
WSMObj.EconomicIMPACT.Elasticities.Supply.IrrigatedArea
WSMObj.EconomicIMPACT.Elasticities.Supply.RainFedArea
WSMObj.EconomicIMPACT.Elasticities.Supply.Feed
WSMObj.EconomicIMPACT.Elasticities.Supply.LiveStock
WSMObj.EconomicIMPACT.Elasticities.Supply.InputsIrrigated
WSMObj.EconomicIMPACT.Elasticities.Supply.InputsRainFed
WSMObj.EconomicIMPACT.Elasticities.Supply.IrrigatedYield
WSMObj.EconomicIMPACT.Elasticities.Supply.RainFedYield
WSMObj.EconomicIMPACT.Elasticities.Supply.Meals
WSMObj.EconomicIMPACT.Prices
WSMObj.EconomicIMPACT.GDP
WSMObj.EconomicIMPACT.WorldMarketPrice
WSMObj.EconomicIMPACT.DomestAndIndustrH2OMonthlyDistrib
WSMObj.EconomicIMPACT.BasinEfficiency
WSMObj.FoodFOA.ProductionCrops
WSMObj.FoodFOA.ProductionLiveStock
WSMObj.FoodFOA.ProductionOilsMeals
WSMObj.FoodFOA.Demands
WSMObj.FoodFOA.NetTrade
WSMObj.FoodFOA.CropCoefficients
WSMObj.PopulationAndStock.Population
WSMObj.PopulationAndStock.StockParameters
WSMObj.Water.GrossRunOffLongTermAvg
WSMObj.Water.PotentialEvapoTranspiration
WSMObj.Water.EffectivePrecipLongTermAvg
WSMObj.Water.GroundH2ORechargeLongTermAvg
WSMObj.Water.InterFlow
WSMObj.Water.GroundWaterCapacity
```

```
WSMObj.Water.BasinEquivalentStorageICOLD
WSMObj.Water.BasinEquivalentStorageDDTo
WSMObj.Water.BasinEquivalentStorageDDTo2
WSMObj.Water.EnvironmentFlowRequirements
WSMObj.Water.DomesticAndIndustrialH2O
WSMObj.Water.DomesticAndIndustrialH2OParam
WSMObj.Water.LiveStockDomesticAndIndustrialH2O
WSMObj.Water.AgroBusinessIndustrialWaterParam
WSMObj.Water.AgroBusinessIndustrialWaterParam2
WSMObj.Water.ManufacturingIndustrialH2OParam
WSMObj.Water.DomesticWaterParam
WSMObj.Water.PotentialCropEvapotranspirOther
WSMObj.WSMDataForIMPACT.LiveStockAndFeedElas
WSMObj.WSMDataForIMPACT.CropRainFedElas
WSMObj.WSMDataForIMPACT.CropIrrigatedElas
WSMObj.WSMDataForIMPACT.MealsElas
```

Each data entry has several fields which assist the user to understand the data.

```
WSMObj.Data.EconomicIMPACT.BasinEfficiency

ans =

      Indices: {[282x1 double]  {1x1 cell}  {1x1 cell}}
   WSMIndices: {3x1 cell}
         Data: [282x1 double]
      WSMName: 'EE_base(u)'
         File: './baseline/sub/xEE.csv'
       Ranges: 'B1:B282'
```

The ―Data" entry contains the actual numerical data. The ―Indices" cell array gives the indices corresponding one-to-one with the data. Several other inputs describe where the data came from, what its name is in WSM, and the excel range used to read the data from the *.csv file. The structure array with understandable names is replicated in the following address so that all of the names in WSM_MatlabPID and WSM_MatlabPrioritized.m are the same as for the original WSM. Data is the same as for that shown above but there is a much less descriptive naming convention. The objects can be explored by typing their names followed by a period (―WSMObj.") and then pressing tab to see all of the options available. This will list both properties and methods available.

```
WSMObj.Data.WSMSimulationData

ans =
```

```
          BES_base: [1x1 struct]
        BES_region: [1x1 struct]
           EE_base: [1x1 struct]
           ETc_oth: [1x1 struct]
          EWR_base: [1x1 struct]
         GDPr_base: [1x1 struct]
          GRO_base: [1x1 struct]
        GWcap_base: [1x1 struct]
        GWrch_base: [1x1 struct]
         IST0_base: [1x1 struct]
          IW0_base: [1x1 struct]
          PEF_base: [1x1 struct]
          PET_base: [1x1 struct]
            README: [1x146 char]
      ddmonth_base: [1x1 struct]
          delas_fe: [1x1 struct]
          delas_fo: [1x1 struct]
         delas_inc: [1x1 struct]
         delas_ino: [1x1 struct]
          delas_ot: [1x1 struct]
      demandr_base: [1x1 struct]
       domind_base: [1x1 struct]
  domwat_param_base: [1x1 struct]
         ind_param: [1x1 struct]
   inda_param_base: [1x1 struct]
   inde_param_base: [1x1 struct]
   indm_param_base: [1x1 struct]
                kc: [1x1 struct]
      livestr_base: [1x1 struct]
    lvstwater_base: [1x1 struct]
     nettrade_base: [1x1 struct]
    oilsmeals_base: [1x1 struct]
   population_base: [1x1 struct]
       prices_base: [1x1 struct]
   production_base: [1x1 struct]
          selas_ai: [1x1 struct]
          selas_al: [1x1 struct]
          selas_ar: [1x1 struct]
          selas_fe: [1x1 struct]
         selas_ini: [1x1 struct]
         selas_inr: [1x1 struct]
          selas_me: [1x1 struct]
          selas_yi: [1x1 struct]
          selas_yr: [1x1 struct]
           stockpm: [1x1 struct]
     wrldprice_base: [1x1 struct]
```

The process of reading in data is not part of the simulation since it takes several minutes. The three objects class definitions are contained in UCM.m, WSM.m, and IMPACT.m. Using this architecture has made passing data from function to function very easy since it only requires passing a handle to one of the objects followed by instructions to unpack only the relevant portions of the data needed. The best way to find out where data is coming from is to review the class constructors in the files (i.e. the function with the name of the class (function [] = UCM()). Whenever data needs to be updated, it is important to rebuild the WSM and IMPACT objects. The UCM object is generated very quickly and is easier to rebuild. The WSM object should be rebuilt first. It can be rebuilt by issuing the command:

```
WSMObj = WSM('./baseline/sub');
```

The string ‗./baseline/sub‘ is a directory path from the codes root directory which contains all of the csv files with the GAMS WSM original data. All of the main data is loaded through a function called BuildData.m. This function has a lot of manual inputs that must be changed if the nature or size of the input data is changing! Data can be altered by altering the csv files, changing any of the excel worksheet parameters in DataBuild.m and then running the command above. There is an option in WSM.m called WSM.Options.RebuildData which allows you to toggle between rebuilding all of the data or just changes everything but the main data in ‗./baseline/sub‘. This allows quick changes to the WSM object such as changing options. After rebuilding the WSM object, the IMPACT object can be built with

```
IMPACTObj = IMPACT(WSMObj);
```

This class constructor also has several functions such as ―GatherIMPACTData.m" which has a lot of manual inputs which reference files and locations which cannot change or else the whole scheme fails. As this effort progresses, connection to the old forms of data input through GAMS files needs to be replaced with a central database of information. Efforts will then need to be made to make the data interface less clunky. Once these objects have been built, they can be saved with a new name such as:

```
Save IMPACTObj09202012.mat IMPACTObj;
```

So that the data can be loaded and accessed very quickly during the simulation. The main simulation can be run through ―**Master_UCM_Coupled.m**" this script will run a convergence loop between UCM-simulator, IMPACT, and UCM based on the objects which are loaded. It has the option to automatically rebuild the objects through setting BuildNewObjects = 1 at the beginning of the code. Since this is a script, no input arguments are needed. Several graphs showing total production, convergence, and worldwide price index will automatically be generated. Scrolling through ―Master_UCM_Coupled.m" will provide access to each of the important functions in the code. The WSM simulator is included as a method of the WSM object. This allows for the code to behave differently based on the options in WSMObj.Options so that the GAMS, PID, and Prioritized demand algorithms can all be included as optional ways to conduct the simulation.

Code Management

The code of all the functions involved are marked in 61 locations with the symbols “!@#$.” This is a way of marking an area which needs attention which cannot immediately be addressed. It also may be next to debugging code which is no longer needed but was forgotten. It is a good practice to always mark code that is not permanent or an area where questions about the theory or validity of the coding need to be addressed. Eventually, all of the !@#$ should be addressed. A running list of issues for the code needs to be generated based on the existing !@#$ marks.

The code has reached a mature enough state that it is a very good idea to assemble a suite of benchmark runs which comprehensively test whether or not everything is still working after a good day of writing code. As the code migrates from preliminary development to building successive revisions good software practices need to be implemented in order to produce a quality piece of software. Verification has been completed for IMPACT and WSM but changes since the verification have already been made.

In addition to software verification, activities such as cleaning up the way data is handled by building a user interface, and trying to investigate whether the code can be sped up by eliminating inefficient algorithms would be very helpful to save time as the capabilities of the code expand.

How to Correctly Use Handle Objects

It is important to understand that the IMPACT and WSM classes are children of the “handle” class. This means that all of the methods and properties of the handle type class are inherited by WSM and IMPACT classes. This makes assignment (“=”) pass a handle rather than assign a new set of data. For example if you issue

```
WMSObj.Options.MatlabOrGAMS = ‘GAMS’;

WSMObj2 = WSMObj;
IMPACTObj2.Options.MatlabOrGAMS = ‘Matlab’;

WSMObj.Options.MatlabOrGAMS

Ans = ‘Matlab’
```

The reason that WSMObj also changed is that setting, WSMObj2 = WSMObj, only made WSMObj2 a handle to the original WSMObj. Changing WSMObj2 is changing WSMObj. This makes passing arguments back from functions automatic. If you have a function F(WSMObj), no output is needed. Setting WSMObj values in the function automatically changes the WSMObj at higher levels above the function also. This needs to be remembered in the programming style to avoid overwriting information.

Function F(WSMObj)

```
WSMObj.Options.MatlabOrGAMS = ‗Matlab‘;

End
```

Using WSMObj as a means to process data is very slow computationally. The conventional method of handling this is to pass WSMObj to a function, extract the data and then pack the data back into the object if that is where the result is wanted. Never use objects in loops or your code will be very inefficient in run time.

DO NOT DO THIS

```
Function F(WSMObj,IMPACTObj)

For I = 1:NumFPU
IMPACTObj.Results.MultiplyPE(I,:) = 50 * ...
WSMObj.Results.PotentialEvapotranspiration.Data(I,:)
End

End
```

DO THIS INSTEAD

```
Function F(WSMObj,IMPACTObj)
% unpack
ETCROP = WSMObj.Results.PotentialEvapotranspiration.Data

For I = 1:NumFPU
   MultiplyPE(I,:) = 50 * ETCROP(I,:)
End
% pack
IMPACTObj.Results.MultiplyPE = MultiplyPE;

End
```

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