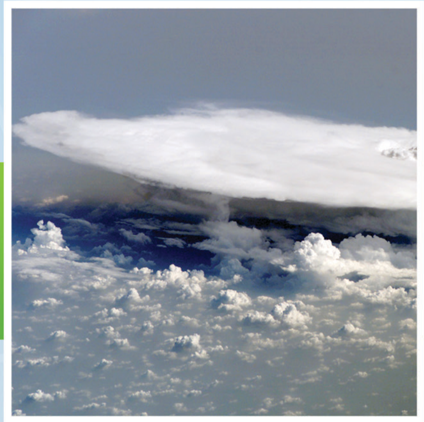
U.S. DEPARTMENT OF ENERGY | Office of Science

DOE/SC-0155

Community Modeling and Long-Term Predictions of the Integrated Water Cycle

REPORT FROM THE SEPTEMBER 2012 WORKSHOP



Preface

Water is a key component of the earth and human systems due to its strong interactions with the energy cycle and its vital roles in the energy-water-land system. Uncertainties in predicting the integrated water cycle can limit our abilities to address the energy and environmental challenges today and in the future. Modeling the integrated water cycle contributes to the Department of Energy's (DOE) core competencies in integrative modeling, drawing from unique and highly relevant research on cloud, aerosol, terrestrial ecosystem, carbon cycle, and subsurface processes, as well as climate and earth system modeling and integrated assessment modeling. Synthesizing new process knowledge and innovative computational methods in integrated models of the human-earth system can advance predictive capabilities relevant to DOE missions.

This report describes the DOE workshop on **Community Modeling and Long-Term Predictions of the Integrated Water Cycle**, held September 2012 in Washington DC. The workshop serves as a launching point and major organizing event to identify challenges and plan the development of next-generation human-earth system models for improving long-term predictions of the regional-scale integrated water cycle. More specifically, the workshop aims to:

1. identify core modeling capabilities while identifying key research gaps, with an emphasis on improving model fidelity

2. reveal relevant and critical capabilities and needs for observations, analytical frameworks, and data management that underpin the development, testing, and validation of our main models and model components

3. engage the research community in strategies for improving synthesis and integration

4. elucidate opportunities for collaborations within DOE and with other agencies and institutions that have complementary and essential expertise in specific aspects of the water cycle

5. improve understanding of the nature and characteristics of long-term scientific information requirements for DOE's energy and environmental missions and, as appropriate, for mission needs of other partner agencies.

The workshop benefited from substantial inputs provided by the broad scientific community and interagency participation. The topical and crosscutting research challenges identified at the workshop have been synthesized into three overarching Science Grand Challenges and three Integrative Modeling Experiments summarized in this report. These challenges represent remarkable opportunities for interagency collaborations to improve predictions of the integrated water cycle for significant scientific and user impacts.

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Community Modeling and Long-Term Predictions of the Integrated Water Cycle

Report from the September 2012 Workshop
Convened by

U.S. Department of Energy
Office of Science
Office of Biological and Environmental Research

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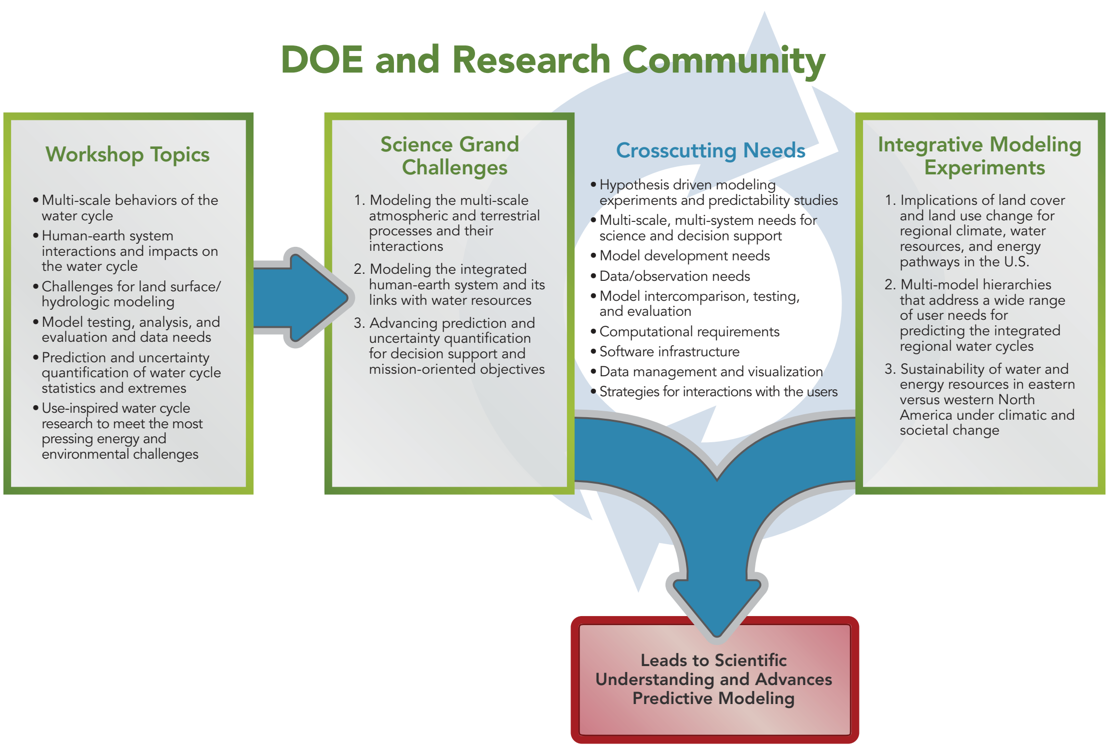
Executive Summary

Water is essential for a wide range of life-sustaining human activities and is a major component underlying a suite of important climate processes and feedbacks that affect regional and global climates. As the hydrological cycle is projected to intensify in a warmer climate, the impacts on human and natural systems will be profound, in particular those on energy production and use, land use, and ultimately, feedbacks to the climate system. Today's scientific uncertainties in predicting long-term changes in global and regional hydrologic cycles and the implications for water supplies and energy production fundamentally limit the Nation's ability to develop sustainable energy solutions.

The water cycle is influenced by human activities related to energy, water and land use. Understanding, modeling, and predicting these influences require knowledge of all components of the *integrated water cycle*, which consists of:

- storage and transport of water in various phases and forms controlled by natural processes in the earth system
- storage and transport of real and virtual water controlled by infrastructures and management of human systems.

Modeling the fully integrated water cycle is a significant scientific challenge that is well aligned with the mission of the Department of Energy's (DOE) Climate and Environmental Sciences Division (CESD): "to advance a robust predictive understanding of Earth's climate and environmental systems and to inform the development of sustainable solutions to the Nation's energy and environmental challenges." In order to identify the challenges of next-generation earth system models (ESMs) capable of skillful prediction of the regional-scale integrated water cycle from seasonal to decadal and century time scales, a workshop on **Community Modeling and Long-Term Predictions of the Integrated Water Cycle** was organized by DOE, with broad interagency and community participation, in September 2012 in Washington DC. The workshop was designed to address critical gaps in modeling long-term, climate-influenced regional water resources as well as the dynamic interdependencies among energy, water, and land systems.



The integrated water cycle is influenced by numerous processes spanning the atmosphere, land surface, ocean, sea ice, and biogeochemical cycles that interact with human systems and their multiple linkages. As a first step, the workshop focused primarily on atmospheric, terrestrial, and societal systems that more directly influence precipitation, land surface hydrology, and water management. Six topics that represent important modeling challenges were discussed:

- Multi-scale behaviors of the water cycle
- Human-earth system interactions and impacts on the water cycle
- Challenges for land surface/hydrologic modeling
- Model testing, analysis, and evaluation and data needs
- Prediction and uncertainty quantification of water cycle statistics and extremes
- Use-inspired water cycle research to meet the most pressing energy and environmental challenges.

The topical and crosscutting research challenges are synthesized into three overarching Science Grand Challenges and three Integrative Modeling Experiments described in the figure and summarized on the previous page. These challenges represent remarkable opportunities for interagency collaborations to improve predictions of the integrated water cycle for significant scientific and user impacts.

Science Grand Challenges

Predicting the evolution of the integrated water cycle is challenging because water cycle processes span a wide range of spatial and temporal scales and because the water cycle is influenced by both human and natural processes as well as their interactions. Water cycle predictions have important societal implications, so the need to provide robust and relevant science for decision making adds another layer of complexity. Workshop participants identified research gaps in the six topical areas, which are synthesized into three science grand challenges.

1. Modeling the multi-scale atmospheric and terrestrial processes and their interactions

Water cycle processes are inherently multi-scale, but current understanding of the mechanisms that determine their scaling behaviors is rudimentary. More research is needed to develop scaling theories for atmospheric and terrestrial processes to provide the basis for improving and constraining parameterizations of clouds, precipitation, runoff, and other related processes, and to provide robust metrics for evaluating model performance.

To date, there is no theory for how models should transition continuously from unresolved to resolved phenomena. There is a need to better quantify the error characteristics of water cycle simulations to understand the resolution-dependent behaviors and to develop methods for modeling multi-scale processes. These new approaches include scale-aware and stochastic parameterizations embedded in atmospheric and terrestrial models including global cloud-system-resolving atmospheric models and hyper-resolution land surface models. Global variable-resolution models can be effective testbeds for evaluating scale-aware parameterizations using observations from data-intensive regions combined with new metrics designed to highlight the multi-scale aspects of water cycle processes. High-resolution data are needed to characterize the synoptic-to-local-scale distributions of water in all its phases for model evaluation.

2. Modeling the integrated human-earth system and its links with water resources

Human systems have significantly perturbed the water cycle through water management and water use. As climate and the environment change in the future, human systems may co-evolve to adapt and mitigate the changes, so their signatures on the landscape and water cycle must be dynamically simulated as an integral part of the human-earth system. Identifying the technological and human perturbations that influence the water cycle is important for defining the building blocks to represent these complex systems in integrated models. This will require models of water management and land use that reconcile the supply and demand of water and land in the context of rapidly changing socio-economic and technological conditions. These simulations should treat the linkages among the Nation's systems for water, agriculture, and energy in coupled integrated assessment models (IAMs) and ESMs that encompass the multi-scale aspects of these complex interactive systems.

Coupled human-earth system models require new model testbeds, robust methods for evaluation, and data to support these rigorous diagnostics. One of the principal challenges is the development of definitive test cases and numerical experiments that test both the process formulations as well as the emergent properties of the simulated water cycle using a new class of metrics. Numerical experiments can also be designed to untangle the role of human versus physical perturbations in past water cycle changes to understand differences across multi-model ensembles, and to assess model uncertainty.

3. Advancing prediction and uncertainty quantification for decision support and mission-oriented objectives

Variability and changes in the integrated water cycle have important implications for resource management and infrastructure planning. Community modeling of the water cycle is faced with a challenging long-range goal to provide actionable predictions that can be used effectively to support decision making. The relative contributions to prediction skill from factors such as initial and boundary conditions, model formulation, and physics parameterizations should be quantitatively assessed in order to develop coherent strategies to advance water cycle predictions. A hierarchy of models can be used to provide insights on emergent phenomena of interest.

Understanding and quantifying uncertainty is critical to advance the utility of model predictions. Exploring different uncertainty quantification (UQ) approaches and automating these approaches in modeling testbeds can facilitate understanding and quantification of uncertainty and thereby support rational model development and sound decision making. Comprehensive metrics based on multivariate relationships and co-variations of extremes for both the physical and coupled human-earth system will be particularly useful. To facilitate feedback from users to inform model development, evaluation, and UQ, and to improve the decision relevance of model predictions and analyses, an exploratory Climate Model Use Team (CMUT) could develop and foster interdisciplinary collaborations to advance use-inspired research.

Integrative Modeling Experiments

To advance the goal of improving scientific understanding and long-term prediction of the integrated water cycle to support decision making, crosscutting research must be undertaken to develop, test, and demonstrate the usefulness of the modeling capabilities. Three integrative modeling experiments (IMEs) focusing on some key science and use-inspired questions were discussed to provide the context to build and connect different elements of crosscutting research.

1. Implications of land cover and land use change for regional climate, water resources, and energy pathways in the U.S.

Diversion of water for bioenergy crops can adversely affect the amount of water available for irrigation of food crops and for cooling of power plants. More broadly, climate change and socio-economic response to climate may alter land use and irrigation practices through different pathways. Increased frequency and/or amplitude of droughts can lead to increased irrigation investments and influence the conjunctive use of surface water and groundwater. Conversely, irrigation and land-use change can affect the variability and extreme statistics of precipitation at local and regional scales. The complex interactions among climate, land use, and water supply and demand have significant implications for future stocks of energy, water, and food. Understanding the nexus among these vital resources requires more tightly integrating and analyzing feedbacks from irrigation and land use on climate, water, and energy systems in an integrated earth system modeling framework. This requires focusing model development towards aspects either poorly represented in or entirely missing from current models. Examples of model components requiring targeted development include better parameterizations for terrestrial hydrologic and vegetation processes, hydrologic responses to land use/land cover change, the full range of crops to mimic actual agricultural diversity, and the combined effects of water diversions, groundwater pumping, aquifers, and irrigation practices. Other needed developments include capabilities for modeling institutional requirements such as water markets, reservoir operations, treaties/compacts, and environmental flows. In combination with a suite of hierarchical numerical experiments, application of observational and computational testbeds to both the individual model components and the coupled simulation systems can advance model evaluation and prediction.

2. Multi-model hierarchies that address a wide range of user needs for predicting the regional integrated water cycle

Crosscutting research is required to address a wide range of user needs for integrated water cycle predictions. Targeting key natural phenomena such as heavy precipitation associated with atmospheric rivers and high-frequency streamflow variations can help focus research to improve prediction targets and better address risk-based decisions. Since the extent to which human influence should be represented as a boundary condition or an integrated component of a given model depends on the application, developing a hierarchy of models with flexibly formulated and interchangeable components will be important to advance both our knowledge and predictions of the coupled system. Understanding the behaviors of complex models requires de-convolution of model errors at the scales of decisions versus errors at larger scales. Numerical experiments are needed to determine which uncertainties at larger scales govern most of the uncertainty at smaller scales, whether any given model hierarchy is adequate for the applications in question, particularly with respect to its fidelity to natural and human system processes, and to test the realism of the model hierarchies under historical conditions that depart significantly from climatological norms. These would facilitate much clearer communication on model controls and uncertainties, better understanding of the bounds on expectations for predictability across spatial and temporal scales, and sounder foundations for risk-based decision making.

3. Sustainability of water and energy resources in eastern versus western North America under climatic and societal changes

North America is distinguished by diverse landscapes and resources with stark contrast between the eastern and western parts of the continent. Water supplies are already stressed by water demands associated with the cooling of power plants in the East and the irrigation of crops in the West. Climate change will likely further intensify stresses to the existing infrastructures for water and energy through alterations in demands for these resources combined with changes in runoff, mean rainfall, and extreme precipitation. It remains a major unsolved problem in integrative modeling to predict the vulnerability and adaptability of the water cycle of western North America fed by high-altitude aquifers in contrast to the less orographically and seasonally variable precipitation regimes of eastern North America while simultaneously accounting for the regionally distinctive profiles of human influence. A focused effort on this problem would provide a critical test of our capabilities to model the integrated water cycle on the spatial and temporal scales that are meaningful to the Nation's regional decision makers. Existing modeling tools lack the accuracy and spatial specificity to predict regional water cycle variability and changes. They further lack the capabilities to represent the fully integrated dynamics of regional climate, water, and energy, especially with respect to managed and human-affected water and energy systems, to address the future challenges faced by resource managers.

To address the challenges of the IMEs, a set of interconnected, interoperable models describing multiple systems operating across a wide range of space and time scales is needed to determine the changes in and interactions among the water cycle, land use, and the supply and demand of energy. Predicting different aspects of the water cycle for different user needs requires strategic development of a hierarchy of model frameworks. Such a hierarchy would help maximize predictability and optimize the application of new and existing data for model calibration across the wide range of scales inherent in the water system. Computational challenges in model coupling, computing resources, and software infrastructure must also be addressed to effectively develop and utilize the models in an ensemble modeling framework to address uncertainty. Engaging the stakeholder community can provide multiple benefits when key decision makers are incorporated into the project from its inception to help ensure adoption of these new model frameworks.

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1.0 Introduction

Water is essential for energy systems, ecosystem services, and a wide range of life-sustaining and other critical human activities. It is also a major component underlying a suite of important climate processes and feedbacks, including the biogeochemical cycles that govern carbon and nitrogen exchanges, the formation of aerosols and clouds, and the feedbacks from water vapor and cloud systems that affect regional and global climates. All of these topics constitute major research thrusts within the Department of Energy's (DOE) current climate research programs. In a reversal of roles, these research thrusts can support improved predictive understanding of the water cycle and its impacts on human systems, because the natural and human systems are connected and exhibit "mutual constraints" with water in all of its phases. For example, in the western U.S., declining mountain snowpack in a warmer climate will impact the availability and timing of water supply, thereby affecting both hydropower generation and the provision of irrigation for food production. Rising water temperatures and declining water supplies can constrain the production of energy from nuclear and thermoelectric power plants because these plants require copious natural sources of fresh water for cooling.

Both observational and modeling studies have suggested an intensified hydrological cycle in a warmer climate accompanied by increasingly uneven spatial and temporal distributions of water and more frequent extremes such as floods and droughts. The impacts on human and natural systems will be both profound and marked by significant effects on energy production, land use, and feedbacks to the climate system. Currently, more than 40% of non-consumptive freshwater withdrawals from major U.S. rivers and streams are for energy production. In addition, the amount of energy required to manage the Nation's water resources is steadily increasing. For example, California devotes 20% of the state's electricity and 30% of the state's non-power plant natural gas just to managing water. As climate conditions change, regions of the country that have been largely immune from such issues will be confronted with similar challenges in what will likely be a highly dynamic regime for provision of water resources. Ultimately, today's scientific uncertainties in predicting long-term changes in global and regional hydrologic cycles, and implications for both surface and subsurface water supplies, fundamentally limit the Nation's ability to develop sustainable energy solutions.

At the global scale, precipitation change is determined by the change in total water vapor and its effect on the energy balance through the water vapor feedback (Stephens and Hu 2010). To the extent that the total water vapor change is predictable from the Clausius-Clapeyron relationship, the global increase of precipitation is a robust signal of greenhouse warming. However, predicting changes to the regional hydrologic cycle is a daunting scientific challenge. The water cycle is influenced by many multi-scale processes including clouds, precipitation, soil moisture, runoff, vegetation, subsurface phenomena, storms, and other weather patterns. The fact that these processes are tightly coupled and evolving with the changing climate means that reliable prediction of the water cycle is an intrinsically difficult problem. Even at the global scale, water cycle budgets simulated by climate models are strongly dependent on model formulation and resolution (Figure 1).

The issues at regional scales are compounded by the fact that changes in regional precipitation are primarily controlled by future changes in circulation patterns that remain highly uncertain. Climate models also display significant biases in simulating the character of precipitation due to current approaches for parameterizing precipitation processes (Stephens et al. 2010). Uncertainties in modeling terrestrial processes and land-atmosphere interactions (Dirmeyer et al. 2006) can further limit skillful simulations of the water cycle. Therefore, projecting future precipitation and hydrologic changes at the basin scale remains a significant challenge.

In addition to these challenges, human activities related to energy, water, and land use have had ubiquitous impacts on the water cycle, and it is likely that these alterations will increase in magnitude and complexity due to climatic and socio-economic drivers. In the U.S. alone, approximately one year's mean runoff from across the Nation is stored behind roughly 75,000 dams (Graf 1999). With only 2% of the rivers running unimpeded, both the amount and timing of streamflow have been significantly impacted by these impoundments (Gleick 2003). As the human and earth systems interact, both the variability of and changes in the water cycle will be dependent on the co-evolution of these coupled systems. More

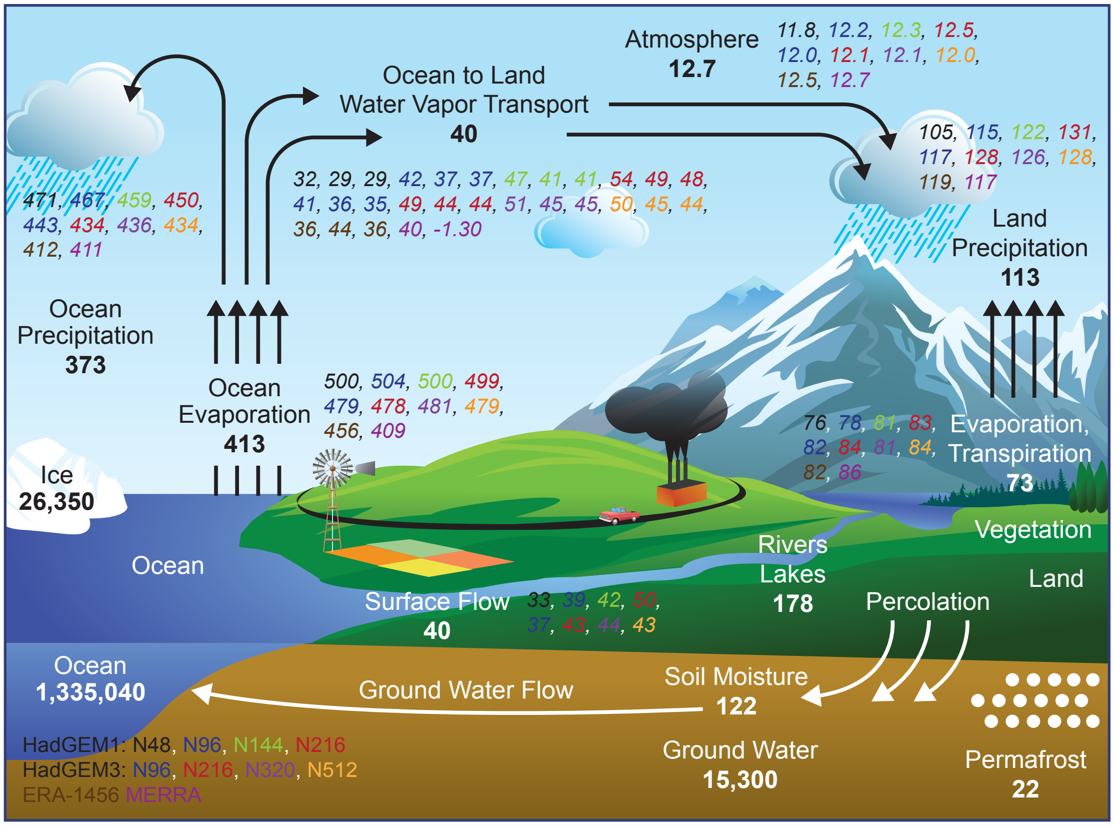

Figure 1. Large differences are found in global water budgets simulated by two versions of a state-of-the-art atmospheric general circulation model (HadGEM1 and HadGEM3) from low resolution (N48) to high resolution (N512). N48 and N512 roughly correspond to grid spacing of 280 kilometers and 25 kilometers, respectively. The image and background with the reanalyses values are from Trenberth et al. (2007, 2011) for 2002–2008, while model values inside the rectangular boxes are from 1979–2002. (Adapted from Milton et al. 2012 and Demory et al. 2012.)

holistically, understanding, modeling, and predicting the water cycle require knowledge of all components of the integrated water cycle. This cycle consists of storage and transport of water in various phases and forms controlled by natural processes in the earth system, and it also includes the storage and transport of real and virtual water controlled by infrastructures and human management systems.

There are significant gaps in representing the impacts of human systems on water cycle processes in ESMs. While some ESMs are beginning to represent irrigation and its impacts on water budgets, water resource management is generally not included. Consequently, the two-way interactions between human and earth systems that directly influence the integrated water cycle are largely omitted from ESM simulations. Groundwater is generally ignored or crudely represented in land surface models, and therefore its influence on surface and subsurface soil moisture and evaporation cannot be dynamically simulated. This also limits our ability to represent groundwater withdrawal from the managed water systems that serve as major sources for water supplies in many regions worldwide. Water demands for applications besides irrigation are also generally not represented in ESMs. The challenges to developing integrated ESMs that represent both human and natural processes are formidable, because the numerous processes and their interactions that must be included span a wide range of scales and complexities. As a result, the predictability of the coupled systems is much less well understood compared to that of the natural system alone.

Water and energy are closely related and mutually constrained, as schematically depicted in Figure 2. In the natural system, the energy cycle and water cycle

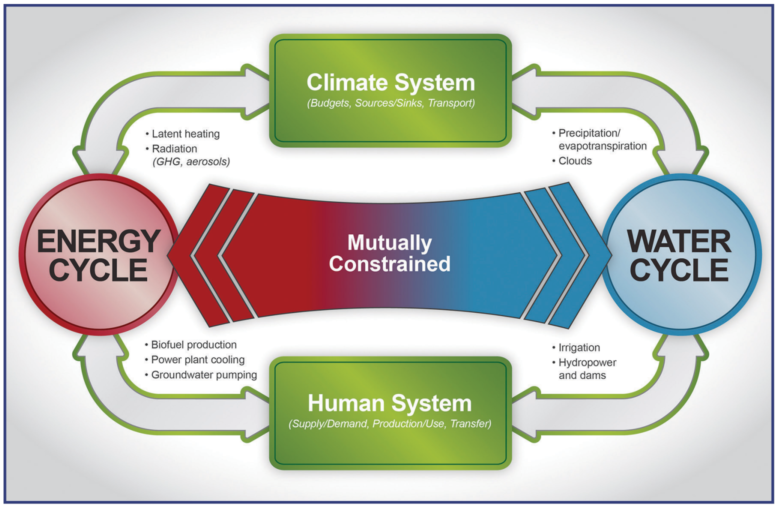

Figure 2. A schematic of the energy cycle and water cycle and their mutual constraints through various natural processes and human system interactions.

are quantified using a combination of empirically and computationally derived budgets, sources and sinks, and transport fluxes. These quantities for energy and water are mutually constrained, because evapotranspiration at the surface is largely balanced by the net surface radiation. Latent heat released from cloud formation is an important source of diabatic heating that drives atmospheric circulation, and the resulting convergence of water vapor flux can provide moist atmospheric conditions conducive for production of precipitation. The precipitation is partitioned in turn between evapotranspiration (latent heat flux) and runoff.

Water and energy are also linked and mutually constrained in human systems that influence energy and water through fluctuations in supply and demand, production and use, and transfer. For example, generating hydropower requires a sufficient supply of water to produce electricity, while pumping groundwater requires a sufficient supply of electricity to irrigate crops.

A large fraction of water withdrawal is associated with thermal power plants for generation of electricity, and the production of bioenergy crops requires significant diversions and withdrawals of water for irrigation and related uses. These are all parts of the interdependent system known as the Energy-Water-Land nexus (Figure 3).

Modeling the fully integrated natural and human components of the water cycle is a significant scientific challenge that is well aligned with DOE's mission needs. The mission of DOE's Climate and Environmental Sciences Division (CESD) is to advance a robust predictive understanding of Earth's climate and environmental systems and to inform the development of sustainable solutions to the Nation's energy and environmental challenges. One of CESD's primary goals is "to synthesize new process knowledge and innovative computational methods

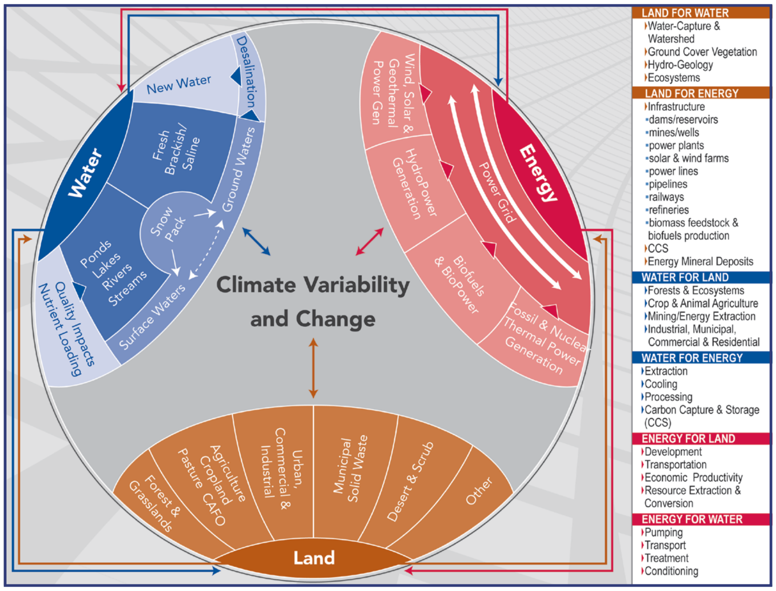

Figure 3. Illustration of the climate-Energy-Water-Land nexus showing illustrative linkages and interactions among the three resource sectors with climate variability and change. (Image from Skaggs et al. 2012.)

in the next generation of integrated models for the human-earth system in order to provide predictive capabilities over a broad range of scales relevant to DOE missions" (DOE/SC-0151. 2012). Hence, modeling the integrated water cycle contributes to the DOE core competencies in integrative modeling, drawing from unique and highly relevant research on cloud, aerosol, terrestrial ecosystem, carbon cycle, and subsurface processes, as well as climate and earth system modeling and integrated assessment modeling. It also contributes to CESD research and broader DOE multi-laboratory studies and modeling capabilities at the energy-water-land nexus, including the recent DOE-led National Climate Assessment study on this topic (Skaggs et al. 2012). As water intersects with numerous aspects of the earth system and human activities, water cycle research broadly supports the missions of many U.S. government agencies. With its crosscutting grand challenges, improving predictions of the integrated water cycle represents a unique opportunity for interagency collaborations with scientific and user impacts.

This report describes the DOE workshop on **Community Modeling and Long-Term Predictions of the Integrated Water Cycle**, held September 24–26, 2012, in Washington DC. The goal of the workshop was to identify challenges and plan the development of next-generation human-earth system models for improving long-term predictions of the *regional-scale integrated water cycle*. Leveraging DOE and DOE-collaboratively funded existing and evolving community-based modeling assets and engaging the broad communities involved in the scientific basis and model development and use, the workshop charted a path forward for synthesizing components in new and directed ways and developing essential new model features and capabilities. The workshop also delivered transformational insights into long-term, climate-influenced regional water resources and energy, water, and land systems interdependencies and dynamics. The workshop was also designed to inform the observational communities about the needs for new data that will enhance community modeling capabilities.

This report summarizes the workshop objectives and organization in Section 2. The workshop primary findings are organized around three science grand challenges and three integrative modeling experiments (IMEs) and described in Section 3 and Section 4, respectively. Section 5 summarizes the integrated water cycle challenges. White papers prepared by the workshop topic leads and co-chairs to stimulate discussion on each of the six workshop topics are included in Appendix A. The workshop agenda, topic leads, and workshop participants are listed in Appendix B. Appendix C lists the references cited throughout the report.

2.0 Workshop Objectives and Contents

The DOE workshop on **Community Modeling and Long-Term Predictions of the Integrated Water Cycle** was attended by 64 invited participants, including faculty from universities and scientists from national laboratories and research centers with expertise spanning a wide range of water cycle research. In addition, 18 invited observers from 8 U.S. government agencies with missions that intersect with the water cycle attended the workshop.

2.1 Workshop Objectives

The workshop provided a forum for the communities engaged in climate, hydrology, and integrated assessment modeling to discuss cross-disciplinary research for more robust predictions of changing regional water cycles. These changes could appreciably affect the development and management of energy and water resources in response to an evolving climate. The workshop objectives were to:

- identify core modeling capabilities while identifying key research gaps with an emphasis on improving model fidelity
- reveal relevant and critical observational research, analytical capabilities and requirements, and new paradigms for data management to accelerate the development, testing, and evaluation of the major models and their components
- engage the research community in strategies for improving synthesis and integration
- elucidate opportunities for collaborations within DOE and with other agencies and institutions that have complementary and essential expertise in specific aspects of the water cycle
- improve understanding of the nature and characteristics of the long-term scientific data required to support DOE's missions in energy and the environment and, as appropriate, the missions of other partner agencies.

2.2 Workshop Organization

The workshop elicited scientific input from the community and identified a set of regional water cycle science grand challenges and potential modeling experiments in climate, hydrology, and integrated assessment. The integrated water cycle is influenced by numerous interactions among atmospheric, terrestrial, oceanic, cryospheric, and biogeochemical mechanisms as well as human systems and their multiple linkages. While research on all these processes is critically important to understanding the water cycle, this initial workshop focused primarily on modeling and analysis of the atmospheric, terrestrial, and human systems that directly influence precipitation, land surface hydrology, and water management. In consultation with members of the science community and organizers of the workshop, DOE advanced a workshop agenda and planning around six major thematic topics identified in Figure 4, that includes a conceptual view of the relationship among these topics.

In addition, a set of scientific questions were identified for each topic and are listed in Six Major Topics and Associated Questions that Set the Stage for the Workshop and Its Focus.

Finally, in preparation for the workshop, topic leads were identified and in consultation with the workshop co-chairs, prepared white papers on the topics that addressed questions, current status, research gaps, and future needs. These white papers were used to stimulate discussion to improve workshop efficiency and contribute to more organized and insightful discussions. They served as entry points rather than constraints to the discussions and were ultimately updated to reflect the workshop outcomes and included in Appendix A.

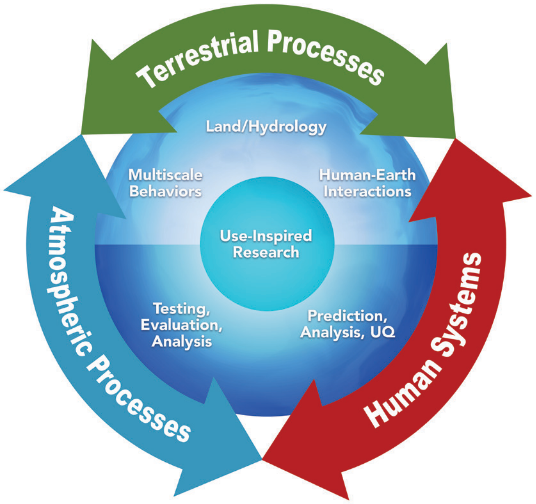

Figure 4. A schematic showing the interactions among atmospheric processes, terrestrial processes, and human systems, and the six topics for discussion at the workshop.

Six Major Topics and Associated Questions that Set the Stage for the Workshop and Its Focus

1. Multi-scale behaviors of the water cycle:

- What are the multi-scale characteristics of the water cycle for the atmospheric and terrestrial systems and the coupled system?
- What are the key multi-scale modeling needs of the community to enable better prediction of water across the complete human-Earth system at regional to global scales?
- What modeling approaches can address the multi-scale challenges of the water cycle? What are their advantages and limitations?
- What are the implications of multi-scale behaviors on modeling water cycle extremes?
- What are the computational and observational requirements for each approach?
- Which case studies or regions are particularly suitable for focused model development and evaluation efforts?

2. Human-Earth system interactions and impacts on the water cycle:

- How vulnerable is the water cycle to human activities? How might human activities trigger transition in hydrologic regimes and what might be the effects?

- What are the key interactions between the human and Earth systems relevant to the water cycle? What processes influence the dynamics of regime transition?
- How might human-Earth system interactions and dynamics influence water cycle extremes such as floods and droughts?
- What are the sources of predictability and uncertainty of the human-Earth system and energy-water-land system interaction?
- What are the priorities in modeling human-Earth system interactions relevant to water?
- Which case studies would help focus model development and evaluation efforts?

3. Challenges for land surface/hydrologic modeling:

- What are the current approaches to and differences among land surface/hydrologic modeling?
- Can land surface/hydrologic modeling address the challenges discussed in (1) and (2)? If not, what are the priorities for future development?
- What are the challenges in using land surface/hydrologic models to understand and characterize the evolution of the terrestrial system in the past?
- How can modeling testbeds facilitate advances in land surface/hydrologic modeling? What are the scientific and technical requirements of the testbeds?

4. Model testing, analysis, and evaluation and data needs:

- How can iterative testing (e.g., through model testbeds) of community models be designed for a robust understanding of model behavior across scales and across the natural and human systems?
- What are the key limitations in current approaches to testing and evaluation of multi-scale models of the water cycle?
- What are the key limitations in current approaches to testing and evaluation of integrative human-Earth system models?
- What synergistic approaches to measurement and modeling can take advantage of modeling testbeds?
- What are the requirements of a data system to facilitate modeling and measurement?
- Which case studies/sites could accelerate focused synergistic modeling and observation activities?

5. Prediction, analysis, and UQ of water cycle mean and extremes:

- What are the skills of current models in predicting characteristics of the regional water cycle including its extremes?
- What are the critical missing capabilities or components in current modeling systems for predicting regional water cycle variability, change, and extremes?
- What improvements can be gained by quantitative assessment of uncertainty in the predictions? What methods are more suited to the particular challenges of the water cycle problem?
- What tools can facilitate integrative research in prediction, analysis, and UQ?

6. Use-inspired water cycle research to meet the most pressing energy and environmental challenges:

- What decisions related to infrastructure planning and management of the energy and water systems are most influenced by water cycle mean and extremes?
- What water cycle information is needed to support relevant decision making?
- What are the modeling, observation, and data system requirements to improve the quality and usage of the relevant water cycle information?
- How does uncertainty in water cycle predictions influence the relevant decision making? What research is needed to characterize and communicate the uncertainty?
- Which case studies/demonstrations could best highlight current capabilities and gaps in linking water cycle research with energy and environmental challenges?

As the workshop progressed, the participants analyzed the six major topics and corresponding white papers and consolidated their thoughts around three science grand challenges discussed in detail in Section 3. Additionally, the participants were charged to identify separate *integrative modeling experiments* (IMEs), described in Section 4, that could serve as foci for channeling progress on crosscutting elements and to robustly test and advance modeling capabilities in a defined application environment.

Summarizing these various work products, Figure 5 illustrates the evolution and flow from the six topical white papers, through the Science Grand Challenges and, ultimately, the Integrated Modeling Experiments presented in Sections 3.0 and 4.0, respectively.

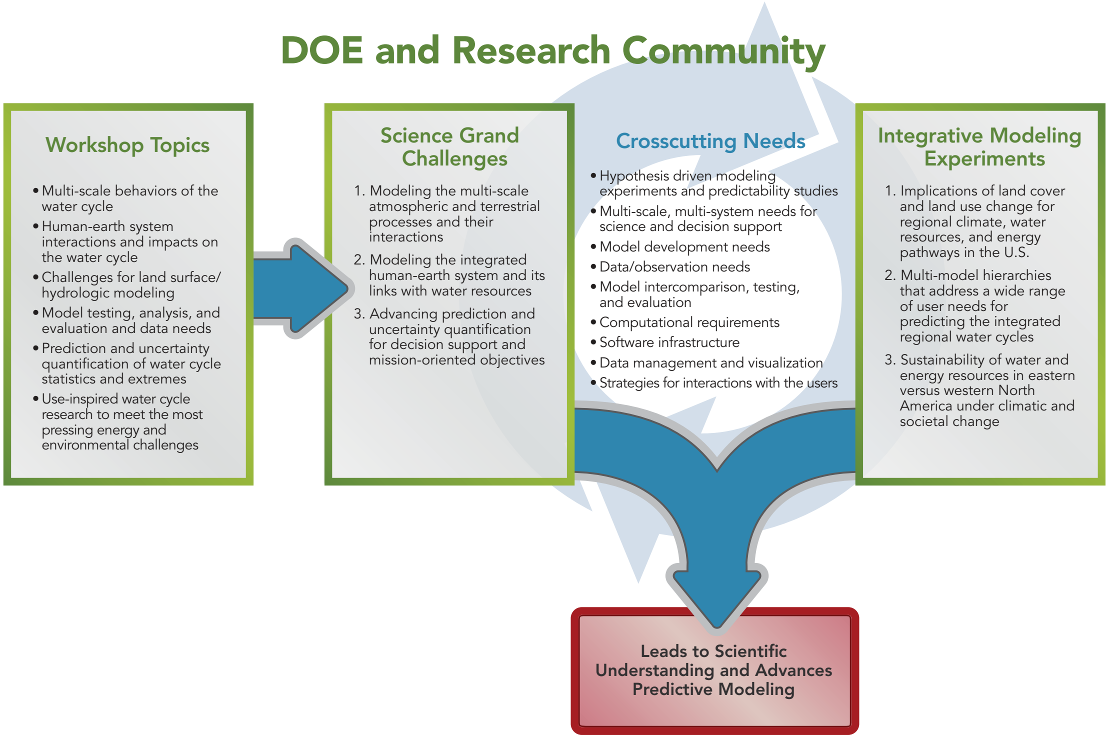

Figure 5. The workshop breakout sessions were organized by workshop topics and crosscutting research needs, leading to research priorities described in the Science Grand Challenges and Integrated Modeling Experiments that advance scientific understanding and predictive modeling.

The exact chronology and format of the workshop is summarized as follows:

- Two topic leads were assigned for each topic and were charged to prepare a white paper to be posted on the workshop website about two weeks before the workshop. The white papers discuss the scientific challenges, current gaps and limitations, and research needs in the future.
- Workshop participants were asked to read the white papers and provide comments before the workshop.
- At the workshop, the topic leads gave a short presentation about the white papers, led the discussion of the six topical breakout sessions, and summarized the outcomes from these breakout discussions during subsequent plenary sessions.
- The topic leads also led the discussion at the crosscutting breakout sessions to discuss the IMEs that cut across all six topics of the workshop.
- On each day, the workshop included plenary sessions in the morning in which the workshop sponsors and organizers presented the background, motivation, and organization of the workshop.
- Subsequently, keynote speakers discussed scientific aspects of the workshop topics, and the topic leads presented their topical white papers and reported back from the topical and crosscutting breakout discussions.
- During the afternoon of the first and second days, the workshop participants joined one of six topical breakout sessions to which they were pre-assigned in order to participate in discussions of topical science challenges and to identify key research directions. A few workshop participants were also invited to give short presentations based on their research to stimulate discussions of the topics.
- On the first and second days, the workshop participants also joined one of three crosscutting breakout sessions to which they were pre-assigned to participate in the development of IMEs.
- During the plenary session on the last day, the workshop chair presented the science grand challenges and IMEs distilled and synthesized from the topical and crosscutting breakout sessions.

2.3 Interagency Participation and Coordination

To conclude, the workshop representatives from each of the eight U.S. government agencies, with missions that intersect with the water cycle, participated in a panel to discuss the implications of the workshop findings for their agencies. The agency panel was made up of one representative from each of eight U.S. government agencies including DOE, the National Aeronautic and Space Administration (NASA), the National Oceanic and Atmospheric Administration

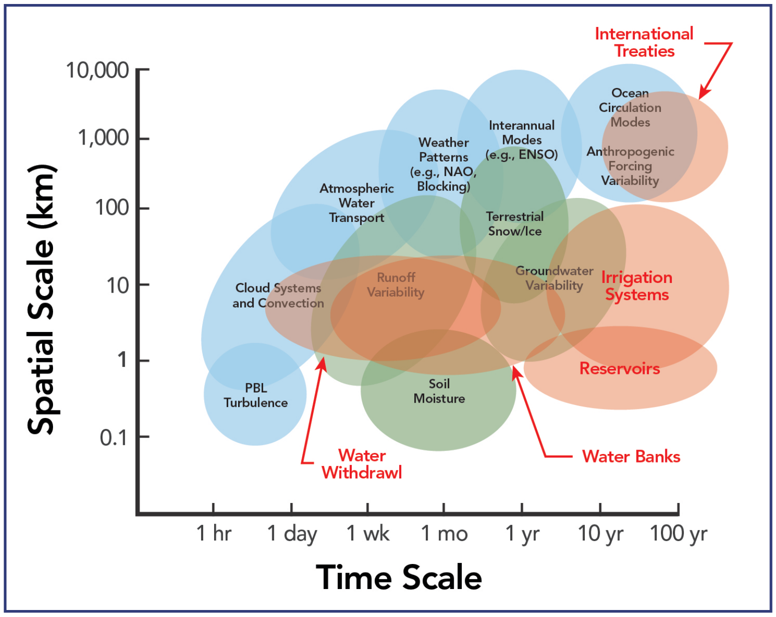

Figure 6. A schematic showing the characteristic space-time scales of atmospheric processes, terrestrial processes, and human systems in the integrated water cycle. These processes span a continuum of scales in both space and time, with significant overlaps among the processes of the three systems.

(NOAA), the National Science Foundation (NSF), the U.S. Geological Survey (USGS), the Department of Agriculture (USDA), the Environmental Protection Agency (EPA), and the U.S. Army Corps of Engineers (USACE). Each panel member was called upon to provide a short summary of insights that address the following specific points to help synthesize final thoughts on the workshop and opportunities for moving forward:

- What science needs/opportunities resonated with you most strongly and why?
- Which of the specific ideas for integrative modeling challenges did you find most appealing and why?
- Where do you see potential opportunities for your agency to engage and what strengths might you bring to a more integrated framework for cross-agency predictive capability?

The agency representatives briefly introduced their research programs related to water cycle research, reflected on the ideas and topics of the workshop that they found interesting and compelling, and identified potential areas for interagency research collaboration related to the major workshop foci and outcomes. They also responded to questions from the audience in moderated discussions. There appeared widespread agency support for the identified research needs and opportunities framed by the science grand challenges and IMEs. The agency representatives addressed specific aspects of the challenges that are critical to their programs, noting the importance of water cycle research and robust modeling capabilities in addressing their missions. Opportunities to leverage activities from existing programs to advance the workshop outcomes were also discussed as well as general enthusiasm for agency collaborations that could move the ideas forward.

3.0 Science Grand Challenges

With significant work completed leading into the workshop, including topics, critical questions related to these topics, and associated white papers, the workshop participants explored these issues through detailed plenary and breakout sessions. Emerging from these discussions were three major scientific challenges, termed grand challenges. The science grand challenges, identified in this section, embody core elements of the six topics but synthesize them around complex, multi-disciplinary issues with significant implications for system understanding, predictability, and utility. The workshop participants believed that this was a necessary step toward synthesis that not only provided a conceptual framing that crosscut the topics but that would contribute to effective planning and team formulation for addressing the major research questions.

Science Grand Challenges

- Modeling the Multi-Scale Atmospheric and Terrestrial Processes and Their Interactions
- Modeling the Integrated Human-Earth System and Its Links with Water Resources
- Advancing Prediction and Uncertainty Quantification for Decision Support and Mission-Oriented Objectives

Predicting the evolution of the integrated water cycle is challenging because water cycle processes span a wide range of spatial and temporal scales. In addition, both human and natural processes, as well as their interactions, influence the water cycle. Because of the wide range and continuum of space/time scales (Figure 6), modeling multi-scale water cycle processes represents a significant challenge. There is also an emerging requirement to model the dynamics of human-Earth system interactions within the same simulation framework in order to predict the variability and changes in the integrated water cycles. Because such predictions have important implications for the development of sustainable solutions for water and energy, the need to provide robust information relevant for decision making adds another layer of complexity and challenge.

While the ultimate scientific solutions to these issues are not immediately clear, the growing need for measures to mitigate risks to energy and water supplies dictates that the community create both satisfactory interim and more optimum long-range solutions. Although exceptionally challenging, there are strong foundations of ongoing research that present opportunities. Leveraging these opportunities could yield significant benefits for the scientific and user communities.

The approaches envisioned by the workshop participants include advancing fundamental understanding of the nature of these problems, developing new methods to advance modeling capabilities and predictions, rigorous testing and evaluation of the methods and models, and formulating the data requirements to enable the scientific endeavors. Developing teams of model developers, process modelers, and data analysis and observational scientists using team approaches could be key to accelerating model development and analysis. Similarly, developing teams of modelers, users, and stakeholders could be critical to advancing team approaches to use-inspired research, and establishing forums to facilitate regular exchanges across teams would aid in addressing the grand challenges.

3.1 Science Grand Challenge 1: Modeling the Multi-Scale Atmospheric and Terrestrial Processes and Their Interactions

Relevant Topical Research Gaps and Needs:

- Develop a strategy to systematically characterize model behaviors with increasing resolution and assess scale dependence of model parameterizations.
- Increase focus on scaling issues and heterogeneity and explore novel approaches for subgrid parameterizations of atmospheric and terrestrial processes.
- Promote research on the multi-scale interactions in the coupled land atmosphere ocean system.
- Further develop a new class of very high-resolution earth system models to explore key aspects of the water cycle.
- Identify key questions for models to address and use hypothesis testing to determine the underlying reasons for complex model behaviors.
- Develop strategies for targeted observations of precipitating systems, especially deep convection over land regions.
- Identify regions for focused model development and evaluation efforts.
- Develop team approaches that foster cross-disciplinary engagement and activities focused upon specific problems.

Refer to Appendix A.1, A.2, and A.4 for more detailed discussion of these topics.

Water cycle processes are inherently multi-scale, as they span a wide range of spatial and temporal scales. Due to nonlinearity, processes at one scale can interact significantly with those operating at another scale. Because there is no clear separation of scales among the critical emergent phenomena, models of the water cycle must cover a broad range of scales. Through scale interactions involving forward and inverse cascades, errors in representing the small scales will necessarily influence the fidelity of the large scales, and vice versa. Our current difficulties in faithfully emulating the multi-scale processes in the atmospheric and terrestrial systems in our existing models severely limits the reliability of the resulting predictions for the future evolution of the integrated water cycle. To meet this grand challenge, significant advances must be made in understanding the multi-scale processes, representing them in models, and evaluating and confronting the models with multi-scale observational data. The key challenges in each area and the research needs are discussed briefly in the sections below.

3.1.1 Understanding the Scaling and Scale Interactions of Atmospheric and Terrestrial Processes

Precipitation and streamflow are of primary importance to the water cycle in the coupled human-Earth systems.

In the atmospheric system, atmospheric dynamics and turbulence can dominate the scaling characteristics of the fluid motions and thermodynamics. Potential temperature and winds obey power law scaling in space combined with a scale-break in scaling regimes at a few hundred kilometers (Nastrom and Gage 1985) that may be related to the damping of gravity waves. From in situ and remote sensing data, specific humidity (Kahn and Teixeira 2009, Pressel and Collins 2011), cloud size (Wood and Field 2011), and rain rate (Wilcox and Ramanathan 2001) also display spatial variability that is governed by power law scaling. As discussed by Wilcox and Ramanathan (2001), rain cells larger than 10^5 km^2 make up less than 2% of the rain cell population, but they contribute more than 70% of the latent heating that drives atmospheric circulation. Similarly, clouds smaller than 10^3 km^2 in size have a 5% chance of producing rain, far less than the roughly 90% chance for clouds comparable to 10^6 km^2. Hence, these scaling properties can be reflected in the statistical characteristics of precipitation such as frequency and intensity. In climate models these statistics are often significantly biased (Stephens et al. 2010) and are highly sensitive to uncertain component parameterizations (Donner et al. 2011). These biases and uncertainties lead directly to systematic errors in simulated soil moisture and streamflow.

Some land surface processes are also found to obey certain scaling laws. For example, peak discharges for individual rainfall-runoff events are shown to scale with the drainage area according to power laws for idealized self-similar channel networks where the power law slope is a function of the scale-invariant Peano network geometry (Gupta et al. 1996). The same scaling law also applies for the peak discharges in observed individual rainfall-runoff events (Ogden and Dawdy 2003) and annual peak discharges (Gupta et al. 2010) in real river basins. However, some challenges remain in predicting the observed scaling slope and intercept for basins of different sizes with different rainfall space-time structures. Under global warming when rainfall characteristics (e.g., intensity and duration) may change, the scaling parameters may also change, although the power law scaling is expected to hold as long as the river networks are self-similar (Gupta et al. 2010).

In the context of precipitation and streamflow, the mechanisms governing how atmospheric and terrestrial processes at different scales interact and how such interactions are modulated by the spatial scales of landscape properties may be particularly relevant to the intrinsic predictability of the coupled atmosphere-terrestrial systems. For example, since surface fluxes play an important role in the development of convection, the appreciable modulation of these fluxes by land surface processes and landscape heterogeneity can affect the spatial organization of convection. Observations confirm that the cloud-system to mesoscale organization of convective clouds is influenced both by the evolving large-scale circulation and the underlying topography. Precipitation generated by convective clouds can in turn influence land surface processes that regulate significant terrestrial feedbacks to the atmosphere. The tight coupling among these processes across scales (Giovannetone and Barros 2009) is an important factor in determining both the life cycle of clouds and surface hydrology for each event as well as the cumulative and upscaled effects across the entire coupled system. Hence, scaling properties and scale interactions have important implications for the temporal and spatial characteristics of precipitation and runoff, the partitioning of runoff between the surface and subsurface component, the amount of moisture stored in the soil column, and the remaining fraction transferred to groundwater reserves.

Despite the prevalence of scaling behaviors in water cycle processes, our understanding is incomplete regarding the dynamics that control which fields exhibit scaling, which values of exponents appear in the power scaling laws, and whether multiple scaling regimes separated by scale breaks are present. Understanding and developing the theories behind the scaling of various water cycle processes is important to advancing our understanding of the processes that control the spatial/temporal variability and the interactions across scales, and how the scaling may change in the future under different climate and/or land-use regimes. This information would serve as a foundation for improving and constraining parameterizations of clouds, precipitation, and runoff through quantitative evaluation of the resulting simulated scaling behavior. In principle, this information could also prove useful in improving the simulation of processes strongly influenced by inhomogeneities in hydrological fields, such as the heterogeneous chemical formation and subsequent scavenging of hydrophilic aerosols by cloud and precipitating systems and sediment discharge in river networks.

Since scaling properties reflect the fundamental nature of different processes, they can also be used to provide robust metrics for evaluating model performance. More research is therefore needed to develop scaling theories for atmospheric and terrestrial processes and to understand the interactions between small-scale and large-scale phenomena for robust predictions of water cycle variability and changes at all scales. Looking beyond the atmosphere/terrestrial science disciplines for knowledge about other multi-scale systems and mathematical/physical theories and tools that are used to study them could advance fundamental understanding and accelerate scientific progress.

3.1.2 Representing the Multi-Scale Processes and the Interactions Across Systems in Earth System Models

Although water cycle processes vary continuously across scales, dynamically and physically based models of the atmosphere and land are based on computational models that numerically solve the basic governing equations discretized in space and time. With advances in computational methods and resources, it is now feasible to run global models at relatively high spatial resolution (Bacmeister et al. 2012, Gall et al. 2011),

Figure 7. Images of clouds. Left: Geostationary Operational Environmental Satellites (GOES) image of low clouds over the tropical Pacific on April 1, 2010; Middle: photograph of trade cumuli in Antigua in January 2005; Right: Moderate Resolution Imaging Spectroradiometer (MODIS) image of midlatitude cyclones off the west coast of the United States. Images courtesy of Rob Wood, University of Washington, and Bjorn Stevens, Max Planck Institute.

From Cloud Scaling to Cloud Modeling

Clouds are an integral part of the climate system. Through their influence on radiation, atmospheric heating/moistening, and precipitation, clouds regulate the global and regional water and energy cycles of the Earth system. Cloud sizes span over four orders of magnitude and exhibit power law scaling behavior. Understanding the origins of the power law scalings that determine the contributions of different cloud sizes to cloud cover, cloud optical properties, and precipitation is fundamental to modeling cloud processes and their thermodynamical influences. Advances in satellite missions have provided valuable data for studying cloud and precipitation scaling over a wider range of scales than is possible with aircraft or ground-based data. These advances have enabled simple physical models such as the fractal cascade model to be tested for representing cloud scaling (Wood and Field 2011).

Recent advances have been made in stochastic physical parameterizations of convection. These methods address the limitations of the convective quasi-equilibrium closures that form the basis of deterministic convection schemes. Examples of stochastic parameterizations include adding random perturbations to deterministic convection schemes (e.g., Buizza et al. 1999, Lin and Neelin 2003, Teixeira and Reynolds 2008), adding stochastic forcing to the streamfunctions resolved by the dynamics (Berner et al. 2005), and coupling a stochastic model into a classical deterministic model (e.g., Majda and Khouider 2002). Continued developments using observations to constrain convective parameterizations and advancing theory of non-equilibrium critical systems (Neelin et al. 2012) are promising directions to close the gap in understanding the physics behind cloud and precipitation scaling and using the information to develop or constrain parameterizations for climate models.

and global variable-resolution models formulated for unstructured grids are useful frameworks that enable local refinement for multi-scale modeling (Ringler et al. 2011). Despite the trend for increasing model resolution regionally or globally, processes such as eddy diffusion that cannot be explicitly resolved by the computational grids must still be parameterized to represent their influence at the grid scale.

To date, there is no theory for how models should transition continuously from unresolved to resolved phenomena. Subgrid parameterizations that invoke certain assumptions are limited in their applicability, with no clear arguments for why the solutions would vary monotonically or converge with increasing model resolution. Parameterizations of subgrid convection fall squarely in this category because a common assumption for the grid size "to be large enough to contain an ensemble of cumulus clouds but small enough to cover a fraction of a large-scale disturbance" is often violated in climate models (Arakawa 2004). An important step to addressing the challenge of multi-scale modeling is to better quantify the error characteristics of cloud and precipitation simulations as a function of scale to improve understanding of the resolution-dependence behaviors.

Hyper-resolution Hydrologic Modeling

The ubiquity of spatial heterogeneity in topography, soils, vegetation, and land use is a major driver of hydrological dynamics in river basins. By controlling surface and subsurface water movement, land surface heterogeneity introduces spatial variability in soil moisture with regional and global impacts on runoff generation, biogeochemical cycling, and land-atmosphere interactions, with regional and global implications. High-resolution modeling would enable better representation of land surface heterogeneity and its effects. In addition, uncertainty introduced by scaling process understanding at the meter scale to the scale of hydrologic and land surface models can be reduced when the models are applied at higher resolution. Wood et al. (2011) presented the needs and challenges for land surface modeling at hyper-resolution, which is defined as *O*(1km) at global scales and *O*(100m) at continental scales.

The impacts of resolving spatial heterogeneity in predicting soil moisture are demonstrated by Roundy et al. (2011) over a small watershed. Figure 8 shows the spatial variability of soil moisture simulated by a land surface model in a sequence of numerical experiments in which increasing spatial heterogeneities associated with precipitation, topography, and soil properties are added one at a time as inputs to the model. By enabling spatial heterogeneity to be explicitly included, high-resolution models can achieve much better skill in predicting the spatial variability of soil moisture with potentially beneficial effects on the fidelity of the runoff and evapotranspiration simulated by the model. Hyper-resolution modeling would also facilitate representations of fine-scale human activities such as reservoir operation, irrigation, urbanization, and the effects of these activities on the water cycle. Advances in satellite measurements and methods to integrate heterogeneous sources of data, together with progress in computing infrastructure and software, provide opportunities for meeting the challenge.

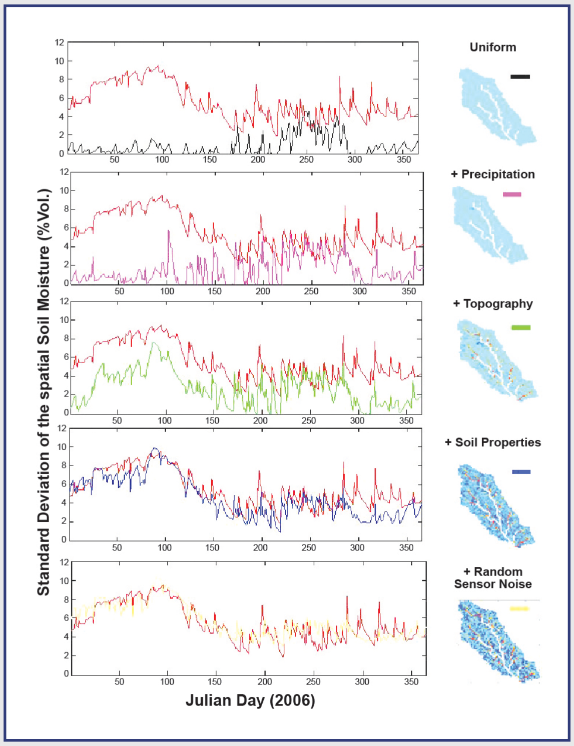

Figure 8. Time series of the spatial variability of soil moisture simulated by a high-resolution land surface model for a watershed shown on the right. Simulations with spatial heterogeneity of precipitation (magenta), topography (green), and soil properties (blue) added sequentially increasingly capture the observed (red) soil moisture variability better compared to the simulation that used spatially uniform inputs (black). Random noise from the soil moisture sensor probe (yellow) accounts for some remaining variability not captured by the effects of spatial heterogeneity.

For terrestrial modeling, subgrid variability of landscape and soil heterogeneity as well as atmospheric forcing can contribute significantly to variability of runoff, so they must be explicitly resolved or parameterized in some ways. Furthermore, some inherent assumptions used in parameterizations are also only valid across a specific range of scales. Therefore, assessing the spatial/temporal scales needed to simulate basin scale water budgets is also an important step towards understanding model response to changes in resolution. Such investigations should take advantage of methodological advances made in generating ultra-high-resolution atmospheric forcing (e.g., statistical methods to combine spatial and point measurements from radar and rain gauges) and land surface parameters (e.g., use of pedotransfer functions to calculate hydraulic properties) to quantify improvements that can be gained by ultra-high-resolution modeling.

Besides characterizing model dependence on resolution, research must be undertaken to improve methods for modeling of multi-scale processes. The scientific community has begun exploring different approaches, including improving subgrid parameterizations of clouds for more scale-awareness to reduce their resolution dependence and developing multi-scale modeling framework (MMF), also known as the "superparameterization" approach (Grabowski 2001, Khairoutdinov et al. 2005, Randall et al. 2003). In the former, different approaches to unify representations of shallow and deep convection (e.g., Park 2012) and unify eddy diffusion and mass flux representations, and introduce stochastic components (e.g., Suselj et al. 2012) have been explored. In the latter, a two-dimensional cloud-resolving model is embedded within each atmospheric model grid cell to explicitly simulate cloud and convection, with feedbacks to the larger scales.

In land surface modeling, improving the spatial structure by using catchment or sub-basin as computational units (e.g., Koster et al. 2000, Goteti et al. 2008, Li et al. 2011), enhancing the subgrid classification of land surface heterogeneity (e.g., Leung and Ghan 1998, Dickinson 1994), and improving parameterizations of subgrid scale processes have been pursued. Similar to the MMF, complex high-resolution three-dimensional models of surface and subsurface flow have been coupled to land surface models to account for vertical and lateral water movement with explicit modeling of groundwater (Rihani et al. 2010).

The approaches discussed should continue to be refined and rigorously evaluated. At the same time, new approaches that bridge the advances in scaling theory and Newtonian theory for stochastic dynamical formulations should be explored (Palmer and Williams 2012; Neelin et al. 2012). Along with advances in computers and computational modeling, continued development of global cloud-resolving atmospheric models and hyper-resolution land surface models (Wood et al. 2011; Famiglietti et al. 2009) may provide long-term solutions for multi-scale modeling of the integrated water cycle.

3.1.3 Model Testbed, Evaluation, and Data Needs

The discussion in 3.1 articulates the needs to quantify the error characteristics of models as functions of model resolution to better understand the resolution dependence of the simulated water cycles. The scientific community is poised to undertake such endeavors using global variable-resolution models that can be configured to run with quasi-uniform and variable resolutions using unstructured grids. Simplified and idealized experiments can be powerful tools to diagnose the behaviors of parameterizations of complex models in a real-world setting. With hierarchically designed numerical experiments, the global variable-resolution model framework can be used effectively to assess the impacts of resolution with different physics parameterizations. As an example, the DOE Development of Frameworks for Robust Regional Climate Modeling project (*http://climatemodeling.science.energy.gov/projects/development-frameworks-robust-regional-climate-modeling*) is developing and analyzing a suite of idealized and real-world simulations from a combination of global quasi-uniform and variable-resolution models (Rauscher et al. 2012) and regional climate models (Hagos et al. 2013) to systematically assess the effects of model resolution, to identify upscaling and downscaling effects, and to detect and quantify the resulting scale interactions. A hierarchy of models of different types can also be used to address model complexity and compensating errors in the most comprehensive models. For example, a very simple water balance model that is tuned to reproduce observed hydrological variability can be used to identify errors in complex land surface models and provide targets for comprehensive land surface models to improve simulations of land-atmosphere feedbacks in ESMs.

Model testbeds are computational frameworks designed to systematically evaluate models and streamline processes for model evaluation, development, and parameter calibration. With local refinement capabilities, global variable models can be effective testbeds for multi-scale modeling to test and evaluate scale-aware parameterizations and to make use of site-specific observations from data-intensive regions. In terrestrial modeling, the benefits of hyper-resolution models can easily be masked by uncertainties in model parameters, many of which are related to land surface properties, and by systematic or random errors in the forcing data. To effectively discriminate among competing parameterizations and the effects of resolution, parameter estimation and sensitivity analysis should be included as an integral component of model evaluation frameworks and testbeds.

In the context of uncertainty, probabilistic evaluation methods can be exploited to evaluate the envelope of model behaviors. New metrics for model evaluation can be designed to focus on the multi-scale aspects of water cycle processes, including the presence and properties of scaling behaviors, scale interactions, and resolution dependencies in simulations. Additionally, metrics based on relationships among variables (e.g., cloud optical depth and radar reflectivity [Nakajima et al. 2010]) and co-evolution of multiple variables (e.g., co-evolution of surface temperature and moisture over the diurnal cycle [Santanello et al. 2009]) or the diurnal co-evolution of cloud size and rain rates are particularly useful for process-level evaluation of model behaviors.

There are significant data needs to support the development and evaluation of multi-scale models. For hyper-resolution land surface models, developing high-resolution model input data such as vegetation and land cover, soil properties including hydraulic conductivity and soil type, and bedrock depth is critically important to realize the full potential benefits of hyper-resolution. In situ and remote sensing data and development of high-resolution data using scaling and geomorphic relationships should continue to be advanced and evaluated.

High-resolution data are also needed to evaluate multi-scale models. These include high spatial and temporal resolution in situ data for critical water components such as evapotranspiration and soil moisture. This may be achieved by augmenting existing climate observation or ecosystem research networks such as the Atmospheric Radiation Measurement (ARM) Climate Research Facility, AmeriFlux, and Next Generation Ecosystem Experiments (NGEE) sites for multi-scale measurements of both atmospheric and terrestrial water cycle processes using a combination of aircraft, multiple eddy correlation sites, and soil moisture arrays (e.g., Cosmic-ray Soil Moisture Observing System [COSMOS, *http://cosmos.hwr.arizona.edu/*]) to capture the inherent variability due to non-linear dynamics.

Data integration is important for evaluating the water cycle in coupled atmosphere-terrestrial systems. Analysis and data integration products, particularly those produced by the Global Energy and Water Cycle Experiment (GEWEX) coordinated field campaigns (Sorooshian et al. 2005, Lawford et al. 2007), such as the First ISLSCP Field Experiment (FIFE) and Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), are useful to help close the regional or basin scale water budget. Despite advances in measurement capabilities and data assimilation techniques, significant uncertainties still exist in many water budget terms in analysis products, particularly in fluxes such as horizontal transport of water vapor, evapotranspiration, and streamflow.

Given the recent progress in assimilating land surface states such as assimilation of soil moisture in the North American Land Data Assimilation System (NLDAS) (Peters-Lidard et al. 2013), application and evaluation of land data assimilation systems should lead to improvements in offline and coupled analysis products. Making use of existing satellite missions (e.g., NASA GRACE [Gravity Recovery and Climate Experiment], ESA SMOS [Soil Moisture and Ocean Salinity]) and new satellite missions (e.g., NASA GPM [Global Precipitation Mission], SMAP [Soil Moisture Active-Passive]) is important to reduce uncertainty in the water budgets for model evaluation. The previous discussion echoes the three strategies discussed in the NRC 2008 report on the individual and combined use of point measurements, remote sensing, and models to provide integrated multi-scale observations of the hydrological systems.

3.2 Science Grand Challenge 2: Modeling the Integrated Human-Earth System and Its Links with Water Resources

Relevant Topical Research Gaps and Needs:

- Improve terrestrial hydrologic cycle process representation with the goal of addressing existing model biases.
- Model the human water use directly, with a particular focus on agricultural and energy uses.
- Advance modeling of the interactions among different human systems, including water management, agriculture, energy system, and urbanization at the appropriate scales.
- Improve representations of the feedbacks to the atmosphere from land surface change and energy system change.
- Model direct human impacts such as the impacts of droughts on nutrition, floods on access to potable water, sea-level rise on infrastructure, and human populations on vulnerability.
- Incorporate the coastal zone in integrated models to represent the coastal biogeochemistry and transport, besides sea-level rise.
- Assess the predictability of the water cycle for the coupled human-earth systems and uncoupled systems, and evaluate model performance.
- Develop hindcast tests for recent water cycle extremes in order to demonstrate credibility for modeling the physical and human systems.
- Use a hierarchical set of models to facilitate understanding and improvement of water cycle predictions from comprehensive models and to understand the interactions between physical models of the water cycle and models of the human systems.
- Support data synthesis and distribution and improve data accessibility for a comprehensive and extensible land model benchmarking system with an emphasis on metrics to evaluate terrestrial processes rather than forcing.

Refer to Appendix A.2, A.3, and A.4 for more detailed discussion of these topics.

Human systems have significantly perturbed the natural water cycle directly through water management and water use. Through intimate ties to water and the landscape, both the production and consumption of energy and the management and use of land have modified the natural water budgets at regional and global scales. Over the longer time periods characteristic of climatic and environmental change, human systems will co-evolve to adapt to and mitigate the causes of these changes. As a result, the interactions of these systems with the surrounding landscapes must be dynamically simulated as an integral part of the human-Earth system. This presents a grand challenge, as we have limited understanding of the co-evolution and predictability of the human and Earth systems. Models to represent such systems are only beginning to emerge. On the other hand, the opportunities to define future directions are enormous, and advances from different disciplines can be brought to bear to transform our ability to predict the integrated water cycle. The subsequent sections provide more details of the research needs identified at the workshop.

3.2.1 Understanding the Roles of Human Systems at Different Spatial and Temporal Scales in the Coupled System

A broad range of human systems can significantly perturb the water cycle at local to subcontinental spatial scales and from hourly to interannual time scales. Dams regulate about two-thirds of rivers worldwide (Abramovitz 1996), and the impoundments alter the amount and timing of streamflow to such a degree that freshwater inputs to the ocean are essentially eliminated from some river basins during long segments of the seasonal cycle. Groundwater withdrawal can lower the groundwater table (Rodell et al. 2009) and thereby affect soil moisture, evapotranspiration, regional climate (Bollasina and Nigam 2011), and sea-level rise (Pohkrel et al. 2012).

Since the beginning of the twentieth century, irrigated area has increased by more than five times worldwide (Rosegrant et al. 2002). Demands for irrigation will likely increase in the future as a result of increasing temperatures and evaporative losses combined with higher likelihoods for more frequent and intense droughts (Seager et al. 2007), and expanding agriculture and biofuel development. Irrigation can perturb the water cycle through withdrawals of water from streams and aquifers that alter their spatial and temporal variability and by enhancements to soil moisture and evapotranspiration in irrigated areas. Increased evaporation from irrigated areas and reservoirs can influence regional climate either at the irrigation sites or further downstream by altering the spatial patterns of mean and extreme precipitation, cloudiness, and temperature (Hossain et al. 2009, Sorooshian et al. 2012). Nutrient inputs from irrigation water returning to the streams can affect water quality and coastal ecosystems (Bennett et al. 2001).

Water use related to energy production and use is also significant, since water is used to cool power plants, drive hydropower generation, grow and process biomass, and mine for oil, gas, coal, and uranium. All electrical generation requires water at some stages of the production processes, including the fuel cycle, construction of the power plant equipment, and the long-term operations of the generating facilities (Macknick et al. 2012). Although only a fraction of water needed to support energy is lost to consumption or evaporation due to these processes, withdrawal of a large quantity of water from streams and aquifers can disrupt the timing and spatial distribution of streamflow. In addition, both the temperature and quality of natural aqueous systems can be adversely affected by the cycling of water through the energy production systems.

The impacts of human systems on the water cycle have been widely documented and studied. Previous research has focused more on assessing the impacts from different human activities either one at a time or with limited numbers of linkages. However, it is increasingly clear that this approach is insufficient since the dense network of interactions among human activities (e.g., a large fraction of groundwater use is related to irrigation) could be appreciably altered or reconfigured in response to climate, environmental, and socio-economical changes. Furthermore the combined effect of this network on the water cycle is unlikely to be a simple linear superposition of individual effects. Hence, the convolution of interrelated human activities and their interactions with the natural water cycle can create complexities not easily understood and can complicate attribution of anthropogenic factors. Identifying the technological and human perturbations that influence the water cycle at different temporal and spatial scales is critically important to understand the interactions between human and Earth systems. Such understanding is essential for defining the building blocks needed to represent the complex systems in integrated models. This will require extensive use of existing data and development of new data, but model sensitivity experiments can also be used to identify critical processes that must be considered.

3.2.2 Representing the Wide Range of Human-Earth System Interactions Across Scales

Given the complexity of the human-Earth systems, the task of predicting the variability and change of the integrated water cycle requires models that capture the key components of the human, natural, and socio-economic systems and their dynamic interactions across all relevant spatial and temporal scales. Because IAMs and ESMs already include many components that represent the human and natural systems, they can provide the foundations for incorporation of new building blocks needed for modeling the integrated water cycle (see the sidebar for an example of an integrated earth system model). This will be informed by the previously discussed research to identify and specify new components that need to be included in the modeling framework. These will necessarily include models of human water use, particularly uses related to agriculture and energy that constitute a large fraction of the water consumed worldwide. While models of a wide range of water uses have already been developed, in general these models are largely driven or tightly constrained by observations of current conditions. Therefore the capacities of these models to skillfully predict the response of human water systems to changes in the climate and environment, technology and management, population, and other important socio-economic drivers must be greatly improved.

To represent the interactions among human systems, and between human and natural systems, direct linkages among water, energy, and land must be developed. This will require modeling of water management and land use that reconciles the supply and demand of water and land (including the demands for food, biomass, and new crops) in the context of rapidly evolving externalities including

An Integrated Earth System Model

A first-generation integrated earth system model (iESM) is under development by a team of researchers at Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, and Oak Ridge National Laboratory to improve climate predictions and enhance scientific understanding of the human-earth system dynamics and climate impacts and adaptation opportunities (*http://climatemodeling.science.energy.gov/projects/improving-representations-human-earth-system-interactions*). The approach being taken is to bring the human system elements of Global Change Assessment Model (GCAM) within the structure of Community Earth System Model (CESM), which includes models of the atmosphere, land, ocean, and sea ice in a coupled modeling framework (Figure 9). As an IAM, GCAM describes the human-earth system including emissions of global greenhouse gases and short-lived species emissions, alterations in land use and land cover, and responses to the impacts of anthropogenic climate change.

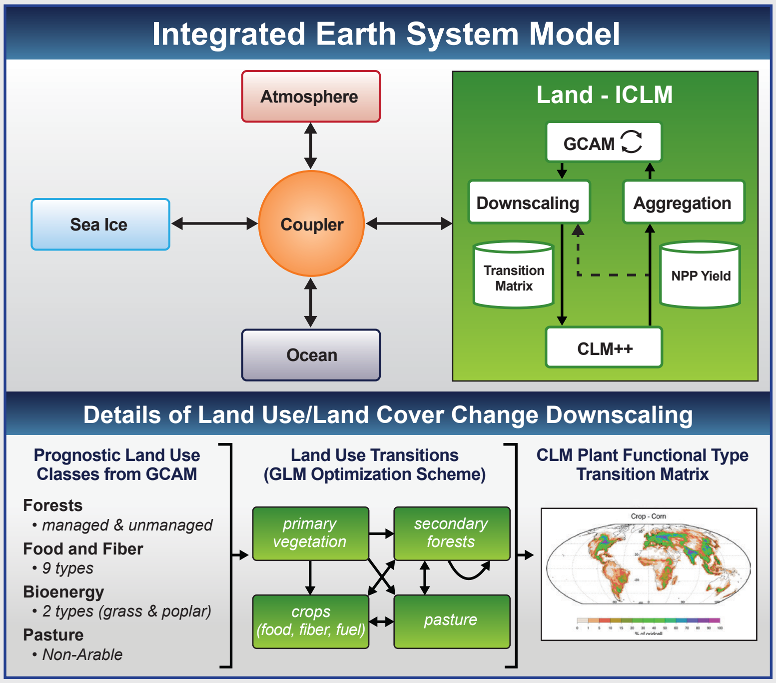

Figure 9. The structure of a first-generation integrated earth system model based on community models, with some details of how land-use/land cover information propagates from integrated assessment model to terrestrial system model.

Developing the iESM is first achieved by linking the GCAM land use allocation model to the land component of CESM—Community Land Model (CLM). In any given time period, the land-use component incorporated from GCAM begins with a set of potential terrestrial ecosystem productivity values for crops, pasture, forests, and other ecosystems. Those ecosystem potentials interact with demands for land products and services, including supplies of and demands for bioenergy from waste and from biofeedstock cultivation. The solution for general market equilibrium across energy, agriculture, and other components of the economy determines the supplies and demands for energy, agriculture, and land. GCAM also solves for emissions of greenhouse gases and short-lived species as well as the reallocation of land use and land cover required to reach the new equilibrium. Regional aggregates of these GCAM outputs are transformed via downscaling algorithms in the Global Land Model (GLM) and other CESM utilities to gridded data inputs to CLM in the coupled CESM, which in turn leads to evolving climate and surface energy and mass budgets. As the CESM integrates forward in time, land surface productivity is upscaled for incorporation into the next time step of GCAM. New linkages between CESM and GCAM are being developed to represent the integrated water cycle in which GCAM simulates water demand and CLM simulates water availability and allocation driven by water markets modeled by GCAM.

population growth, technological succession and, socio-economic transformations. Coupling IAMs and ESMs is critical to integrating models of the human and natural systems. Such research has begun, but to facilitate modeling of the integrated water cycle, new pathways that couple IAMs and ESMs must be established, and redundant or overlapping components must be reconciled or consolidated. These pathways include, for example, linking human impacts on river systems to impacts on economic and environmental viability in river estuaries and coastal zones. This will ensure that basic conservation principles are met and processes intimately tied to the water cycle are represented consistently.

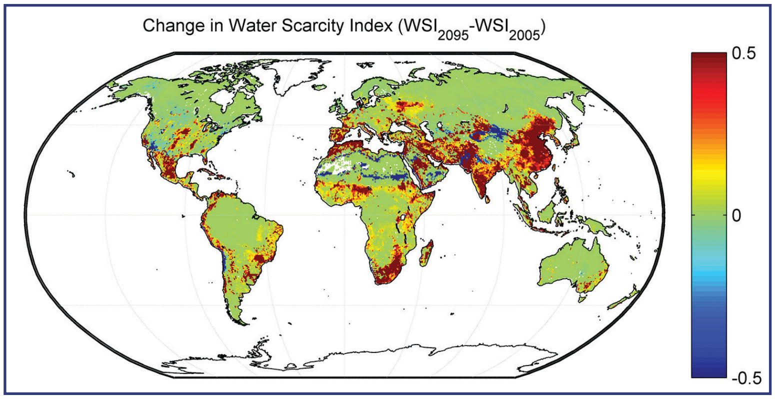

Figure 10. Change in water scarcity conditions between 2005–2095 calculated on the basis of future water availability and potential demand as reflected in a no-climate policy scenario and a single set of technology assumptions (Figure from Hejazi et al. 2013.)

Human systems are inherently local and regional in scales, but their individual and collective influences can span local to global scales through exchanges with the atmosphere, land, and ocean. The influences extend to less readily measured but equally significant transfers of water within human systems such as the virtual water trade (Oki and Kanae 2004). An important challenge for modeling the coupled human-Earth systems is addressing the multi-scale aspects introduced by human systems. Modeling approaches such as nested, global high-resolution, and variable-resolution models offer telescoping capability to the very fine resolutions where human systems and their impacts may be more realistically simulated, but the relative merits of these different approaches remain to be evaluated.

Developing a phased approach favors more tractable modeling systems to aid in understanding and analysis of model behaviors as more complexities are introduced. Maintaining a hierarchy of models with different degrees of complexities and coupling can provide opportunities for cross model evaluation and analysis and allow different fundamental and use-inspired science questions to be effectively addressed.

3.2.3 Model Testbed, Evaluation, and Data Needs

Introducing human systems to ESMs creates a very different class of models that requires new model testbeds, evaluation methodologies, and data for verification and calibration. One of the main challenges centers on developing basic test cases and numerical experiments, including hindcasting, which can be used to evaluate human system models and integrated human-Earth system models. Although experiences and lessons from model evaluation and intercomparison of IAMs and ESMs can provide some guiding principles, it should be noted that the conceptual frameworks for simulating the integrated human-Earth system will evolve, and as a result there should be significant opportunities to explore new ideas and tools for analysis and evaluation. It would be useful to develop cases for contrasting conditions such as how human systems may be vulnerable to or help mitigate extreme conditions including droughts and downpours, particularly since the conventional cases used to test the physical science in atmospheric or terrestrial models tend to ignore the role human systems have in mitigating or amplifying the response. Besides evaluating the fidelity of the models, understanding model sensitivity to model inputs, parameters, and structures should be equally important in informing model skill and uncertainty.

Taking advantage of the multi-scale model testbeds discussed above, coupled models of human and Earth systems can be introduced together with a suite of test cases and numerical experiments already standardized for systematic testing and evaluation of new parameterizations or modules. New metrics will have to be introduced to evaluate models across different modeling contexts to ensure the evaluation and cross-validation of the wide range of features of these models, including economics, consumption, damages, water and land use, reservoir storage, and regulated flows. Carefully designed numerical experiments can help address a potentially important source of "hidden" systematic model errors in coupled models caused by the compensation of errors from different components that, in combination, yield reasonable results despite potentially serious issues in the component formulations. Developing a set of dispositive metrics and accompanying falsifiable tests for these experiments within a testbed framework can help discriminate true model successes—getting the right answers for the right reasons will enhance confidence in the models used for projections. By eliminating literally unrealizable states of the climate and society caused by systematic compensating errors, this activity would also increase the utility of future scenarios that have traditionally been the predominant product of IAMs in the past and will continue to be a key application for upcoming national and international assessments.

In addition to data sets needed to model and evaluate the natural water cycle, the data requirements for modeling and evaluating models of the human systems are significant. Data regarding the types and amounts of water and energy use, for example, are relatively limited in the developing world. Even in the developed nations, data on water use may be intermittent or incomplete where water use has not been metered carefully, and institutional and disciplinary barriers may also limit data accessibility. Certain types of measurements are subject to uncertain data provenance and lack of adequate metadata that can reduce the reliability and utility of these observations. Limitations of the spatial and temporal scales of data such as temporally resolved water use data at the basin level must also be overcome. Due to these general issues regarding data adequacy, regional test cases focusing on states or countries with more comprehensive, reliable, and accessible data can be particularly useful for model testbeds and evaluation.

3.2.4 Advancing Understanding of the Role of Human-Earth Interactions in Water Cycle Changes

The long-term effects of water, energy, and land use on the water cycle are ubiquitous. At shorter time scales, management of human systems such as the operations of reservoirs can affect how the water cycle responds to seasonal and interannual variability and extremes including floods and droughts. Over longer time scales, the co-evolution of human and earth systems makes it far more challenging to understand how interactions between the human and earth systems, in particular the roles of infrastructure and management, have affected past water cycle changes. Testing the models' ability to simulate the water cycle response to human or physical perturbations is necessary if the models are to be used to improve prediction of water cycle variability, improve management of water resources, reduce vulnerability to extremes, and assess adaptation and mitigation in the context of climate and environmental changes in the future. This also elevates the issue of predictability of the integrated human-earth system, and therefore numerical experiments to advance such understanding are of fundamental importance.

Hence, an important and interesting use of integrated human-earth system models is to attribute the effects of human versus physical perturbations on past water cycle changes. In addition to demonstrating the utility of the models, attribution studies can provide useful information on missing or misrepresented processes in the models for continued improvement. Guided by observations and different types of data, cases can be selected and documented to discriminate among unforced variability or secular changes in the water cycle and human systems from interannual to decadal time scales. Numerical experiments can be designed to assess the individual and combined role of different human and physical perturbations. Model testbeds can facilitate the implementation of numerical experiments with different workflows and input and output data. Besides improving understanding of past changes, the cases can also be used in model intercomparison experiments to understand differences in model behaviors and provide a context of uncertainty.

3.3 Science Grand Challenge 3: Advancing Prediction and Uncertainty Quantification for Decision Support and Mission-Oriented Objectives

Relevant Topical Research Gaps and Needs:

- Develop a hierarchy of modeling tools with broad stakeholder engagement for policy-relevant analysis spanning global to regional issues.
- Encourage focused analysis on the climate-water-energy-food nexus, considering both the physical dynamics combined with social, cultural, and institutional aspects of allocation and demand of water, land, and energy resources.
- Further develop metrics on decision-relevant extremes and distributions with a particular focus on the co-variation of extremes.
- Better integrate the concepts of risk and uncertainty in the design of climate-resilient infrastructure and climate policy analysis.
- Advance research on uncertainty to improve the use of water cycle predictions and for communication with the user communities.
- Produce high-frequency and high-resolution water-cycle reanalysis using a model-assimilation system, and fill critical observational gaps for the physical water budget.
- Expand water cycle observations to include the evolving socio-economic systems, technologies, and human activities that produce or consume usable water.
- Promote more interaction with the user community for functional impacts.

Refer to Appendix A.2, A.5, and A.6 for more detailed discussion of these topics.

Variability and changes in the integrated water cycle have important implications for managing resources and infrastructure planning. A particular challenge for community modeling of the integrated water cycle is to provide actionable information that can be used effectively to support decision making in the context of water, energy, and land in an evolving climate. To be useful, model predictions must achieve certain levels of accuracy at the spatial and temporal scales relevant to the decision end points and must include information that can be used in an uncertainty analysis framework for decision making. Communications among modeling groups, prediction centers, and users are important to inform model development and delivery of products that meet the users' needs. This science grand challenge addresses the suitability and application of models for informing decisions and policies that broadly intersect water and energy.

3.3.1 Advancing Model Predictions

To improve the usefulness of model based water cycle predictions, increasing model resolution is generally considered important since it may improve model skill by explicitly resolving processes over a wider range of scales. Higher resolution also allows models to take advantage of more spatially resolved input data, such as land surface parameters, and to explicitly incorporate human systems that are inherently more local and regional in scale. Therefore, increasing model resolution may potentially improve accuracy and spatial specificity in model predictions so that the results can be utilized more effectively in resource management and planning. However, as discussed in the context of multi-scale modeling, the asymptotic characteristics of models in the limit of very high resolution are neither well understood nor characterized due to the non-linear interactions between physics parameterizations and model resolution. Furthermore, high-resolution model predictions at shorter lead times may derive improved skill from just the specification of high-resolution initial conditions, which reduce the error growth associated with small-scale processes and their upscaled effects, rather than from asymptotic reductions in errors associated with model formulations or parameterizations. If so, similar improvements may not be apparent in longer-term predictions where initial conditions play a more minor or negligible role.

Therefore, in the context of model predictions, there is a need for systematic explorations of the impacts of resolution and process representations and their interactions on predictions from seasonal, decadal, and century time scales. Research supported by NOAA and NASA on climate and hydrologic predictions could be leveraged to advance this goal. Quantitative evaluation of the relative contributions to prediction skill from various factors such as initial conditions, boundary conditions, model formulations, and physics parameterizations is also important for developing coherent strategies to advancing water cycle predictions at all pertinent time and space scales. Developing and maintaining a hierarchy of models that span from global to watershed or basin scales would represent a useful capability for global and regional policy formation on energy, water, and food security.

3.3.2 Developing Uncertainty Quantification, Metrics, and Observations

Characterization of uncertainty is fundamental to all scientific investigations, but it is also highly relevant for using predictions for resource management and planning in the context of risk mitigation. Uncertainty in water cycle predictions may come from lack of knowledge or imperfect knowledge about water cycle processes and the integrated system due to their complexity and multi-scale characteristics, inadequacy of the approaches used to model the processes and the system as a whole, and chaotic behavior that limits predictability.

Understanding and quantifying uncertainty should be an important component of modeling research to advance the use of model predictions. Advanced UQ methods have been applied in atmospheric and land surface modeling to provide systematic analyses of model sensitivity to input parameters and to calibrate these parameters for optimum predictive skill. One of the systematic initiatives to apply UQ to global hydrological modeling is the DOE Climate Science for Sustainable Energy Future (CSSEF) project (http://climatemodeling.science.energy.gov/projects/cssef-climate-science-sustainable-energy-future). The work by Hou et al. (2012) is illustrative of the sensitivity analyses and calibration exercises underway in support of the land surface UQ activities within CSSEF. Using extensive perturbed-parameter experiments, Hou et al. have identified three subsurface parameters that govern more of the variance in surface fluxes and runoff than other hydrologic parameters in CLM (Figure 11). By comparing observations with model simulations using perturbed parameters, they have shown that it is feasible to calibrate these parameters to improve model skill.

CSSEF has also shown that the systematic errors in simulations from the Community Atmosphere Model (CAM) for the diurnal variability of precipitation in the U.S. Central Great Plain are relatively robust to the choice of UQ methodology. Systematic exploration of the multi-dimensional parameter space of moist physics has motivated efforts to reduce structural uncertainty through parameterization improvements, including promising new approaches such as stochastic physics. Automating UQ approaches and procedures in modeling testbeds have already demonstrated the capacity of these techniques to facilitate understanding and quantification of uncertainty in model components and model predictions. These results in turn could potentially inform both model development and the use of model predictions to support decision making.

Since uncertainty plays a role in all decision making, frameworks have been developed to utilize predictions for operations and planning under uncertainty. However, there is still a need to develop deeper understanding of the relationship between uncertainty and decision making. UQ methods can be applied to analyze “acceptable risk” for a given decision end point. The robustness of the results to changing contexts of decision making must also be evaluated to explore prospects for constraining the large uncertainties inherent in the integrated human-Earth systems. At this present time, we still cannot bound the magnitude, much less the sign, of the decision making feedbacks as functions of space, time, and major exogenous factors.

The definitions of performance metrics used to assess model sensitivity or calibrate model parameters are central to the UQ enterprise. As there are many water cycle processes relevant to water and energy operations and planning, there is a growing imperative to assemble a comprehensive set of metrics to capture model behavior and assess model fidelity using multivariate relationships. The importance of extreme events to decision making was highlighted

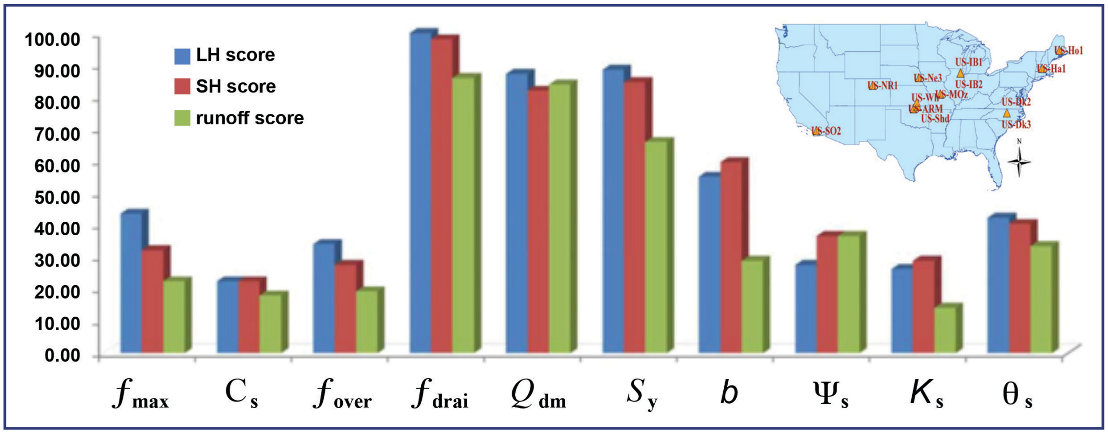

Figure 11. Overall significance of 10 hydrologic parameters in CLM over 13 Ameriflux sites determined by a UQ framework. The simulated latent heat flux (LH, blue), sensible heat flux (SH, red), and runoff (green) are most sensitive to three parameters associated with parameterizations of subsurface processes (f_{drai}, Q_{dm}, and S_y) in CLM.

at the workshop in the context of risk management, especially for regions influenced by extreme events such as tropical cyclones, squall lines, and atmospheric rivers. It would be especially useful to identify the characteristics of extremes relevant for decision making and to design metrics appropriate for reliable quantification and evaluation of projections for these phenomena. Special attention should also be directed to metrics on co-variations of extremes: for example, the coincidence of heat waves and stagnant conditions that could increase the vulnerability of the electrical networks due to higher energy demand for cooling coincident with lower wind energy production.

To evaluate water cycle predictions, observations of local to global water cycle budgets including both storage and transfer are critical. Despite advances in observing systems with increasing spatial and temporal coverage and inclusion of a larger number of variables, closing the water budgets at basin scale remains a significant challenge. Even at global scale, large differences exist among water budget terms estimated from different global reanalysis products (Trenberth et al. 2011). Model-assimilation system for the water cycle will be increasingly critical for producing high-frequency and high spatial resolution water cycle reanalysis. Advances in assimilating variables associated with moist physics such as condensation or diabatic heating may further reduce uncertainty in estimates of water budgets.

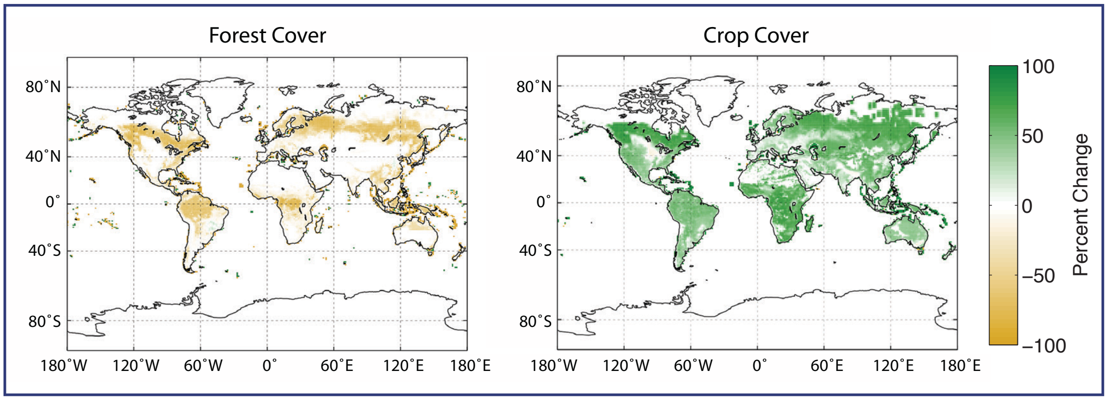

Figure 12. Potential land cover changes by the year 2100 under an energy scenario that does not value carbon on land. Results show significant decreases of forested area (left) and increases in agriculture area (right). (Figure from Jones et al. 2013, in press.)

3.3.3 *Developing a Team Approach to Use-Inspired Research*

Delivering useful and relevant predictions adds a new layer of complexity to integrated water cycle research. Ultimately, improvements in the usefulness of models and the application of simulations in decision making will require extensive two-way interactions between modelers and stakeholders. Such a team approach could improve the decision relevance of model predictions and analyses and facilitate the exchange of feedback from users to the climate community to inform model development, evaluation, and UQ. Developing Climate Model Use Teams (CMUT) may provide a stable environment to nurture a team approach to advancing use-inspired research.

The water-energy-food nexus was more extensively discussed at the workshop as a prime example of a major scientific challenge as well as an opportunity for use-inspired research on the integrated water cycle. There is a need to improve prediction and understanding of how water availability will influence (1) energy sector development (and vice versa), (2) food sector development (and vice versa), and (3) the trade-offs in food/energy sector development. Simulations of the water-energy-food nexus will require extensive information regarding the requirements for water supplies, water demands, and institutional operations. The additional knowledge of the physical system needed to specify requirements for water supplies includes runoff variability and timing, frequency between high and low flows, and groundwater recharge. The information needed for demand-side requirements includes the links between precipitation and irrigation/industrial/municipal practices, the relations of societal demands to economics, and the amount of water transferred to the atmosphere via evaporation and transpiration. The information on institutional requirements needed to model the water-energy-food nexus includes the operations of water markets and reservoirs together with the treaties, compacts, and historical practices that govern permissible diversions.

Integration of all the knowledge into models represents a formidable challenge because the availability of data, particularly proprietary data, may be insufficient and processes must be scaled from regional scale to large river basin scale. USDA, USGS, and USACE can provide significant knowledge, data, and modeling expertise to address this challenge. Using team approaches like that proposed for a CMUT, modelers and decision makers can jointly define use cases, develop demonstrations and testbeds, develop and share data, and document lessons learned. Through long-term collaborations, knowledge of relevance can be mutually developed and transferred throughout the community.

4.0 Integrative Modeling Experiments

Integrative Modeling Experiments:

- Implications of land cover and land use change for regional climate, water resources, and energy pathways in the U.S.
- Multi-model hierarchies to address a wide range of user needs for predicting the regional integrated water cycle
- Sustainability of water and energy resources in eastern versus western North America under climatic and societal changes

The important goals of modeling the integrated water cycle are to improve scientific understanding of the critical human and Earth systems and their interactions, improve long-term prediction of the integrated water cycle, and improve the effective use of models for decision support. To advance these objectives, crosscutting research must be undertaken to develop, test, and demonstrate the usefulness of the modeling capabilities. To address the challenge of crosscutting research, a comprehensive research program needs to consider modeling elements, including:

- Hypothesis-driven modeling experiments and predictability studies
- Multi-scale, multi-system needs for science and decision support
- Model development needs

- Data/observation needs
- Model intercomparison, testing, and evaluation
- Computational requirements (e.g., computing resources, common software infrastructure for model/data development)
- Software infrastructure (e.g., tools for model/data integration and interoperability)
- Data management and visualization
- Strategies for interactions with the users.

To begin addressing the science grand challenges described in the previous section, workshop participants identified three Integrated Modeling Experiments (IMEs) illustrative of the crosscutting challenges and described below. Each IME focuses on some key science and use-inspired questions and specific use cases that provide the context to build and connect different elements of crosscutting research.

4.1 Integrative Modeling Experiment 1: Implications of Land Cover and Land Use Change for Regional Climate, Water Resources, and Energy Pathways in the U.S.

The motivation for this IME is due to two phenomena explored earlier in the workshop report. The first is the link of water resources to the energy system. In the U.S., the energy system is a large contributor to water withdrawals, and agriculture is by far the largest source of consumption (i.e., loss to the atmosphere through evaporation). Changes in the agriculture sector, such as expansion of irrigated agriculture as a potential adaptation to climate change, can therefore affect energy by reducing the amount of water available for cooling for thermoelectric power generation or create additional conflicts in systems where water is already a limiting resource during the growing season. Increases in the demand for biomass for energy production, whether for liquid fuels or for electricity generation, represent a particularly direct form of this potential conflict over water resources. The second phenomenon, also described in some detail earlier in the report, is the need for better representation of the impact of irrigation and changes in land use and land cover in the terrestrial components of earth system models. Changes in irrigation and land use/land cover clearly affect the degree to which the atmosphere "sees" fluxes of water from the surface and therefore affect the physical climate system on regional scales. The degree to which these effects scale up to larger spatial regions is not well-simulated at present, both due to lack of understanding of how such atmospheric phenomena scale from local to regional to synoptic scales and due to lack of observations necessary to drive modeling studies.

4.1.1 Gaps and Key Questions

This IME would address several specific scientific questions that seek to explore the inter-relationships of changes in the Earth system and human decision making.

- How do changes in irrigation in agriculture and land cover and land use change impact local, regional, and global climate and climate variability including phenomena such as mesoscale convective systems, diurnal cycle of precipitation, and extremes?
- How could climate change and socio-economic responses to climate change alter irrigation practices and land use/land cover change under various policy scenarios?
- Will increased frequency/amplitude of droughts lead to increased irrigation investments, and how could this feedback onto climate and water resource availability?
- For different policy scenarios, are adaptations to water availability creating a vulnerability on the water side that did not show up on the energy side?

4.1.2 Research Elements

Addressing the questions in this IME would require additional development in all three components of integrated human-earth system models. Enhancement to the IAM components of these models would be required to support more realistic hydrology, especially on the scales of smaller basins; the ability to model changes in crop productivity due to drought; and the means to project the human response to changes in water availability, including increases in the spread of irrigated agriculture and investments in accessing ground water resources to adjust to drought conditions.

For the terrestrial components of ESMs, similar developments would also have to be undertaken. Greater attention to the interactions among alterations in land cover, shifts in vegetation, and systematic changes in the hydrologic cycle would be required. These interactions between land surface models and IAMs would need to be carefully specified to ensure that fundamental physical quantities (for example, net primary productivity) are defined and evolved in a self-consistent fashion across the entire modeling network. The next generation of these model components should include representations of dynamic root systems, detailed parameterizations of turbulence in plant canopies, more realistic crop models that dynamically model planting and harvest dates and fertilization for a greater variety of crops including those needed for biofuels, and modeling soil degradation such as related to agriculture and ranching. Irrigation as a physical phenomenon will also need improvement, although the ability to do so is currently limited by data availability.

The atmospheric components of ESMs will also require development. The atmospheric branch of land-atmosphere interactions will need to be

Opportunities for Interagency Collaboration on Water Cycle Extreme

Drought is a recurrent feature in many parts of the U.S. Multi-year droughts, in particular, are very devastating and costly. In 2012, the U.S. experienced the most extensive drought since the 1950s, with over 60 percent of agricultural land exposed to severe or greater drought. As drought severity rapidly increased in early July during a critical time of crop development, yields and production of many field crops were far below the levels under normal growing conditions. The shortage of water supply also strained energy production, since water is needed for cooling of power plants, hydraulic fracturing in oil production, production of bioenergy crops, and many other energy-related applications. At the same time, energy demand for air conditioning increased during the heat wave. Both natural variability and anthropogenic climate change have contributed to droughts in the U.S. in recent decades. With climate and hydrological models projecting continental drying in many regions such as the Southwest (Seager et al. 2007, Cook et al. 2010, Cayan et al. 2010), there is an increasing need to understand, monitor, and predict drought and its impacts.

On the other extreme, heavy precipitation also has significant impacts on the society. Atmospheric rivers can bring tropical air masses with abundant moisture and warm temperature to the U.S. west coast. The resulting heavy precipitation and rain-on-snow-induced rapid snow melt is a major cause of flooding in California (Ralph et al. 2005) that challenges the management of multi-objective reservoirs. Ice storms, which primarily consist of freezing rain, are most common in the northeastern U.S. and northern Midwest (Changnon 2003). Although less frequent, ice storms can also impact the southeastern U.S. as they come with greater precipitation amounts. Freezing rain can cause widespread and long-lasting impacts as it "sticks" to tree limbs and power lines, causing electrical power outages and disrupting transportation, with cascading economic losses through business closures, damages to infrastructures, and adverse effects on agriculture (Call 2010). Ice storm frequency may not decrease in a warmer world, especially in regions that remain below freezing (Kunkel et al. 2013). There is a potential for damages to increase with increasing precipitation amounts projected for certain regions in the future.

Highlighting the complex interactions among climate, water, energy, and land that have far-reaching societal impacts, water cycle extremes present significant opportunities for interagency collaborations on the integrated water cycle. Coordinated research can leverage capabilities, resources, and stakeholders across multiple agencies to significantly advance:

- understanding and modeling of processes in the atmosphere, land, ocean, and their interactions, which all contribute to predictability of water cycle extremes at different time scales
- multi-model ensembles for more robust prediction and UQ
- observation, monitoring, and data assimilation
- modeling and computational frameworks for prediction, evaluation, and analysis
- team approaches for cross-disciplinary research.

improved at fine spatial scales in order to improve the representation of turbulence and the exchange of materials from local environments to larger spatial scales. In addition, diurnal cycles, including precipitation, will require more faithful representation.

Approaches for addressing the challenges of this IME would benefit from being closely tied to observational systems. Because of the intrinsically local and regional scales of the phenomena being modeled in this IME, it would be especially useful to explore new approaches using regional observational testbeds that encompass a range of land-cover types and agricultural landscapes, and levels of irrigated. Taking advantage of measurement sites such as ARM sites and National Ecological Observatory Network (NEON) sites would be ideal because of the existing investment in instrumentation and remote measurements. In addition, such sites would also fulfill a fundamental requirement to be functional over multiple years rather than just for a single campaign season. Multi-year measurements will be necessary to quantify some low-frequency aspects of natural climate variability and the human response to that variability.

Three categories of numerical experiments can contribute to this IME. The first category is model sensitivity experiments to investigate the atmospheric

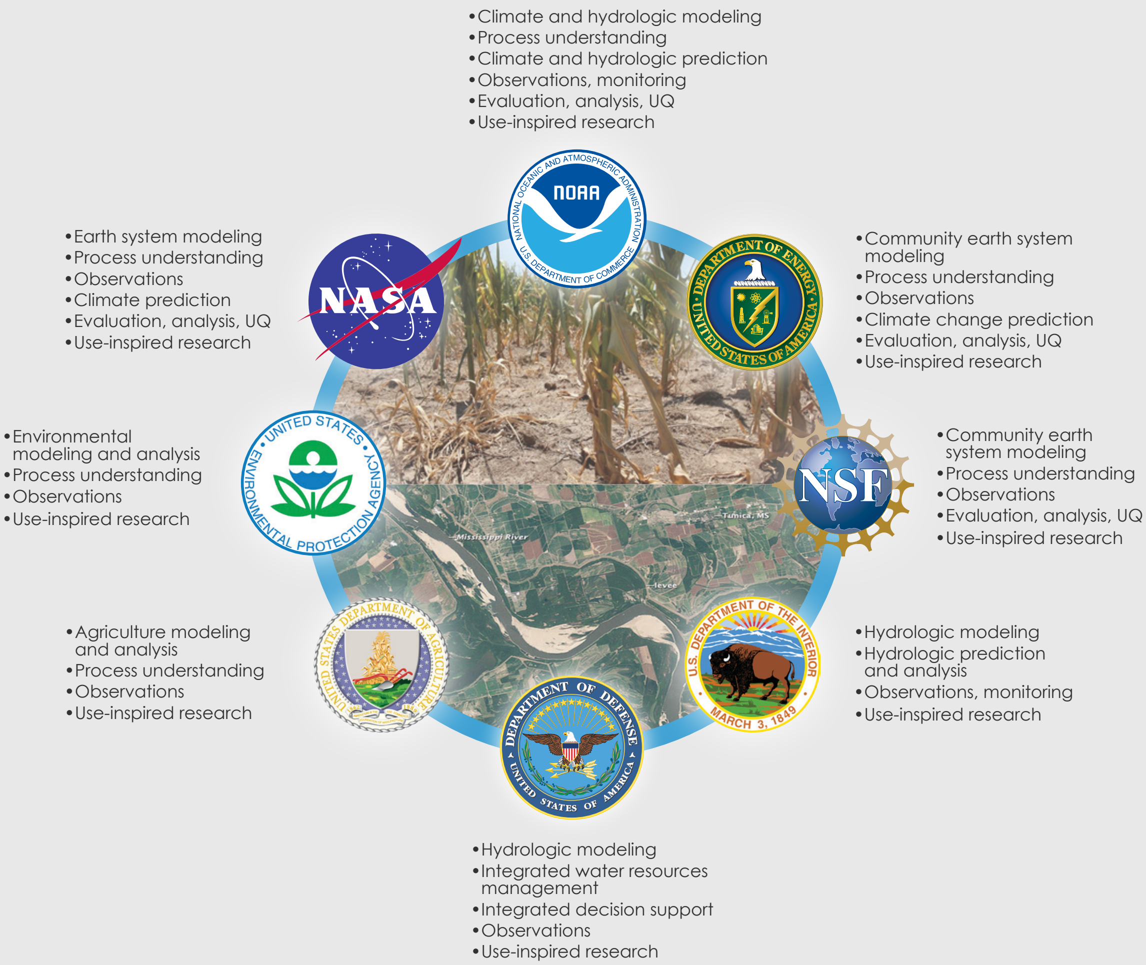

Figure 13. Capabilities and research supported by U.S. government agencies for advancing research on water cycle extremes.

responses to prescribed changes in land cover, land use, irrigation. These would focus on a variety of scale dependencies using variable-resolution atmospheric and land model components.

The second category would more specifically apply to the IAM components of the integrated human-earth system models. These experiments would involve hindcasting and evaluation of the ability of the IAMs to simulate land cover changes, in particular those changes that are the result of changing agricultural demand and practices. This is a current focus of much research in the IAM and agricultural productivity modeling communities.

The third category would be experiments specifically designed for integrated human-earth system models. Coupled experiments would be able to explore interactions between climate variability and human decision making. For example, a coupled model system is essentially required to investigate the regional climate consequences of decisions to expand irrigated agriculture as a response to drought conditions. The final design of such numerical experiments will have to be carefully considered so as to build on developments in each of the individual components.

4.2 Integrative Modeling Experiment 2: Multi-Model Hierarchies to Address a Wide Range of User Needs For Predicting the Regional Integrated Water Cycle

This IME is focused around the problem of delivering actionable predictions from a unified modeling framework to a broad range of users and decision makers. This is an inherently difficult issue for several reasons.

First, how can the community develop climate model frameworks that can deliver actionable projections? At present, the fidelity of the rainfall produced by the multi-model Intergovernmental Panel on Climate Change (IPCC) ensemble degrades systematically relative to observations at scales smaller than synoptic storm systems (IPCC WG1 2007). In addition, the ensemble produces a range of projections for the western U.S. for 2100 that range from drastic decreases to significant increases in total precipitation for each of the scenarios evaluated (IPCC WG1 2007). These two findings illustrate that current models require considerable further development in order to deliver realistic and internally consistent predictions of rainfall that would be useful in operational settings. Significant progress will require moving beyond the current paradigm of improving global models and then downscaling the output for regional and local applications. Instead, the community could consider developing hierarchies of global climate, regional hydrological, and local operational models that are optimized to function as an integrated system for the required predictions.

Of course, a central issue is to define what is meant by "actionable". In the context of the water system, our present simulation capabilities may be more suitable for risk management and investigation of the properties of "black swan" conditions such as persistent major droughts than for actual long-range planning. However, even if the requirements for actionable predictions are relaxed to the requirements for risk management, it is not clear that the climate community can produce useful probability distributions for these "black swan" conditions given the unknown probability distributions for the major drivers of predictive spread, which include the basic structural and parametric uncertainties in the underlying models. Despite these difficulties, there are several notable successes to date. These include the consensus predictions for the switch from snow to rain over the western U.S., the increased incidence of extreme rainfall due to basic climate physics, and the amplification of existing wet/dry patterns by the forces driving climate change. However, identifying consistent model projected climate change signals remains difficult for regions with large natural variability, so recognizing and quantifying such constraints is important. To advance further, it would be very useful to develop observationally based metrics specially designed to address specific user-driven needs for prediction of key aspects of the water cycle at the relevant spatial and temporal scales to augment the conventional metrics designed by and for the climate community. These metrics would connect the applications of the hierarchical model output to acceptable error tolerances in that output. For example, in order for predictions of streamflow to be useful in operational contexts, the modeled streamflow would have to conform with that observed on timescales and within tolerances determined through discussions with the end users in water agencies.

Second, models for operational water management tend to be characterized by specialization to the regions and systems of interest. Of course, specialization and regionalization are required for the data describing each system, including information on the locations of watersheds, networks of water catchments and diversions, patterns of seasonal precipitation, distributions of groundwater, requirements for natural ecosystems, and supplies and demands for water-related resources. What is less clear is to what extent a general modeling framework is possible in practice, or even in principle, that could be tailored for different regions and different user communities simply by exchanging the external data describing those regions and uses. Even if such a framework could satisfy the requirements from the diverse community of water managers, the broad range of spatial and process detail involved means it is likely the framework would require a hierarchy of models operating from regional to watershed and local scales.

Third, this IME includes the human influence and interactions in addition to natural processes in shaping changes in the water cycle and the predictions and predictability of it. In order to determine the resilience of existing and planned infrastructure, it is critical to develop a strategy for separating climate change from human influence on the water cycle. Land-use changes and other human activities may be as significant as climate change in the evolving stresses applied to natural and human water systems. In addition, the human dimension, legal regimes, and impacts of decision making can exceed natural variations, thereby confounding the task of determining the background variability on which climate change is imposed. The key research questions center (1) on the scales where the interactions between human and natural systems are particularly strong and (2) on the upscale and downscale impacts of these interactions. Resolution of these questions would help in the design of the multi-model hierarchies for end use, for example by identifying the scale "breaks" between weak and strong interactions that could be reflected in the ranges of scales treated by each component of these hierarchies.

4.2.1 Gaps and Key Questions

Several major open issues need to be resolved to address this IME:

- What are the limitations on predictive skill and predictability of the water cycle as functions of spatial and temporal scales of the end-use applications? It is likely that these limitations are also dependent on the geographic region in question, given the appreciable differences between the hydrological systems in the eastern and western U.S.
- What are the critical trade-offs among model resolution, complexity, and fidelity for decision making? What level of complexity is sufficient for any given decision to be made with a high degree of confidence?
- How can the model developers and end users best reconcile predictions based upon completely different representations of the underlying system dynamics? Examples include differences between empirically calibrated versus more mechanistic models of individual river basins, differences among the impacts on climate change simulated by the wide range of IAMs available to the community, and differences between IAMs and conventional physical climate models.
- How should one quantify the uncertainty across a hierarchy of models from simple models to extremely complex coupled models with detailed representations of hydrological processes? What are the appropriate UQ frameworks for collections of models for the same water systems? How should decision makers make use of the wealth of simulation outputs and associated UQ assessments that will be provided to them?

4.2.2 Research Elements

The new model development and evaluation outlined in the scientific grand challenges described in Section 3 should help accelerate progress towards greater predictive skill. Much of the research and UQ required for more robust predictions down to local scales is already inherent in, for example, the multi-scale grand challenge. However, the distinguishing characteristic of this IME is the imperative to develop strategies for two-way interactions between developers and users. This will require determining who the users are, what their needs are, what the technical requirements are for the new model frameworks based on those needs, and what the users' criteria are for acceptance and adoption of the frameworks based upon their requirements for fidelity to the observational record. The goal is to identify joint activities for researchers and users that would lead to the improved use of models for decision support, and in turn to link small-scale decision support needs to large-scale model development.

The objectives of this IME include creation of a flexible and extensible process to inform technical requirements for the model frameworks based on elicited user needs. The investigation should target how planners perceive the decision making process and how they interact with other information providers in the process of their deliberations. Effective utilization of this information will probably require engagement by real stakeholders in the model development/evaluation process through the introduction of people at the interfaces between model developers and end users dedicated to serving both communities. The conventional model development process will be further transformed by new requirements to balance the mix of multiple models with different complexities, the needs for systematic simplifications based on scale dependencies, and the needs of the target user communities. Resolution of the challenge of this IME will also necessitate exploration and implementation of easier ways to link to major community models for non-center researchers: for example, a real or virtual facility where the scientific community can contribute to model assessments and development.

Several types of numerical experiments would serve as the pillars for this IME, including:

- *Uncertainty quantification as a function of scale:* Some of the first challenges are to determine which uncertainties at larger scales govern most of the uncertainty at smaller scales, and to ascertain which of these uncertainties are most amenable to control or reduction. These challenges can be addressed using a series of "perfect model" experiments where single or multiple components of the hierarchy are treated as exact representations of the real world, and then the impacts of structural, parametric, boundary, and initial-condition uncertainty elsewhere in the hierarchy are propagated down to the scales pertinent for end use.
- *Determination of requirements for process fidelity:* Additional challenges follow from the issue of whether any given model hierarchy is adequate for the applications in question, particularly with respect to its fidelity to natural and human system processes. For example, how much process enhancement in global models for the treatments of surface and subsurface water is required for useful predictions? Should some of the most widely used operational water allocation models be shifted to a more mechanistic foundation? These questions can be addressed through a series of benchmark calculations in which, for example, DOE's most advanced subsurface models are used to treat the disposition of subsurface water in a critical application region. Systematic reduction in system fidelity (e.g., transition from 3D to 2D transport, etc) in the benchmark codes will help determine the critical levels of process fidelity required for a wide array of end-use applications.
- *End-to-end tests of model hierarchies on historical water scarcity/excess:* The key condition for the adoption of model hierarchies is realism under historical conditions that depart significantly from climatological norms, e.g., droughts and unusually wet conditions linked to the ENSO, etc. The hierarchies should be tested using best available meteorological and hydrological data for range of scales spanned by the component models. The advantage of the model hierarchy is that one or more components of the hierarchy can be replaced by historical data to attribute errors in the whole system to errors in specific components. This class of experiments is highly integrative since it will require detailed historical data on natural and human influences on the water systems under consideration.

4.2.3 Scientific and User Impacts

The scientific impacts of addressing this IME would be improved capabilities to predict and understand key societal components of the water cycle, development of a hierarchy models with flexibly formulated and interchangeable components for hypothesis testing across alternative structure/

parameterization choices, and enhanced leverage of boundary organizations to set user needs base modeling goals. The user impacts would be much clearer communication on model controls and uncertainties, better understanding of the bounds on expectations for predictability across spatial and temporal scales, and sounder foundations for risk-based decision making.

One key outcome is specification of applications to evaluate coordinated use of model frameworks/hierarchy for actionable stakeholder needs. This outcome would be supported by multiple goals, including

- Determination of the extent to which human influence should be represented as a boundary condition or as a fundamentally integrated component
- Application and integration of physical global and regional climate models, IAMs, and engineering models (e.g., applied models for future energy needs) for treatment of the water cycle.

A second key outcome is prototyping and, where scientifically feasible and defensible, implementation of model frameworks driven by actionable requirements to predict the water cycle for different user needs. The core activity to produce this outcome is to develop "limits of predictability" for the climate system. This outcome would be supported by several interlocking research projects, including:

- Improvement of both physical and integrated models to simulate high-frequency changes in rivers and other critical sources of fresh water
- Development of observationally based metrics at appropriate spatial and temporal scales to address specific user-driven needs for prediction of key aspects of the water cycle
- Quantification of the uncertainties in decision-relevant quantities in model components and the integrated model framework
- Identification of readily achievable targets for near-term prediction directly relevant to decision making in user communities engaged as partners in model development and evaluation.

4.3 Integrative Modeling Experiment 3: Sustainability of Water and Energy Resources in Eastern versus Western North America Under Climatic and Societal Changes

North America is marked by diverse landscapes and resources characterized by stark contrast between the eastern and western parts of the continent. Western North America has a distinct seasonality marked by a relatively wet winter and dry summer. Cold-season precipitation from Pacific storms provides the dominant source of water, a large fraction of which is stored in mountain snowpack and released as snowmelt runoff that peaks in spring or early summer. The precipitation is subject to significant spatial variations, since the mountains throughout the region efficiently capture atmospheric moisture on the windward side and cause semi-arid conditions over vast regions behind the coastal mountain ranges. Agriculture, which accounts for roughly 84% of all withdrawals and 96% of water consumption (Kenny et al. 2009), introduces peak demands for water to support irrigation during the summer season. Given the quite uneven spatial and temporal distributions of water supply and demand, storage and release using extensive networks of reservoirs, dams, and canals play essential roles in managing water resources in the West. Variable and limited surface water supplies are often supplemented using extensive withdrawals of groundwater that often lead to unsustainable overdrafts of fossil aquifers. In contrast, eastern North America has a humid climate with smaller seasonal precipitation differences and little phase lag between precipitation and runoff. Agriculture is mostly rain-fed and accounts for less than 20% of water withdrawal and consumption. A large fraction of water withdrawal, on the other hand, is used for thermoelectric cooling (Kenny et al. 2009), and this is reflected in the uneven distribution of water withdrawal associated with power plants (Figure 14). Hence, water management has very different objectives in the East compared to the West.

Extreme events pose significant challenges in managing water in both East and West. In the West, the occurrence of winter floods is heavily affected by atmospheric rivers that bring warm moist conditions accompanied by heavy precipitation (Ralph et al. 2005, Leung and Qian 2009). In the East, a mix of

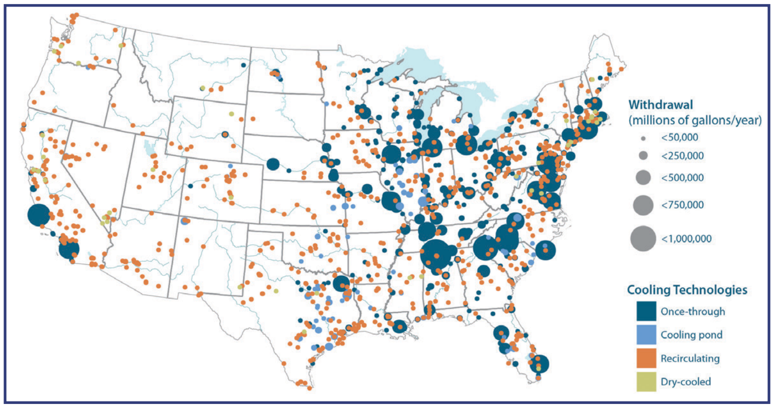

Figure 14. Power plant water withdrawals: East versus West. (Source: Averyt et al. 2011)

weather phenomena such as hurricanes, squall lines, mesoscale convective systems, ice storms, and lake effect snow contribute to floods and/or disruptions to energy and transportation infrastructures in different seasons. Both regions are influenced by different spatial patterns that can severely impact water supplies with associated repercussions on energy production and agriculture.

4.3.1 Gaps and Key Questions

The supplies of water are already stressed in many parts of North America by the demands for water for cooling power plant in the East and irrigating crops in the West (Averyt et al. 2011). In some parts of both regions, it is likely that climate change will further intensify stresses on water supplies through changes in precipitation, evaporation, and runoff, as well as through changes in water and energy demand in response to higher temperatures and evaporative losses. Variations in runoff as well as water/energy demands will challenge management strategies for reservoirs to fulfill competing demands for hydroelectric power generation, water supply, recreation, and in-stream flows. Projected changes in extremes such as increase in the intensity and duration of droughts for the southwestern U.S. (Seager et al. 2007) and in the intensity and frequency of heat waves (Meehl and Tebaldi 2004) would further add significant stress to the existing water and energy infrastructures.

The water cycle of western North America is fed by discharge from high-altitude watersheds following the large, seasonal accumulation and sublimation of mountain snowpack. The water cycle of eastern North America is fed by discharge from lower-altitude watersheds following a smoother annual cycle of precipitation from winter storms and summer convection. Predicting the vulnerability and adaptability of the contrasting regimes in these regions, each with their own profiles of human influence, is an important crosscutting challenge. Such an effort will provide a critical test of our capabilities to model the integrated water cycle on temporal and spatial scales that are meaningful to the Nation's regional decision makers. Existing modeling tools lack the accuracy and spatial specificity to predict regional water cycle variability and changes. They further lack the capabilities to represent the fully integrated dynamics of regional climate, water, and energy, especially with respect to managed and human-affected water and energy systems to address the challenge.

4.3.2 Research Elements

To investigate the overarching question, a set of interconnected and interoperable models describing multiple systems and processes involving different scales is needed to determine the changes in the water cycle, the supply and demand of energy, and their interactions. Modeling approaches could include global variable-resolution models or nested models. In either approach, the models must span local-to-global length scales and hourly-to-interannual time scales in order to simulate water, energy, and human systems and their interactions with sufficient fidelity. In addition, this effort must represent the linkages between managed water system and water consumers mediated by a large network of public and private utilities, government agencies, and other regulatory bodies. The supply and demand of water and energy must be explicitly simulated, and this requirement will place additional emphasis on describing, modeling, and understanding human systems. These systems are tasked with managing, allocating, consuming, and altering water and energy stocks and fluxes in a complex and continually evolving environment directly affected by these decision making processes. Hence, this IME entails meeting the challenges to model multi-scale processes and the integrated human-Earth systems and testing, evaluating, and intercomparing the predictive skill of these models from seasonal to decadal and century time scales in a coordinated and systematic fashion. There are significant computational challenges inherent in the assembly of coupled models, provision of leadership-class computing resources, and development of flexible and extensible layered software infrastructure. These challenges must also be addressed in order to effectively develop and deploy the models using the kinds of massive ensemble required for reliable UQ and risk assessment.

Observations are a core element in an iterative process to evaluate and improve models. This IME should be informed by a wide range of observations including in situ, remote sensing, and census data that capture the east-to-west variation in climate, land surface processes, and human systems characteristics. New approaches to quantify the human elements would integrate and synthesize information on managed water and energy supply, demand, transfers/transmissions, and social and economic data. Model experiments, including hindcasts of past well-observed stresses and forecasts of changes to the water and energy, can in turn serve to evaluate the adequacy and quality of the data collection and monitoring processes.

Engaging the stakeholder community is an important element of this IME that could prove highly beneficial for both the scientific and policy-oriented participants. This kind of engagement has been shown to be most effective when key decision makers are incorporated into the project from its inception in order to develop buy-in and key user guidance. Although this IME addresses important DOE missions and goals, there are ample opportunities for substantial participation by other government agency partners, academics, and stakeholders with mandates and expertise on various facets of water, energy, and climate. Such engagement can help refine science questions and hypotheses, inform modeling requirements and evaluation metrics, advance model components and parameterizations, and facilitate exchange and integration of data from diverse sources. All these activities could help ensure that more complete information can be created to identify alternative futures for energy and water sector adaptive pathways.

4.3.3 Scientific and User Impacts

Accomplishing the goals of this IME would deliver new understanding and modeling capabilities of the integrated water cycle that should be valuable to the Nation's decision makers and will also be transferable to other regions. More specific scientific impacts include capabilities in predicting water cycle variability and extremes, modeling water and energy demand and use and their interactions with Earth system processes, and accounting for human decisions. It builds coordination and synergies across multiple science groups and cultures, provides opportunity for involvement of decision-making partners, and combines science and policy in a joint framework. Ultimately it provides better insight and predictive skill for decision makers to support sustainable provision and management of water and energy resources.

5.0 Summary

Understanding and modeling the integrated water cycle was widely recognized by the workshop participants as a fundamental objective to advance our ability to address the Nation's challenges in energy and the environment. This workshop broadly discussed the integrated water cycle in the context of its complexity and characteristics. Despite the significant advances made in the last decades in modeling the earth system using coupled, computationally intensive numerical models, significant gaps remain between the climate community's current abilities to predict water cycle changes and the Nation's emerging needs to rationally manage critical resources while simultaneously maintaining a healthy environment.

Critical gaps were identified that reflect aspects of modeling the integrated water cycle that elude skillful predictions. First, water cycle processes are inherently multi-scale, but we have limited understanding of their scaling behaviors and the mechanisms that govern the scaling regimes. Insufficient efforts have been devoted to applying the insights from scaling theory to constrain and improve key parameterizations of water cycle processes. Second, the water cycle is influenced by both natural and human systems, but we lack comprehensive understanding of how these systems interact at different space and time scales. This in turn constrains our knowledge regarding critical issues including the sources of and limits to the predictability of the coupled system. Existing ESMs do not fully integrate the human systems to represent the myriad modes of dynamical interactions between these systems and earth system processes. In addition, existing modeling testbeds and methodologies for model evaluation and diagnostics do not adequately address the multi-scale and integrated human-earth system modeling challenges for predicting the regional and global integrated water cycle. Finally, the significant societal relevance of water cycle predictions sets firm requirements for actionable information to support decision making. The combination of low predictive skill, inadequate uncertainty information, and insufficient model metrics relevant to end users are hampering meaningful use of long-term water cycle predictions for resource management and planning. To address these science grand challenges, it is imperative to develop both short- and long-term solutions to meet the energy and environmental challenges of today and in the future.

Use-inspired research motivates integrative approaches that transcend the science grand challenges to ultimately evaluate and demonstrate scientific progress. Three IMEs for crosscutting research were identified at the workshop. The IMEs broadly address the modeling challenges related to the water-energy-food nexus, the creation of modeling frameworks driven by actionable requirements of water cycle predictions and responsiveness to multiple user needs, and the sustainability of water and energy supplies across the Nation's heterogeneous landscapes and patterns of water use. Addressing the challenges of these IMEs will require targeted development of a hierarchy of interconnected and interoperable models representing natural and human systems across scales, progress in model evaluation and analysis, utilization of advanced UQ, and unification of science- and user-driven metrics. It will also require substantial advances in computational infrastructure and deep engagement with the stakeholder community.

Water cycle research broadly cuts across multiple disciplines and the missions of multiple government agencies. Workshop participants particularly underlined the needs to develop team approaches that foster trans-disciplinary engagement and activities targeting specific problems in order to address the science grand challenges and IMEs. The challenges identified at the workshop represent remarkable opportunities for interagency collaborations for significant scientific and user impacts.

Appendix A:

As discussed in Section 2, the workshop was organized around six topics to improve both understanding and long-range predictions of the integrated water cycle. These topics address understanding and modeling of the multi-scale characteristics of the water cycle, understanding and modeling the interactions between human and Earth system processes, advancing modeling of the terrestrial system, diagnosis and evaluation of model behaviors, improving water cycle prediction and uncertainty quantification, and advancing use-inspired research to meet future energy and environmental challenges. White papers discussing the scientific challenges, current gaps and limitations, and future research priorities of each topic are included in this Appendix. These white papers supplement the discussion of the science grand challenges described in Section 3, which represent syntheses of the multiple challenges identified in each topic.

A.1 Multi-Scale Behaviors of the Water Cycle

Robert Wood, Xubin Zeng, Bill Collins

Critical Research Gaps and Needs

- Develop a strategy to systematically explore behavior of models with increasing resolution.
- Promote research that emphasizes the coupled nature of the land atmosphere ocean system.
- Develop strategies for targeted observations of precipitating systems (especially deep convection), especially those over land regions.
- Further development of a new class of very high-resolution ESMs to explore key aspects of the water cycle.
- Improve representation of subgrid processes within atmospheric and land surface models.
- Develop team approaches that foster cross-disciplinary engagement and activities focused upon specific problems.
- Identify regions for focused model development and evaluation efforts.

A.1.1 Scientific Challenges

The water cycle is an inherently multi-scale phenomenon (Figure A1) involving water vapor, clouds, and precipitation in the atmosphere; evaporation from ocean; evapotranspiration from land; and other terrestrial processes including soil moisture, runoff, groundwater, and streamflow. This complexity makes the water cycle extremely challenging to understand and predict. Water is important not only because it controls precipitation, but because it is an important energy source that drives the climate system, thereby influencing extremes, such as prolonged droughts currently affecting a large part of the U.S. In addition, the water cycle is closely coupled to biogeochemical cycles. The terrestrial branch of the water cycle is also strongly affected by human activities.

Evaporation occurs on large spatial scales over the ocean and land but is strongly affected by low-level winds and humidity that are affected by small-scale turbulent mixing in the planetary boundary layer. Small-scale heterogeneities in soil moisture and land surface type further complicate the transports from the surface into the PBL. Moisture is transported vertically and horizontally by a diverse array of phenomena from relatively small-scale convective clouds to synoptic-scale conveyor belts and atmospheric rivers. Water returns to the surface primarily in intermittent and localized precipitation events that are driven by, and operate on scales smaller than, most current predictive models. Because the ocean is such an important source of moisture even over continents, its intrinsically long timescales (interannual to multi-decadal) strongly modulate moisture transport pathways by changing the atmospheric circulation in poorly understood ways. Superimposed on the natural variability are changes in the water cycle driven by anthropogenic forcing agents such as greenhouse gases and atmospheric aerosols, together with land-use changes that impact evapotranspiration, soil moisture, and runoff.

Prediction of the water cycle, especially on annual to decadal timescales, is essential for a variety of end users (e.g., agriculture, infrastructural planning, insurance, emergency management). These users need to understand not only this long timescale variability but also how it influences the critical small-scale processes like atmospheric convection and precipitation. This will require an investment

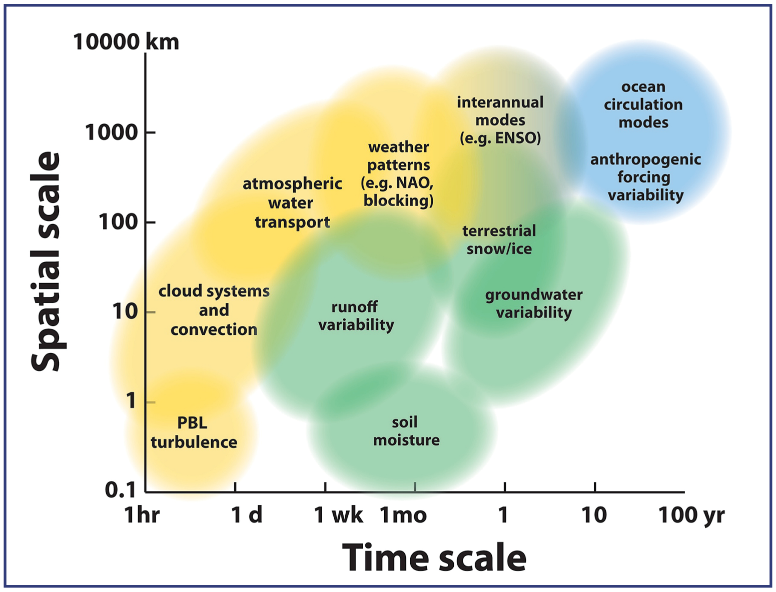

Figure A1. The time and space scales of key components of the water cycle.

not only in system modeling but in the development of observational capabilities and networks that can provide key process-scale understanding needed to improve models and evaluate their predictions.

A.1.2 Current Status and Research Gaps

Through the analyses of observational data from comprehensive field campaigns, surface-based observational networks (such as DOE's ARM Facility), satellite remote sensing, and modeling at a range of scales, our understanding of the multi-scale processes of the water cycle has been improved (Tao et al. 2009, Arakawa et al. 2011, Wood et al. 2011b). Progress has been made in recent decades to improve prediction (Saha et al. 2012). Increased computing power has enabled us to increase the climate model resolution continuously in recent decades. Today's climate models for IPCC assessment [e.g., CESM] have a horizontal resolution of ~1° in the atmosphere with several subgrid tiles of land surface types (Lawrence et al. 2011). The water cycle is a challenge beyond the remit of any single agency, but DOE has made important investments in climate modeling (e.g., supporting a large part of the current CESM development), in observing and understanding key atmospheric processes through the Atmospheric System Research program (particularly radiative energy flows and how they are impacted by the atmosphere including moisture, clouds and aerosols), and in understanding how ecosystems respond to climate variability. Most climate models now have the capability for comprehensive coupling of the land, ocean, and atmospheric dynamic systems.

Major gaps still remain. Most climate models still perform poorly in representing key aspects of the

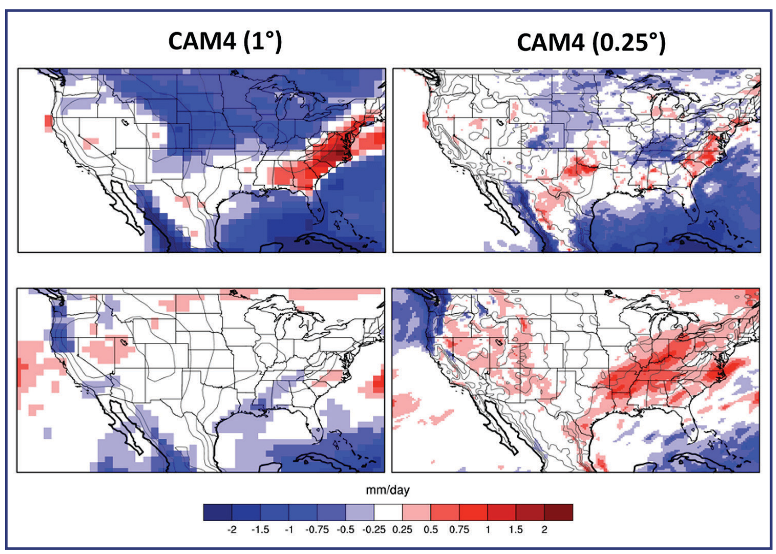

Figure A2. CAM4-simulated precipitation difference at 1° and 0.25° resolutions between 2081–2100 (using CESM-simulated bias-corrected sea-surface temperatures (SSTs) under the RCP8.5 scenario) versus 1981–2000 (using observed SSTs). (Figure courtesy of Julio Bacmeister.)

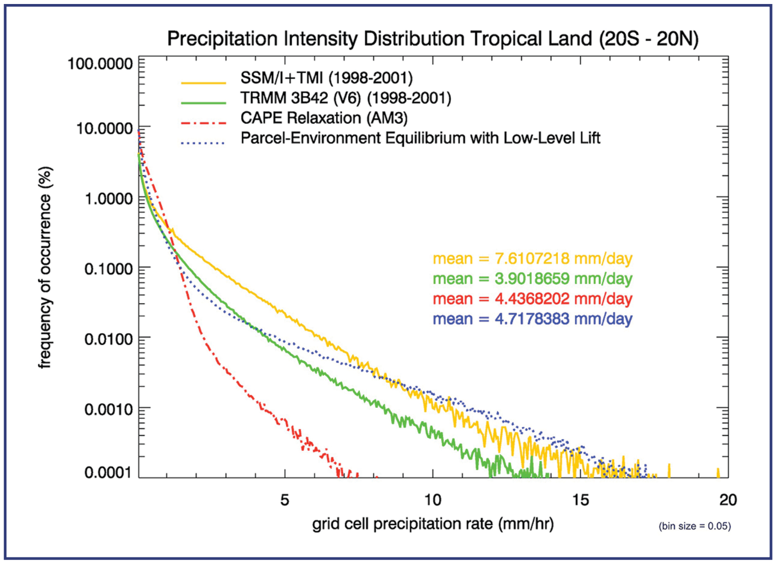

Figure A3. Geophysical Fluid Dynamics Laboratory (GFDL) AM3-simulated precipitation frequency and intensity with two different cumulus parameterizations. (Adapted based on results from Donner et al. 2011.)

water cycle. Boundary-layer processes remain poorly represented, especially in how they drive the transition from shallow to deep convection that determines the diurnal cycle of precipitation over land (Grabowski et al. 2006). The development of deep convection in most climate models is far too insensitive to moisture in the free troposphere (Del Genio et al. 2010), which limits the organization of large-scale convective systems. While global cloud-resolving modeling (with a horizontal grid spacing of 1–2 kilometers) is possible for short time integrations, highly non-linear aerosol-cloud-radiation and convective processes still have to be treated through subgrid parameterizations in global climate studies (Randall et al. 2003).

As a consequence of the poorly handled convection and other factors involving the water cycle, the statistics of precipitation are not well modeled (e.g., Kjellstrom et al. 2010). We therefore have a very poor understanding of how extreme precipitation events may respond to natural and anthropogenically driven changes in climate on decadal-to-centennial timescales (Zhang et al. 2007). For instance, Figure A2 shows that the use of different spatial resolutions in CAM4 could alter not only the magnitude but also the sign of precipitation change in the twenty-first century. Figure A3 illustrates that cumulus parameterizations are implicated in climate model's inability to simultaneously simulate mean state and variability.

On the large scale, climate models are currently unable to simulate the observed pace at which the subtropics are expanding (Seidel et al. 2008). This expansion is likely to be driven not only by increasing greenhouse gases but also by more poorly simulated constituents such as ozone and aerosols (Allen et al. 2012). The changing patterns of moisture transport associated with subtropical expansion are a major driver of future precipitation patterns over the southern U.S. (Lu et al. 2007). The prolonged drought over the U.S. Southwest and northern Mexico may well be an indication of more permanent conditions to come in future decades (Seager et al. 2007).

Land-atmosphere feedbacks are strongly controlled by the availability of surface moisture, but climate model representation of soil moisture and its variability on seasonal-to-interannual timescales is particularly poor (Seneviratne et al. 2010). While three-dimensional soil moisture movement can be simulated at a grid spacing of meters over a small domain, only the vertical movement of soil moisture (along with the parameterization of horizontal runoff) is considered in climate modeling studies (Zeng and Decker 2009).

High-quality climate data are still lacking, due to the long-term challenges in platform stability, sensor degradation, continued and committed support, and data stewardship (NRC 2004). In addition, there are still key observational gaps in basic monitoring of the water cycle. Over oceans, passive microwave precipitation estimates are of high quality, but these are much less reliable over land. Current soil moisture measurements are sparse and are poorly representative of a region given the tremendous small-scale variability in surface type and soil properties (Zreda et al. 2012).

A.1.3 Research Gaps and Needs

Future research should address poorly represented processes that limit our predictive capabilities of key aspects of the multi-scale water cycle. In particular, there are a number of key gaps that should shape future research.

- **A strategy to systematically explore behavior of models with increasing resolution.** The two-way interactions between small- and large-scale phenomena and processes are poorly understood. There is a need to develop scaling theories for atmospheric and land processes, and current understanding of resolution-dependence of model representations of the water cycle is inadequate. A systematic exploration of how key aspects of the water cycle change as model resolution increases is critical and will allow us to (a) evaluate scales at which key phenomena and couplings with land surface models emerge; (b) develop understanding of how small-scale processes upscale to regional and global scales; and (c) develop scale-aware parameterization for lower-resolution 'workhorse' models. Collaborative teams should be introduced to design experiments, specify necessary model outputs, and design evaluation strategies and new metrics.

- **Research that emphasizes the coupled nature of the land atmosphere ocean system (rather than atmosphere alone).** The monitoring of snowfall and its subsequent melt, sublimation, and runoff is in particular need of innovation and advancement. Innovative methods also need to be developed that can assimilate spaceborne, airborne, and surface in situ observations to provide consistent and integrated data sets (particularly over land) to better understand the multi-scale nature of the water cycle.

- **Strategies for targeted observations of precipitating systems (especially deep convection), especially those over land regions.** A focus on extreme precipitation events and their hydrological impacts is critical for understanding decadal and centennial water cycle variability. Future priorities should include a better understanding of the coupling of precipitating systems with the large-scale atmospheric flow, land surface heterogeneities, orography, soil moisture, and atmospheric aerosols.

- **Development of a new class of very high-resolution ESMs to explore key aspects of the water cycle.** Such models may not replace climate models used for decadal-to-centennial prediction, but can be used to identify key regional to global processes and connections between system components that are poorly handled in the climate models. Atmospheric and land scientists need to work together to develop and test land-atmosphere coupled very high-resolution regional models that can resolve clouds (~1-kilometer scale) and simulate the three-dimensional movement of soil moisture (with a land horizontal grid spacing of ~100 meters). This would bring the water cycle modeling much closer to human activities (e.g., river flow management, reservoir operation). Innovation in software engineering and parallel computing will be needed for high-resolution global climate modeling and for the analysis of the huge amount of model output.

- **Representation of subgrid processes within atmospheric and land surface models.** Most large-scale models represent subgrid variability in a rather ad hoc and self-inconsistent manner. The subgrid parameterization of processes (e.g., clouds, turbulence, topography) within each coarse model grid cell (e.g., ~1°) represents a fundamental uncertainty of climate models. Making the subgrid parameterization even more challenging is the fact that different subgrid processes strongly interact with each other. Innovative approaches are needed to explore how the very high-resolution models discussed can be used to develop substantially simplified treatments of the physical and chemical processes that can be transferred to lower-resolution climate models that can run on decadal-to-centennial timescales.

- **Team approaches that foster cross-disciplinary engagement and activities focused upon specific problems.** Establishing teams of model developers, process modelers and observational scientists is critical. An example is the U.S. Climate Process Team approach started by NSF and NOAA. Other examples are the Decadal and Regional Climate Prediction Using Earth System Models (EaSM) program from NSF, DOE, and USDA and the Frontiers in Earth System Dynamics (FESD) program from NSF. DOE should foster improved collaboration between the national laboratories and university researchers using team approaches. Dedicated science teams focused on specific cross-disciplinary research themes for relatively short periods (e.g., 3–5 years) should be encouraged.

- **Regions for focused model development and evaluation efforts.** Because the primary mechanisms for the scale interactions in the water cycle (including extremes) are expected to be dependent on regions and climate regimes, it is important to have comprehensive case studies over specific regions based on science, societal needs, and data availability. Three examples are given here for illustration: (a) the western U.S., with fragile water supply strongly affected by snowmelt, complex terrain, and strong land-atmosphere-ocean interactions; (b) the southern United States (from Southwest to Southeast) with strong land-atmosphere-ocean interactions and affected by drought, monsoon (over the Southwest), strong and potential global expansion of the subtropics; and (c) Amazon with strong land-atmosphere coupling in energy, water, and carbon fluxes and the future state of rainforests uncertain.

A.2 Human-Earth System Interactions and Impacts on the Water Cycle

Anthony Janetos, Mohamad Hejazi, Ruby Leung, Kenneth Strzepek

Critical Research Gaps and Needs

- Model human water use directly with particular focus on agriculture and energy uses.
- Model interactions among human systems—water management, agriculture, energy system—at appropriate scales and in the context of a changing climate/environment.
- Model feedbacks to the atmosphere from land surface change and energy system change by taking the current suite of one-way coupling IAM experiments of land-use impacts (e.g., Representative Concentration Pathways (RCP), biofuel penetration scenarios) to the next step (i.e., two-way) where results indicate a strong potential for feedbacks.
- Assess the predictability of the water cycle for both coupled human-Earth systems and uncoupled systems, how human systems affect model predictions, and performing model evaluation for IAMs.

The purpose of this white paper is to provide background on several topics of importance in understanding the interactions of human decision making on water use, especially in the energy and agricultural sectors, and variability and change in the hydrologic cycle and the broader earth system. The paper is not meant to be encyclopedic, but to highlight major points for discussion in the DOE workshop. At the end of the paper, the authors discuss several ideas for modeling research that are meant to serve as a foundation on which to build in the workshop.

A.2.1 Scientific Challenges

Human influence on the water cycle is profound and varies with scale. For example, humans have altered the flow of water on land by building dams and transferring water, stressed river systems through excessive water use practices (e.g., crop irrigation and thermoelectric cooling), and degraded freshwater biodiversity by reducing river flows and warming water temperatures. Also, human-induced changes to climate and land use systems impact the water cycle and are known to alter precipitation distribution, extremes, and sea level rise. Modeling feedbacks to the atmosphere from human-induced land surface and energy system changes and understanding the uncertainties in the physical and dynamical response of the climate system are important advances. For example, are there thresholds in the extent and/or expanse of land use change that are big enough to matter in climate models? Thus, a more complete representation of human activities in earth system models is warranted.

IAMs also need to incorporate direct linkages between water and land/energy in the modeling framework to more realistically model the interactions among human systems. The challenge lies in introducing water endogenously within IAMs at the regional scale to facilitate modeling the interactions among the competing water users (e.g., growing demand for food and biomass crops and water) and assessing the impact of water stress on solar/dry-cooling deployment in the Southwest, and how these interactions might change if the climate/environment changes. Moreover, IAMs simulate physical quantities as well as economic behavior that should be observable. But this is an extremely difficult problem because the preferences and structure of the economy change over time, and data are not readily available for long periods. Thus, assessing the persistence of societal decisions—is there "predictability" over short time periods (years to decades)—and identifying areas where good model performance is unattainable without the socio-economic drivers are interesting challenges. Nonetheless, model evaluation for IAMs remains a challenge.

There is also a need to take the current suite of one-way coupling IAM experiments of land-use impacts (e.g., RCP, biofuel penetration scenarios) to the next step (i.e., two-way) where results indicate a strong potential for feedbacks. Another important phenomenon is urbanization, which is under-represented in both IAMs and climate models. The challenge is in figuring out the best way to represent this at regional scales. Scale is another important issue. What's "good" for a user, and how does that relate to the modeling framework? How do we cross both spatial and temporal scales, and what are the appropriate questions that can be posed and addressed at a given scale are important questions, and they pose different implications for modeling needs. Other important modeling advances include modeling biogeochemical flows in earth system models, accounting for direct human impacts (e.g., drought and nutrition, floods and access to potable water, sea-level rise and infrastructure, mortality and disease from extreme events), projecting extremes, and improving spatial projections of both the human populations and aspects of their vulnerability.

A.2.2 Current Status and Research Gaps

A.2.2.1 Background on Human Influence on Water Cycle at Different Scales: Trends

Humans have extensively altered river systems through impoundments to meet their growing water demands, and they regulate the flow of about two-thirds of all of Earth's rivers (Abramovitz 1996). Globally, there are about 945,000 dams above 15 meters high storing about 6,500 km^3 of water (Avakyan and Iakovleva 1998), or 15% of the total annual river runoff (Gornitz 2000). In the United States alone, only 2% of the rivers run unimpeded, and about 75,000 dams can store a volume of water equaling almost 1 year's mean runoff of the nation (Graf 1999). The World Commission on Dams (WCD) reports that at least 45,000 large dams have been built worldwide since the 1930s, and about ~7,200 km^3 of surface flow is stored in reservoirs, man-made lakes, and ponds. Evaporation from these storage units (~240 km^3), from water application to crops (~7,600 km^3/year) and grazing lands (~14,400 km^3/year) and from the virtual water trade in crops (~1,000 km^3/year), collectively impact all aspects of the global water system (Vörösmarty et al. 2004, Oki and Kanae 2006). A global overview of dam-based impacts on large river systems (292) shows that 172 systems (59%) are affected by dams, and 139 systems (48%) remain unfragmented by dams in the main channel; 119 systems (41%) have unfragmented tributaries; and only 102 systems (35%) are completely unfragmented; and basins that are impacted by dams experience about 25 times more economic activity per unit of water than do unaffected basins (Nilsson et al. 2005). As a result, human management of water resources, including reservoir storage and excessive groundwater withdrawal, has altered the flow regime of some major river basins (Gleick 2003; Nilsson et al. 2005).

Humans have also stressed river systems through excessive water use practices to the extent that little water reaches the sea from major rivers (e.g., the Colorado, the Nile, and the Ganges [Rosegrant et al. 2002, Postel 1999]), and major inland water bodies have shrunk significantly in size (e.g., Aral Sea and Lake Chad, due to water diversions for agriculture [Micklin 1988, Kotlyakov 1991]). In places where water is scarce, humans have tapped into non-renewable (fossil) groundwater sources (Gleick 1993), and the extraction of groundwater reserves is almost universally unsustainable and has resulted in declining water tables in many regions (Rosegrant et al. 2002, Postel 1999). For example, three-quarters of the water supply of Saudi Arabia currently comes from fossil water (Gornitz et al. 1997). Thus, humans have transformed the hydrologic cycle to provide freshwater for irrigation, industry, and domestic consumption (Postel et al. 1996, Vörösmarty et al. 2000). At present, as much as 6% of Earth's river runoff is evaporated as a consequence of human manipulations (Dynesius and Nilsson 1994). Barnett et al. (2008) show that up to 60% of the climate-related trends of river flow, winter air temperature, and snow pack between 1950 and 1999 are human-induced. When comparing the impact of climate change by the 2050s to the impact of water withdrawals and dams on natural flow regimes that had occurred by 2002, Döll and Zhang (2010) found that climate change could alter seasonal flow regimes significantly (i.e., by more than 10%) on 90% of the global land area (excluding Greenland and Antarctica), as compared to only one quarter of the land area that had suffered from significant seasonal flow regime alterations due to dams and water withdrawals. Due to climate change, the timing of the maximum mean monthly river discharge will be shifted by at least one month on one-third of the global land area. Finally, although increased temperature and decreased soil moisture will act to reduce global crop yields by 2050, the direct fertilization effect of rising carbon dioxide concentration will offset these losses (Long et al. 2006).

The climate system regulates the amount of water being circulated in the terrestrial biosphere, and climate change is expected to accelerate water cycling, induce changes in seasonal patterns, and increase the frequency of extreme events (Oki and Kanae 2006, Huntington 2006). Climate change and changes in land use and land cover are also expected to influence the amount, timing, and reliability of regional fresh water in different directions (Milly et al. 2005), and consequently, are likely to affect water supply resources (Rowan et al. 2011) by influencing the amount of runoff volume and groundwater recharge to replenish aquifers (Wada et al. 2010). The components of the surface hydrologic cycle affected by climate change include atmospheric water vapor content, precipitation and evapotranspiration patterns, snow cover and melting of ice and glaciers, soil temperature and soil water content, and surface runoff and stream flow (IPCC 2008).

There is evidence that climate change is likely to cause an intensification of the global water cycle (Huntington 2006) and an increasing precipitation intensity (Wentz et al.,2007), to consequently increase runoff particularly at high latitudes (Milly et al. 2005) and flood risk (White et al. 2001). Trenberth (2005) found that increased heating leads to greater evaporation and thus surface drying, thereby increasing intensity and duration of drought. With 1°C warming, the water-holding capacity of air increases by about 7%, thus increasing water vapor in the atmosphere and probably providing the biggest influence on precipitation. The increased supply of moisture can produce more intense precipitation storm events and is expected to accelerate water cycles and thereby increase the available renewable freshwater resources. Although this would mean more runoff is potentially available for humans, alleviating the growing stress conditions, changes in seasonal patterns and increasing probability of extreme events may offset this effect (Oki and Kanae 2006). Global-scale discharge changes remain a key indicator of potential acceleration of the hydrologic cycle (Huntington 2006) and an important input for quantifying rates of global mean sea level rise (Munk 2003). Recent discussion of the intensification of the hydrological cycle has included analysis of trends in global freshwater discharge (Syed et al. 2010).

Freshwater biodiversity has declined faster than either terrestrial or marine biodiversity over the past 30 years (Jenkins 2003). The declining river flow rates have been a major cause of species loss (Postel and Richter 2003) in some regions and are likely to be further reduced by warming temperatures, reduced precipitation, and increased water withdrawals (Vörösmarty et al. 2000, Alcamo et al. 2003). The construction and operation of 45,000 large (15-meter high) dams worldwide during the twentieth century (World Commission on Dams 2000), in conjunction with the many that are planned, ensure that humanity's effects on aquatic biological systems will continue (Humborg et al. 1997).

From an ecological perspective, the fragmentation of river corridors by dams (Nilsson et al. 2005) has severely altered the global flux of water and sediment from continents to oceans through the world's river basins (Syvitski et al. 2005, Vörösmarty et al.

2004), thus posing significant threats to native river biodiversity on a global scale (Poff et al. 1997, Bunn and Arthington 2002). Xenopoulos et al. (2005) found that "in rivers with reduced discharge, up to 75% of local fish biodiversity would be headed toward extinction by 2070 because of combined changes in climate and water consumption. Increases in river N drive the eutrophication of most estuaries, causing blooms of nuisance and even toxic algae, and threatening the sustainability of marine fisheries (Nixon et al. 1996)." The high degree of regional warming that occurred in the European Alpine area during the second half of the twentieth century has extended the stratification period of Lake Zurich by 2–3 weeks (Livingstone 2003). Schneider and Hook (2010) studied "the surface temperatures of 167 large inland water bodies distributed worldwide between 1985 and 2009 and observed rapidly warming mean nighttime surface water temperature with an average rate of 0.045°C yr^{-1}."

The main contributors to the current rise in global mean sea level of about 2 to 3 mm yr^{-1} are thought to come from the loss of land-based ice masses such as ice sheets, ice caps, and mountain glaciers, and from the thermal expansion of the oceans (Kabat et al. 2005). Pokhrel et al. (2012) indicate that "global sea level has been rising over the past half century, and thermal expansion of oceans, melting of glaciers and loss of the ice masses in Greenland and Antarctica are commonly considered as the largest contributors." Changes in terrestrial water storage are also likely to affect sea level (Lettenmaier and Milly 2009). Pokhrel et al. (2012) found that "a sea-level rise of about 0.77mm per year between 1961 and 2003, about 42% of the observed sea-level rise, can be attributed to the combination of unsustainable groundwater use, artificial reservoir water impoundment, climate-driven changes in terrestrial water storage and the loss of water from closed basins." Wada et al. (2012) found that "the contribution of groundwater depletion to sea-level increased from 0.035 mm yr^{-1} in 1900 to 0.57 mm yr^{-1} in 2000, and is projected to increase to 0.82 mm yr^{-1} by the year 2050." Famiglietti et al. (2011) "measured using satellites recent rates of groundwater depletion in California's Central Valley (highly-productive agricultural area where groundwater often supplies the bulk of the water required for irrigation), and concluded that the basins are losing water at a rate of 31.0 mm yr^{-1} and a volume of 30.9 km^3 for the study period between 2003 and 2010."

In the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report, the projected rise in sea level from 1990 to 2100 was 9–88 cm with a mid-estimate of 48 cm (Church et al. 2001). The Fourth Intergovernmental Panel on Climate Change (IPCC 2007) projected a global sea level rise of 18 to 59 centimeters from 1990 to the 2090s, plus an unspecified amount that could come from changes in the large ice sheets covering Greenland and Antarctica. Nicholls et al. (1999) found that "a global rise in sea level of about 38 cm from 1990 to the 2080s, up to 22% of the world's coastal wetlands could be lost by the 2080s, and up 70% when combined with other losses due to direct human action." Given that 21% of the world's population already live within 30 kilometers of the coast (Gommes et al. 1997) and these populations are growing at twice the global average (Bijlsma et al. 1996), Nicholls et al. (1999) suggest that "the number of people flooded by storm surge in a typical year will be more than five times higher due to sea-level rise by the 2080s, and many of these people will experience annual or more frequent flooding."

A.2.2.2 Sensitivities to Human Decision-Making: Importance of Agriculture and Energy

Pressure on global water resources is mounting (Postel 2000, Jury and Vaux 2007, Alcamo et al. 2007), with rising population and economic growth around the globe driving higher water demands for municipal, agricultural (crop production), and industrial (energy, manufacturing) water purposes. From 1900–2000, global freshwater withdrawals—domestic, industrial, and agricultural—grew from an estimated annual 580 km^3 to 3830 km^3, with a more than five-fold increase in agricultural water withdrawal, and much larger, nearly eighteen-fold increases in industrial and domestic withdrawals (Shiklomanov 2000). Continuing growth in sectoral water use is likely to be similarly uneven. Thus, while irrigated agriculture (A), industrial (I), and domestic (D) withdrawals currently account for approximately 70%, 20%, and 10% of the total, respectively (Shiklomanov 2000), several global water models project converging shares over the next decades, so that sectoral withdrawals amount to 41% (A), 28% (I), and 31% (D) (Alcamo et al. 2007), 52%, 37%, and 11% (Shen et al. 2008), or 60%, 20%, and 20% (Davies and Simonovic 2011) of the total by 2075. This convergence results from differing trends in key determinants of sectoral water use. Specifically, agricultural water use is likely to grow relatively slowly, albeit from a large initial volume, because the global area of irrigated land is not expected to expand dramatically in the next few decades (Bruinsma 2009, Postel 1999), and irrigation projects tend to be fairly inefficient with much improvement possible (Gleick 2003)—although climate change is likely to increase crop-water requirements (Döll 2002). In contrast, industrial and domestic water uses are more closely linked to rising gross domestic product and population (Alcamo et al. 2003, Vörösmarty et al. 2000) and may therefore grow rapidly even as water resources become increasingly scarce.

Postel et al. (2006) estimated a global mean annual runoff volume of 40,700 km^3/year: 7,774 km^3/year in remote flows that are inaccessible to human use and 20,426 km^3/year of uncaptured floodwater that flows directly to the world oceans. Only the remaining 12,500 km^3/year as geographically and temporally accessible runoff, of which 2,350 km^3/year is needed for instream water uses. Thus, humans' access to renewable water is about 10,150 km^3/year.

Withdrawal is the amount of water taken from the water supply system (lakes, groundwater aquifers), and consumption is the amount of water that is made unavailable to users in a basin (e.g., evaporated or transpired) (Shiklomanov 2000). Humans currently withdraw 8% of the total annual renewable freshwater and 54% of accessible runoff (UN/WWAP 2003) and modify the timing of global runoff sufficiently to make us significant players in the hydrological cycle (Biemans et al. 2011, Poff et al. 2007). Further, more than two billion people currently live in highly water-stressed areas (Postel, 2000) (similar estimates given by Vörösmarty et al. 2000 and Arnell et al. 2011) because of the uneven distribution of runoff in time and space, and the situation is likely to worsen in the future as regions are subjected to more extreme climate conditions and rapidly growing demands in water-use sectors (Vörösmarty et al. 2000). By 2025, according to the World Resources Institute's 2000 Pilot Analysis of Global Ecosystems, at least 3.5 billion people, or 48% of the world population, will live in water-stressed river basins.

The consequences of imbalances between water supply and demand are already well-known and are occurring in many basins around the globe (Postel 1999, Siebert et al. 2010). Ecological damages include the depletion of rivers (e.g., Yellow River in China [Yang et al., 2004]), lakes (e.g., Aral Sea [Micklin, 1988, 2007]), and aquifers (e.g., in India due to excessive groundwater irrigation [Rodell et al., 2009]); human and economic impacts include reduced crop production, reduced power production (Rübbelke and Vögele 2011), and restrictions on industrial and domestic activities that use water (Jury and Vaux 2007). Growth in municipal and industrial demands as well as increased environmental flows will lead to increased water stress in many regions of the globe.

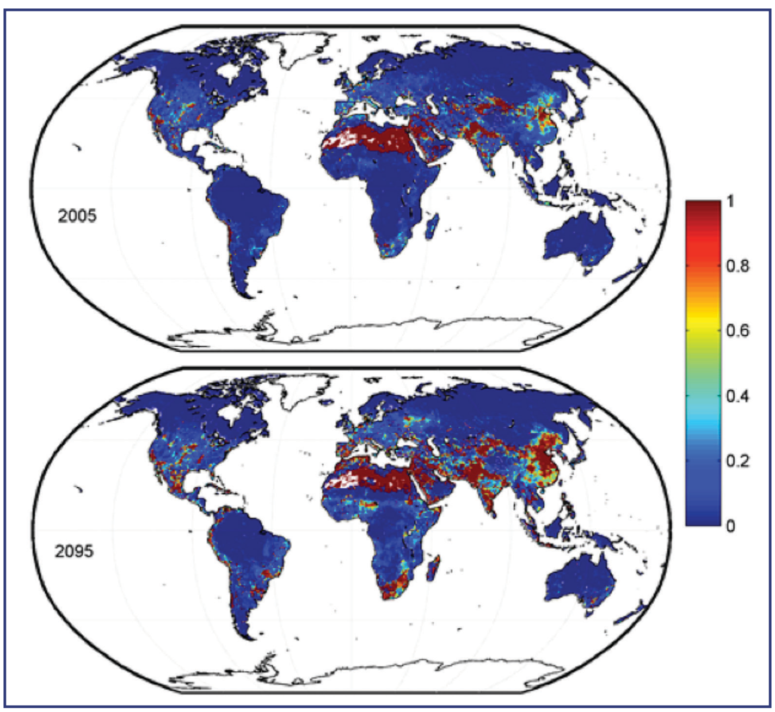

Figure A4. Water scarcity conditions in years 2005 and 2095, calculated on the basis of future water availability and potential demand as reflected in a no-policy scenario and a single set of technology assumptions.

Irrigated area has increased by more than five times to 250 million hectares worldwide as compared to the beginning of the twentieth century (Rosegrant et al. 2002). This has been instrumental in boosting agricultural yields and stabilizing global food production and prices, while in some regions it has also resulted in lower groundwater tables, damaged soils, and reduced water quality (Rosegrant et al. 2002). Kerr (2009) found that "the world's most intensively irrigated region of eastern Pakistan across northern India and into Bangladesh (hosting 600 million people) is depleting its groundwater by 54 cubic kilometers per year." Rodell et al. (2009) show that "groundwater is being depleted at a mean rate of 4 cm per year (17.7 km^3 per year) over the Indian states of Rajasthan, Punjab and Haryana (including Delhi) during the period August 2002 to October 2008, with a 109 km^3 net loss of groundwater depletion." Two-thirds of the global area equipped for irrigation in 1995 will suffer from increased water demands under climate change (Doll 2002). Agricultural and human wellbeing will be negatively affected by climate, with a potential of a 20% increase in child malnutrition by 2050.

Following moderate climate and global change scenario assumptions, severe future alterations in discharge regimes are expected to lead to unstable regional trends in hydropower potentials with reductions of 25% and more for southern and southeastern European countries (Lehner et al. 2005). More recently, van Vliet et al. (2012) found that "thermoelectric power in Europe and the United States is vulnerable to climate change owing to the combined impacts of lower summer river flows and higher river water temperatures. Using a physically based hydrological and water temperature modeling framework in combination with an electricity production model, they show a summer average decrease in capacity of power plants of 6.3–19% in Europe and 4.4–16% in the United States depending on cooling system type and climate scenario for 2031–2060. In addition, probabilities of extreme (>90%) reductions in thermoelectric power production will on average increase by a factor of three." They concluded that "considering the increase in future electricity demand, there is a strong need for improved climate adaptation strategies in the thermoelectric power sector to assure future energy security."

A.2.2.3 Sensitivities to Human Decision-Making: Land-Use in Catchments

Worldwide changes to land use are being driven by the need to provide food and fiber to more than six billion people (Foley et al. 2005). Foley et al. articulate that "global croplands, pastures, plantations, and urban areas have expanded in recent decades, accompanied by large increases in energy, water, and fertilizer consumption, along with considerable losses of biodiversity." They further explain that "such changes in land use have enabled humans to appropriate an increasing share of the planet's resources, but they also potentially undermine the capacity of ecosystems to sustain food production, maintain freshwater and forest resources, and regulate climate." Biofuel development will have dramatic impact on agricultural land use and irrigation demand.

Land-use practices have influenced the global carbon cycle and, possibly, the global and regional climate system (through changes in surface energy and water balance) (Foley et al. 2005), and roughly 35% of anthropogenic CO_2 emissions over the past 150 years have come from land use (Houghton and Hackler 2001). For example, Foley et al. found that "land conversion can alter regional climates through its effects on net radiation, the division of energy into sensible and latent heat, and the partitioning of precipitation into soil water, evapotranspiration, and runoff." Modeling studies demonstrate that land cover changes in the tropics affect climate largely through water-balance changes, but changes in temperate and boreal vegetation influence climate primarily through changes in the surface radiation balance (Snyder et al. 2004). Large-scale clearing of tropical forests may create a warmer, drier climate (Costa and Foley 2000), whereas clearing temperate and boreal forest is generally thought to cool the climate, primarily through increased albedo (Bonan et al. 1992). Land use changes can have dramatic impacts on GHG emissions that impact regional and global climate. Land use can also disrupt the surface water balance and the partitioning of precipitation into evapotranspiration, runoff, and groundwater flow. Surface runoff and river discharge generally increase when natural vegetation (especially forest) is cleared (Costa et al. 2003). For instance, the Tocantins River basin in Brazil showed a ~25% increase in river discharge between 1960 and 1995, coincident with expanding agriculture but no major change in precipitation (Costa et al. 2003).

Land use has also caused declines in biodiversity through the loss, modification, and fragmentation of habitats, degradation of soil and water, and overexploitation of native species (Pimm and Raven 2000). During the past 40 years, there has been a ~700% increase in global fertilizer use (Tilman et al. 2001) and a ~70% increase in irrigated cropland area (Rosegrant et al. 2002, Gleick 2003). Anthropogenic nutrient inputs to the biosphere from fertilizers and atmospheric pollutants now exceed natural sources and have widespread effects on water quality and coastal and freshwater ecosystems (Bennett et al. 2001).

Intensive agriculture increases erosion and sediment load and leaches nutrients and agricultural chemicals to groundwater, streams, and rivers. In fact, agriculture has become the largest source of excess nitrogen and phosphorus to waterways and coastal zones (Bennett et al. 2001). Urbanization also substantially degrades water quality, especially where wastewater treatment is absent. The resulting degradation of inland and coastal waters impairs water supplies, and causes oxygen depletion and fish kills (Bennett et al. 2001, Townsend et al. 2003)."

A.2.2.4 Sensitivities of Precipitation to Human Influences: Local/Regional and Global

The effect of land use/land cover change (LULCC) on precipitation has been well documented (e.g., Pielke 2001, Pitman 2003), and some of the prevailing LULCC scenarios include: grass conversion to dryland and irrigated agriculture, forest conversion to agriculture, urbanization, biomass burning, and afforestation/reforestation (Pielke et al. 2007). For example, Pitman et al. (2004) found that large-scale land cover change explains the observed changes in rainfall and temperature in southwest of Western Australia in the mid-twentieth century. Pielke et al. (2007) stated that "conversion from grasslands or croplands to forest (afforestation or reforestation) leads to a decrease in albedo and increases of LAI, roughness length and rooting depth (Pitman, 2003), thus, modifying the near-surface energy fluxes, which can influence temperature and humidity (Pielke, 2001), and precipitation." In general, precipitation increases when land is reforested/afforested with respect to a current land cover (Pielke et al. 2007). Land transformation from forest to agriculture or pasture increases albedo and decreases surface roughness, and model simulations suggest that the net effect of this transformation is to increase temperature and decrease precipitation regionally (Gornitz et al. 1997).

Irrigation increases atmospheric humidity in semiarid areas, often increasing precipitation and thunderstorm frequency (Milly and Dunne 1994). Douglas et al. (2006) investigated the impacts of agricultural intensification over the Indian monsoon region, found that mean annual vapor fluxes have increased by 17% (340 km^3), and attributed two thirds of this increase to irrigation. Irrigation and agricultural activity during the growing season are also responsible for significantly modulating the surface temperatures over the Indian subcontinent (Roy et al. 2007). Furthermore, Kishtawal et al. (2010) showed "a significantly increasing trend in the frequency of heavy rainfall climatology over urban regions of India during the monsoon season," and "that urban areas are more likely to experience heavier precipitation rates compared to those in nonurban areas."

Pielke et al. (2007) indicated that "urban areas radically restructure the local energy budget and thus lead to different boundary layer structure (Arnfield 2003, Shepherd 2005). The anthropogenic influence also includes altering the aerosol environment. These changes likely lead to alterations in urban precipitation frequency, intensity, and patterns." Note that although urban land accounts for about 2% of the available land, 45% of the world' population is concentrated there (Arnfield 2003).

Forest fires and biomass burning are responsible for large smoke plumes with aerosols (tiny particles), which can potentially affect the regional climate system and potentially the hydrological cycle (Ramanathan et al. 2001). Pielke et al. (2007) explain that "aerosols serve as cloud condensation nuclei which affect the formation of cloud droplets (Cotton and Anthes 1992); thus the extensive input of aerosols from fires could significantly affect cloud properties and rainfall. Air pollution can have local and global impacts on climate. Aerosol-induced reductions in surface radiation are likely to decrease global rainfall (Lohmann and Feichter 2005)." Lin et al. (2006) found that biomass burning in the Amazon provides strong input of aerosols into the atmosphere, enhancing precipitation, cloud properties, and radiative balance. And their results are "consistent with previous observational and modeling studies that pointed to dynamical effects from aerosols that invigorate convection, leading to higher clouds, enhanced cloud cover, and stronger rainfall".

Scientists have also postulated that large dams can contribute to enhanced regional precipitation and extreme weather patterns (Hossain et al. 2009). Hossain et al. state that "the increased evaporation from the open-water surface of a reservoir and irrigated land will alter both average and extreme precipitation patterns through a feedback mechanism." Furthermore, they argue that "dam-driven land cover change can trigger changes in extreme precipitation patterns, and irrigated land near multipurpose reservoirs is seen to enhance thunderstorm development more than natural land cover conditions do (e.g., before the dam was built) (Pielke et al., 2007)." Kishtawal et al. (2010) recently showed that "increased urbanization downstream of large flood control dams can also trigger heavy rainfall patterns. Avissar and Liu (1996) showed that LULC patchiness can enhance heavy rainfall. Lohar and Pal (1995) support the notion that atmospheric moisture added by irrigation can increase rainfall, provided that mesoscale conditions are met. Thus, large dams, defined by the International Commission on Large Dams (ICOLD) as having a height greater than 15 meters from the foundation and holding a reservoir volume of more than 3 million cubic meters, have the potential to vastly transform local climate, landscapes, regional economics, and urbanization patterns."

Pielke et al. (2011) argues that "LULCC can result in mesoscale and regional climate change if the areal coverage of the landscape conversion is large enough. A spatial heterogeneity of approximately 10–20 km has often been considered sufficient for creating mesoscale circulations under convective conditions though smaller scales approximately 2–5 km are also often sufficient to trigger changes in boundary layer dynamics (Baldi et al., 2005). For the monsoon effects, the threshold may be larger. The irrigation effects for northwest India, for instance, suggest that the required landscape change is probably on the order of 50–100 km to affect the synoptic convergence patterns."

The Amazon River has the largest discharge of any river and accounts for 18% of all of the riverine input to the oceans (Subramaniam et al. 2008). Cowling et al. (2008) investigated "the relationship between Amazonian vegetation and surface water dynamics, specifically, the recycling of water via evapotranspiration (ET)." They found that the absolute value of recycled water is lower when accounting for vegetation as a result of increasing atmospheric CO_2 that in turn promotes lowering of stomatal conductance and increase in water-use efficiency. Precipitation is reduced by an extra 30% in the simulating the vegetation effect over the duration of their climate change simulation.

Human water use through massive irrigation can enhance evaporation and subsequently affect the regional climate system. For example, Douglas et al. (2006, 2009) showed that the dramatic increase in irrigation in India over the past several decades may destabilize the region's monsoon system and consequently propagate westerly, affecting other neighboring monsoons in India and Africa (Janicot et al. 2009). In Amazonia, deforestation and expansion of irrigation land over the past several decades has led to a 25% increase in runoff (Coe et al. 2009). A positive feedback loop where deforestation leads to less evapotranspiration and subsequently less precipitation which can lead to more deforestation, and so on, has been postulated by Coe et al. (2009). These examples illustrate some of the known effects of human actions in the global water system and how they propagate to affect natural processes. Human-induced climate change through elevated GHG emissions can also have a cascading effect on both the physical and the human systems. For example, studies suggest that climate change is responsible for elevated temperatures and more extreme weather, elevated CO_2 fertilization, shifts in rainfall and runoff patterns, and ultimately changes on yield. Those changes can impose many important consequences to the human system. Depending on the prevailing climate change scenario, there will be different implications to human land, water, energy, and food choices. Those choices are likely to change the global map of water demand and scarcity and consequently feedback to affect the water cycle.

A.2.3 Future Research Needs

The preceding sections clearly identify the many different ways in which we already know that the interaction between the hydrologic cycle and human decision making, in the context of the entire earth system, can affect the amounts; distribution; and future supply, demand, and use of water. But the quantitative details of all the interactions of water, decision making, and the earth system are not always as clear as one would need for the purpose of improving decisions about water, based on the best available science. Likewise, the importance of the underlying scientific uncertainties in terms of how they might affect decisions about water is not well understood. We thus see at least four areas of research needs in which scientific research and modeling could proceed in order to understand these interactions more completely.

A.2.3.1 Modeling Human Water Use Directly

As discussed earlier in this paper, there are considerable statistics in the industrialized nations on the ways in which humans appropriate water for different uses, and how that appropriation affects flow regimes, the supply of fossil water, etc. However there are very limited data in the developing world. Even in the developed nations, data on water use can have surprising gaps, especially where the use of water has not been metered carefully (if at all). The capacity to model how those uses might change over time is less well developed. There is good capacity to model changes in the use of water as a function of existing technologies and practices in both the energy and agricultural systems, but limited in the municipal and industrial sectors. Given that all these uses are driven by population and economic drivers, there is far less capacity to model how use might change as the mix of energy and agricultural technologies and practices change, and therefore to understand the interaction of that evolution with the hydrologic and earth system. This is an area in which immediate progress could be made.

There is an urgent need for data, especially at the subnational and river basin scale and geospatially linked to withdrawal points. Water demands need to be linked to specific water supply and not to grids. Global data are very limited in quantity and quality before 1995, and Food and Agricultural Organization of the United Nations (FAO) water global water demands data are still limited to 2000. We need additional time-series and cross-sectional data at all scales to evaluate our models of dynamic water demand behavior.

A.2.3.2 Modeling the Interactions Among Human Systems (Water Management, Agriculture, Energy System) at Appropriate Scales

A main message of the initial review of the literature is that there are strong interactions among the earth system, the hydrologic cycle, and water use. In the US National Climate Assessment, for example, the Energy-Water-Land Technical Input Report (Skaggs et al. 2012) portrays the intersections of these sectors as a major gap in knowledge. Filling this gap will require the further evolution of integrated modeling platforms that allow variation in any one of these sectors to interact with the others. Designing such model integrations to allow systems interactions to be isolated and examined individually will be important for understanding systems behaviors and diagnosing model errors from individual models and the coupled models. Questions of appropriate scale will naturally arise in integrating human systems, but appropriateness of scale will depend on the inherent time/space scales of the processes relevant to the particular question being asked, and on the availability of data and information on use. New modeling frameworks must be evaluated at appropriate scales with observational data in order to understand their sensitivity to measurement and modeling uncertainty. Exploring a hierarchical framework that may provide a tractable approach for evaluating integrative and multi-scale models could be beneficial. It is important to understand and improve the consistency of the economic, policy, and population scenarios used to project water demand with the climate change scenarios that are the results of the GHG emission from the associated economic, policy and population scenarios.

A.2.3.3 Ability to Model Feedbacks from Land Surface Change and Energy System Change to the Atmosphere

There is still limited knowledge about the sensitivity of water use to changes in the availability of precipitation, runoff, streamwater, and groundwater, which limits our ability to model future water use. Quite a bit is known in general about the exchange of water between ecosystems (including especially agricultural systems) and the atmosphere. But in general, there are large uncertainties in modeling changes in the atmospheric water cycle (e.g., water vapor, cloud, and precipitation) as a consequence of changes in water use decisions, because the land-atmosphere coupling strength in coupled land-atmosphere models with different model parameterizations varies significantly in regions (so-called "hot spots") where land-atmosphere interactions are important. Because there is the potential for such changes to be large (for example if a large and intensive bioenergy industry were to develop), it will be extremely important to develop and test models that are capable of simulating those feedbacks and then understanding how they might affect the future evolution of the earth system.

A.2.3.4 Ability to Simulate and Analyze Multiple Scenarios

While there is every reason to expect the development of modeling platforms that can integrate the hydrologic cycle, the earth system, and human decision making to continue to proceed, we cannot anticipate that such models will be able to predict the future course of human decision making about water. Instead, we will need to have both the modeling knowledge and the computational resources to allow the generation and analysis of multiple scenarios—both as an exercise in the evaluation of parametric and structural uncertainties in the models, but also as a way to evaluate the importance of different decision-making methods for the water sector, and as a way to explore alternative potential futures.

A.2.3.5 Understanding Predictability of the Water Cycle in the Context of the Coupled Human-Earth Systems

Non-stationarity of the hydrologic cycle has important implications for the design of water systems. Similarly, changes in the water systems due to technological and other changes can influence the hydrologic cycle through many pathways across a wide range of time and space scales. Understanding the predictability of the water cycle in the context of the coupled human-earth systems is important for framing questions that could be addressed and provide guidance for designing prediction systems that exploit the sources of predictability at different time/space scales to achieve predictive skill. While the predictability of the climate system from intraseasonal to century time scales has been extensively studied (though our understanding of the predictability at different time scales still varies), much less is known about the predictability of the coupled human-earth system, partly because models that represent both human and earth system processes are less well developed for such studies, and the framework for evaluating predictability of the coupled system has not been widely discussed. Efforts to systematically assess the sources of predictability of the coupled human-earth system and understanding its predictability are important towards prediction of the integrated water cycle.

A.3 Challenges of Representing and Predicting Multi-Scale Human-Water Cycle Interactions in Terrestrial Systems

David Lawrence, Reed Maxwell, Sean Swenson, Sonya Lopez, Jay Famiglietti

Critical Research Gaps and Needs

- Increase focus on scaling issues and heterogeneity to include exploration of novel approaches for subgrid scale parameterization, as well as general research into scale dependence and scale behavior.
- Improve terrestrial hydrologic cycle process representation with the goal of addressing existing biases.
- Support data synthesis and distribution efforts and improve data accessibility with the goal to develop a comprehensive and extensible land model benchmarking system with an emphasis on metrics that evaluate terrestrial processes rather than forcing.
- Expand representation of human water management of and vulnerability to water cycle including crops, irrigation, groundwater withdrawal, reservoir management, urbanization, and impact of disturbances such as land cover change.

A.3.1 Scientific Challenges

The presence of water in all its forms is a fundamental feature of Earth's climate, and the transport of water between land, ocean, and atmosphere is tightly coupled to the cycling of energy and carbon. Water is critical to virtually all human endeavors including food and energy production, consumptive use, and environmental protection. Consequently, there is an emerging societal need for information about water at regional and global scales, especially with respect to understanding vulnerabilities in the water system under a changing climate (e.g., changing frequency, duration, intensity, and distribution of future droughts and floods or assessing the sustainability of renewable or limited water resources). However, representing the terrestrial water cycle in models at regional and global scales on daily to century timescales remains a challenge. Hydrological models exist for a variety of purposes, at a variety of spatio-temporal scales. For example, runoff-routing models may be used to study a flash flood from a single precipitation event in a relatively small catchment, while equilibrium groundwater models may be used to estimate steady-state subsurface flow paths within large regions. Similarly, vegetation models range from scales of individual leaves to biomes.

Several fundamental aspects of the terrestrial water system remain poorly modeled, including the hydrologic response to land cover and land-use change. Furthermore, modeling the effects of human activity on the water cycle as well as the vulnerability of humans and ecosystems to changes in the water system are relatively new endeavors for ESMs, requiring both model development and validation. Creation of a terrestrial systems model capable of simultaneously meeting all of these demands through synthesis and integration of existing knowledge manifest in hydrologic, land surface, ecosystem, and human dimensions models will require a sustained and cooperative community effort. In this white paper we provide a brief perspective on existing models and set forth a description of some required advances for terrestrial systems models. These advancements would expand our ability to address the host of scientific challenges and opportunities that focus on water in the terrestrial realm.

A.3.2 Current Status and Research Gaps

Originally designed as a terrestrial boundary condition for GCMs, land surface models focused on biogeophysical aspects of the terrestrial system such as partitioning of precipitation into runoff and evaporation, snow accumulation and melt, and the impact of these processes on surface albedo and surface turbulent and radiative flux exchange (e.g., Manabe et al. 1970, Betts et al. 1996, Ek et al. 2003). In recognition of the important role that the biosphere has on the modulation of evapotranspiration, subsequent generations of land surface models incorporated dynamic vegetation controls, eventually including prognostic biogeochemical models (Pitman 2003, Friedlingstein et al. 2006, Bonan et al. 2011). More recently, land models have begun to integrate groundwater modules (Liang et al. 2003, Maxwell and Miller 2005, Fan et al. 2007, Leung et al. 2011) and efforts to extend these models to include fully integrated descriptions of terrestrial hydrology have also

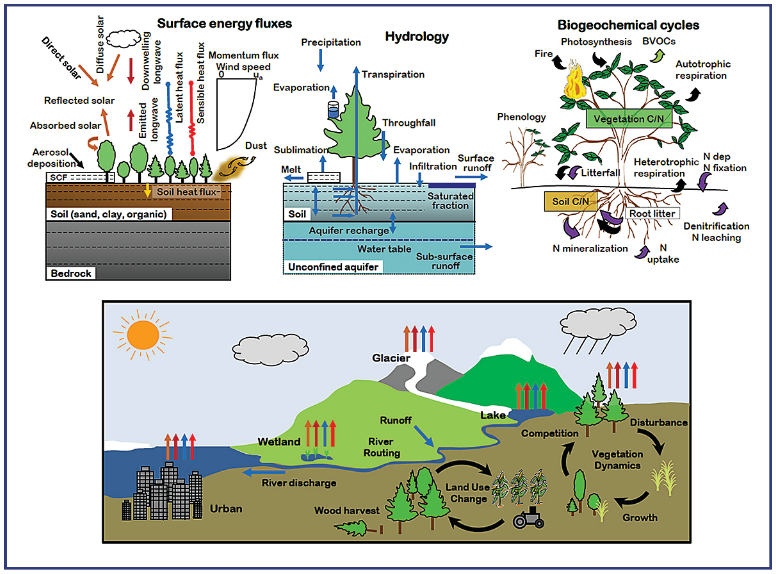

Figure A5. Schematic diagram depicting processes represented in the Community Land Model (CLM4, Lawrence et al. 2011).

been done (e.g., Panday and Huyakorn 2004, Qu and Duffy 2007, Kollet and Maxwell 2008), though not typically at the global scale.

On the whole, the current generation of land models is quite comprehensive (Figure A5), and as a result of decades of model development these models can perform many of the tasks of traditional stand-alone hydrologic models. Nonetheless, existing parameterizations are continually being improved upon, steadily increasing the fidelity of the terrestrial water representation in ESMs. However, many gaps remain, especially in representing the broad scope of human-water interactions, with respect to understanding and developing mechanisms to address the scale dependence of existing parameterizations. Additionally, recent advances in hydrological modeling such as distributed hydrology and groundwater flow need to be incorporated into global terrestrial systems models. These opportunities for improvement will be the focus of the remainder of this document.

Here, we review current land model limitations and identify potential avenues for improvement. Two paths of land surface model development are needed: (a) to improve the parameterizations of currently modeled hydrological variables and (b) to expand the representation of water in land surface models to include human water management, especially with respect to food and energy production and use, as well as for societal and ecosystem vulnerability to projected changes in the water cycle.

A.3.2.1 Improve the Parameterizations of Currently Modeled Hydrological Variables

The current-generation climate and ESMs are designed to simulate the evolution of the biogeophysical and biogeochemical states of the land surface and subsurface and the fluxes that describe these changes. This task comprises the calculation of the surface energy and moisture fluxes to the atmosphere, the return of precipitation to the oceans via rivers and streams, and the cycling of above- and below-ground carbon and nutrients. In transient simulations, these processes may be modulated by changes in land use and land cover.

To varying degrees, biases exist in the terrestrial hydrological cycle described by current-generation ESMs. Such biases are manifested directly in surface turbulent fluxes and indirectly in the representation of the carbon and nutrient cycles. Simulations of soil moisture, river discharge, and latent heat fluxes often cannot accurately reproduce observations from the historical period over the whole range of ecosystems. The Global Land Atmosphere Coupling Experiment (GLACE) found considerable disparity in the strength of land-atmosphere interaction, both across different models and between different versions of the same model (Koster et al. 2004, Lawrence et al. 2007) due to differences in both land and atmosphere processes. The recent Land-Use and Climate, Identification of robust impacts (LUCID) model intercomparison demonstrated that models equally differ with respect to the biogeophysical response to land cover change, with the models being especially divergent in their hydrologic response (Pitman et al. 2009). The effect of water stress on vegetation productivity and ecosystem development is also poorly represented in models. Finally, several recent studies have demonstrated that improvements in the representation of the biological control of ET are still needed, particularly with regard to within-canopy and above-canopy turbulence and vertical canopy scaling of leaf properties (Bonan et al. 2011, Bonan et al. 2012).

The biases highlighted by observations and the divergence of model behavior in intercomparison studies suggest that the processes controlling the cycling of moisture through the terrestrial system and between the land and atmosphere are inadequately understood and/or represented in land surface models. A recent study by Koster and Mahanama (2012) provides an excellent framework in which land models and their simulation of hydroclimate means and variability can be evaluated and improved. The method relies on the assumption that the relevant soil moisture-evapotranspiration and soil moisture-runoff relationships are, to first order, universal. Using a simple water balance model, one can demonstrate the degree to which they interact to determine spatial distributions of hydroclimatic means and variability. In the process, the simple model provides estimates for the underlying relationships that operate in nature (Figure A6) which can be compared against more complex land surface models, and with expert intervention, the emergent relationships can be reworked in the land model to better conform to reality.

There are a number of possible reasons for the current model limitations. Wood et al. (2011b) describe several major challenges facing the land surface/

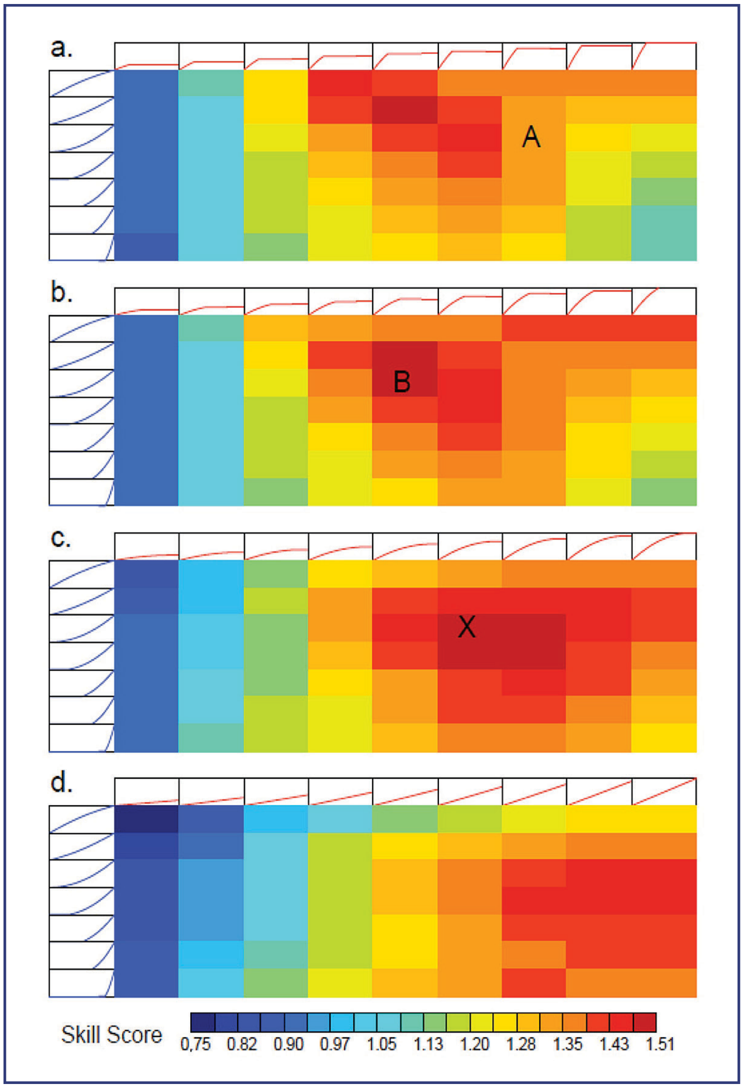

Figure A6. Variation of skill score focusing on means and variability of hydroclimatic variables as a function of imposed E/Rnet vs W relationship the red curves along the top of the panel) and imposed Q/P vs W relationship (the blue curves along the left side of the panel). The x-axis and y-axis for the E/Rnet and Q/P curves span the range (0, 1). The skill score for a given combination of relationships is indicated by the color of the cell lying in the corresponding column and row. (b)–(d) As in (a) but for a (b) second, (c) third, and (d) fourth set of E/Rnet relationships. Letters mark combinations that are discussed specifically in the paper. (See Koster and Mahanama [2012] for details.)

hydrology modeling community that are relevant here. These include:

- improved representation of land-atmosphere interactions including ongoing investigation into the required spatial information on soil moisture and evapotranspiration
- improved representation of surface-subsurface interactions due to fine-scale topography and vegetation
- developing the required in situ and remote sensing global data sets through which a robust model evaluation/benchmarking system can be developed (see Section A.4).

In particular, the relationship between the spatial and temporal scales at which processes are studied and the scales at which they are modeled are typically not well understood. For example, snow and soil moisture, which may vary on spatial scales of meters, are generally modeled as uniform distributions on scales of tens to hundreds of kilometers. Similarly, the highly heterogeneous nature of model inputs, such as soil hydraulic properties and the lack of information on their vertical distribution, leads to commensurate uncertainty in the bulk values chosen for use at the model grid scale. Vertical model domains often span a fixed depth, when in reality spatial variations in soil depth can strongly impact soil moisture storage and the relative magnitudes of runoff and surface heat fluxes. Put succinctly, the challenge of heterogeneity in all its forms remains tantamount.

The existing representations of the terrestrial water cycle are not only imperfect but are also incomplete in most large-scale land surface models. For example, neither flooding nor wetlands are typically explicitly represented despite their importance in determining surface fluxes and biogeochemical cycling. The direct

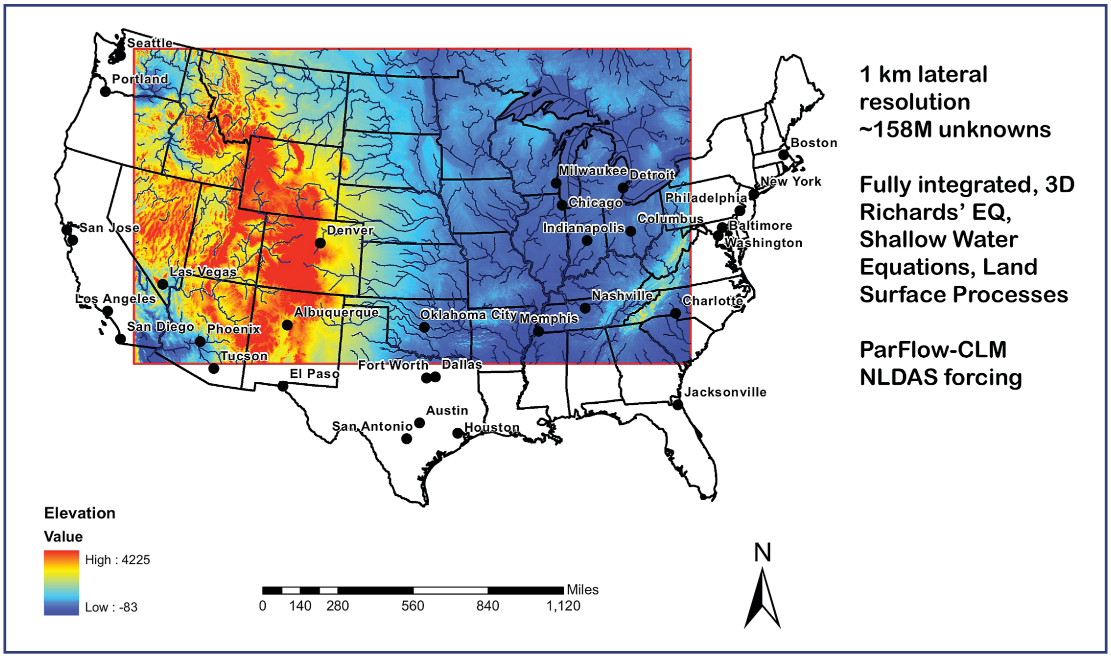

Figure A7. A proof-of-concept, 6.3M km² domain of a land surface model fully integrated with a 3D model of subsurface flow covering much of the conterminous U.S.

effect of vegetation type on runoff generation is largely absent in current land surface models, though it is a feature included in most physical hydrology models. Some land surface models used in ESMs have recently incorporated bulk groundwater components; however, many have not. As the models shift towards higher resolution, groundwater and lateral subsurface flow are likely to be more important. Extension of global land models to include fully integrated descriptions of terrestrial hydrology (e.g., Panday and Huyakorn 2004, Qu and Duffy 2007, Kollet and Maxwell 2008) is also required (Figure A7). Though significant efforts have advanced the understanding of coupled physical hydrologic processes, these efforts have yet to extend to both global spatial and decadal to century temporal scales needed by GCMs.

A.3.2.2 Expand Models to Include Human Water Management

The effects of human activities must also be considered within the framework of hydrologic modeling. Historically, human alterations (i.e., water impoundment, urbanization, irrigation) to the water cycle have not been incorporated in large-scale terrestrial systems models, but we know that humans strongly altered natural hydrologic components such as streamflow, groundwater and aquifer storage, soil moisture, and evapotranspiration. Preliminary efforts to include simplified human intervention such as irrigation (Sacks et al. 2009) and human water withdrawal and reservoir operations (Pokhrel et al. 2012a) into global models have demonstrated that including these effects can substantially alter the regional water balance and the simulated climate. Impervious surfaces in urbanized areas have changed drainage networks, thus altering surface and subsurface flowpaths and causing a significant reduction in recharge rates (Ma et al. 2004); future climate projections anticipate a further reduction in recharge rates and groundwater availability (Döll 2009). Globally, the population continues to grow, and with it the need for water importation. Human activity not only alters water transport, but also adversely affects both water quality (i.e., metal transport, fertilizer cycling) and availability for consumption and irrigation.

To properly incorporate the impacts human interactions have with the water cycle, several processes must be implemented within a model design including groundwater pumping, surface water reservoir diversion, conjunctive water use and water management, crop and irrigation routines,

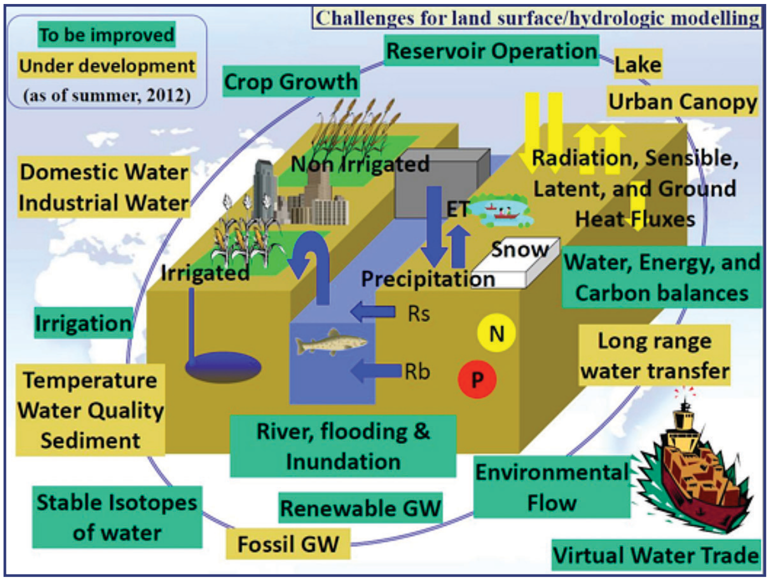

Figure A8. Schematic diagram depicting water processes in the H08/MATSIRO that is used within the Model for Interdisciplinary Research On Climate (MIROC) modeling system, with emphasis on new and missing anthropogenic water processes.

urbanization effects (climate, infiltration, surface drainage, pollutant transport, etc.) and water quality (both non-point and agricultural). A central challenge to incorporating anthropogenic alteration of the terrestrial water cycle is the collection and development of applicable global data sets including those for human consumptive use (now and in the future), irrigation-equipped areas and practices, reservoir location and operation, and aquifer location and volume (Figure A8).

Looking further into the future, as more advanced representations of human interventions of the water cycle are incorporated into global terrestrial systems models, a fundamental question will arise as to whether or not it is possible to couple hydrologic modeling and human-water interactions with human decision-making models. To this end, a significant future direction in addressing human-water interactions will be greater incorporation of IAMs, which provide projections on human energy and food production, into the modeling framework. Increasingly tight integration with IAMs means that we will need to consider how land models should be developed such that the viability of various choices related to energy and food resources can be investigated. Such integrated assessments might address questions about food scarcity, optimal locations for certain crops, and predicting outcomes based on hydrology and future climate. There are also challenges associated with respect to the collection of global and regional socio-economic information and linking this to the modeling framework; however, this work is essential in order to understand long-term changes in the water cycle essential for resource planning.

A.3.3 Research Gaps and Needs

Ease of use for a variety of disparate users ranging from climate modelers to hydrologists to water managers needs to be maintained as a fundamental model development principle. In a similar vein, detailed long-term planning is required to address the general problems of rapidly increasing model output storage and analysis requirements. The challenges for improving terrestrial systems models within the larger hydrologic cycle include both processes description (improving existing processes and expanding to new processes, particularly multi-scale and including human impacts), data availability (both input and observational), coping with uncertainty (both model and parameter) and community outreach to build confidence and to improve model performance (such as training and benchmarking activities).

A.4 Model Testing, Analysis, and Evaluation and Data Needs

Martyn Clark, Steve Klein, and Ruby Leung

Critical Research Gaps and Needs

- Identify key questions for models to address and use hypothesis testing to determine the underlying reasons for complex model behaviors.

- Develop hindcast tests for recent extremes of the water cycle in order to demonstrate credibility for models of the physical systems and human dimensions.
- Use a hierarchical set of models to facilitate understanding and improvement of the water cycle predictions from comprehensive models as well as the interactions between physical water cycle water cycle and models of the human dimensions.
- Fill critical observational gaps, particularly for terms in the physical water budget and for all technologies and human activities that produce or consume usable water.

A.4.1 Scientific Challenges

Models used in advancing understanding and prediction of the integrated water cycle must address two key aspects: (a) the multi-scale characteristics of the water cycle such as the wide range of scales and scale interactions represented by cloud and precipitation processes and (b) the requirements for integrating human dimensions such as water demand and water use in ESMs. These aspects will present new challenges for model testing, evaluation, and analyses, as existing approaches generally focus on model skill in simulating or predicting phenomena that cover a relatively small range of spatial/temporal scales, lack an emphasis on scale interactions, and pay limited attention to human dimensions and their interactions with natural processes.

The modeling of moist processes (precipitation, clouds) is a long-standing weakness of all atmospheric models. This arises fundamentally because the range of spatial and time scales of precipitation far exceeds what current models can explicitly simulate. Despite noticeable progress, the remaining deficiencies are still significant, particularly to aspects of precipitation such as frequency, intensity, duration, and thus they will impact the predictions of the water cycle by any atmospheric model. There is some hope that once computer resolutions approach the 1-kilometer scale, the main convective scale events responsible for major precipitation events can be reasonably modeled. However, the large computational expense of such models precludes routine use except over limited areas through nested or variable-resolution models. These models may be useful for cases where the interactions between large and small scales are minimal or can be characterized as one-way (e.g., in a regime driven by synoptic-scale activities). These models may also be used when the goal is to use the very fine resolution atmosphere models (resolutions of 1-kilometer or less) to model any important interactions that happen at small scales with the land surface. To model the human component, these models could be coupled to the human-earth system models, but the limitation of this modeling approach would be the requirement that human interactions between the large and regional scales be minimal.

If one employs a nested or variable-resolution modeling system, the predictions of an integrated modeling system may suffer from the fact that the large scale comes from a coarser resolution simulation that does not treat the moist processes with the same fidelity as the high-resolution region. This deficiency is true whether or not there are one-way or two-way interactions between the high and coarse resolution regions. Thus one key aspect of model testing must be to isolate the errors associated with the dynamical approach for high-resolution modeling, such as represented in the variable-resolution or regional modeling approach described above, from errors associated with physics parameterizations and their dependence on spatial resolution. Developing frameworks and testbeds to clearly delineate these errors, in the context of water cycle processes, is important to establishing credibility with models of multi-scale processes.

Compared to models of the natural systems that are generally more physically based, models of the human systems, particularly the social systems, may be more data-driven (e.g., parametric models), and some models are prescriptive rather than predictive by design. Two primary goals for models of the human systems are to quantify demand for water under various future scenarios and to assess the effects of limited water availability on human decisions. Necessarily, methods used to evaluate human system models may differ from that used to evaluate climate or environmental models. The coupling of human and earth system models is at a very early stage. Given the challenges in evaluating human system models such as water demand models, water management models, land use models, and the more comprehensive IAMs, evaluating coupled human-earth system models is even more challenging and may require new approaches and frameworks.

One key challenge of diagnosing deficiencies in integrative human-earth system models is the ubiquitous problem that errors in one model component may compensate for errors in another model component, resulting in a system-scale response that appears realistic even though individual model components have an unrealistic representation of the processes they are intended to represent. This problem may potentially be quite pronounced in the very complex integrative human-earth system models, where the system-scale response depends on unanticipated interactions among individual system components. Addressing the problem of compensatory errors requires both (a) extensive model analysis to understand sensitivity of individual model components and interactions among components and (b) extensive model evaluation activities that evaluate the fidelity of individual components, component interactions (feedbacks), and the system-scale response. Similar to the concerns of compensating errors in integrated human-earth system models, modeling the multi-scale processes in the water cycle may face the same challenges. Errors in one scale (e.g., the large-scale atmospheric environment or basin scale response to precipitation) could potentially compensate for errors in another scale (e.g., convective systems or hydrologic processes at watershed scale), and how such compensation plays out may depend on the approaches used to model processes across scales. Thus a key challenge in testing and evaluating models for simulating multi-scale water cycle processes is to understand their behaviors and fidelity over a wide range of scales.

Given that compensatory errors plague both physical models and human-earth system models, there is great chance the coupling of these models will create a complex modeling system with significant potential for incorrect behaviors. A central goal of model testbeds is to understand the behavior of the models so that we can separate true model successes for the right reasons from model successes arising through compensating errors. To achieve this understanding, hypothesis testing and detailed analysis of the underlying reasons for model behavior must be undertaken, and it is essential to have a good set of questions for the modeling systems to address. Without understanding the physical/human basis of model predictions, we will not have any confidence that our systems will be of predictive use, especially when encountering new extremes or out-of-sample tests; past performance can only be trusted so much.

Sometimes, a hierarchy of models of different types can be used to address model complexity and compensating errors in our most comprehensive models. An example, provided by breakout speaker Randy Koster, is the use of a very simple water balance model to identify errors in complex land surface models. This simple water balance tracks only the total mass of soil moisture and computes runoff (Q) normalized to observed precipitation (P) and evaporation (E) normalized to the net radiation input (R_{net}) based upon pre-specified formulations of these quantities as a function of normalized soil moisture. Driven by observed precipitation and radiation, the simple water balance model was run many times with a comprehensive set of evaporation and runoff function pairs. From this ensemble, the pairs that allow the simple water balance model to best mimic

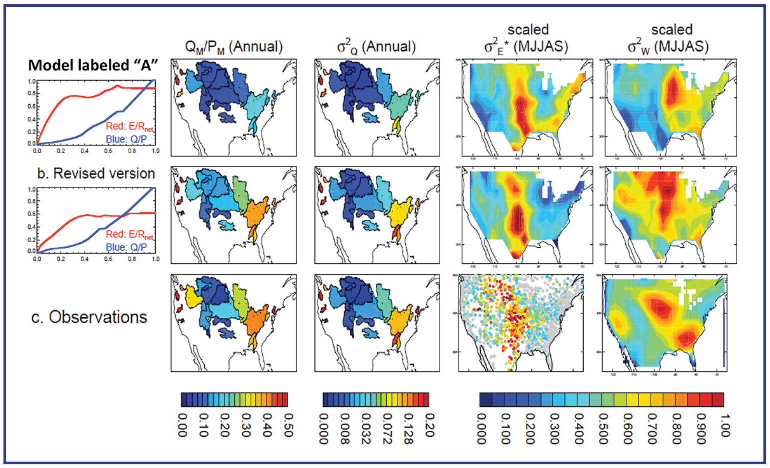

Figure A9. Results from a simple model can be used to inform the functional form of E/R_{net} used by the model labeled "A" for highly improved simulation of hydrological means and variability.

observed hydrological means and variability were determined. These optimized pairs for the behavior of evaporation and runoff are then the targets that modifications to the comprehensive land surface model should aim to reproduce. Results with this method are encouraging (Figure A9).

A.4.2 Current Status and Research Gaps

A.4.2.1 Model Intercomparison Experiments

Model intercomparison experiments have been a popular activity to understand the capability of different models. Since the first Atmospheric Model Intercomparison Project (AMIP) (Gates 1992), there have been many other intercomparison projects including both uncoupled and coupled models (Coupled Model Intercomparison Project, CMIP (e.g., Taylor 2009), as well as focusing on specific aspects of the models such as cloud feedbacks (e.g., CFMIP). Some key examples in hydrology include the Program for Intercomparison of Land surface Parameterization Schemes (PILPS) (Pitman and Henderson-Sellers 1988), the Distributed Model Intercomparison Project (DMIP) (Reed et al., 2004), and GLACE (Koster et al. 2004). These experiments have been successful community activities, providing a forum for model developers to evaluate and address model shortcomings and gain insights about model behaviors.

As with climate models, some boundary conditions are needed to constrain the human system models to simulate past events or conditions. Hampered by the paucity of out-of-sample data (most available data are already used to develop the models) and difficulty in simulating the evolution of the social systems, model intercomparison and sensitivity analysis may be more useful than hindcast experiments for understanding and diagnosing model behaviors. These methods have indeed been used by the integrated assessment modeling community to provide insights on model behaviors and model sensitivity to initial conditions or model structures (e.g., Luderer et al. 2009).

Despite the significant experience gained through generations of model intercomparison experiments, many efforts have been ineffective in understanding inter-model differences. This shortcoming stems from two main reasons: First, from a purely logistical perspective, when comparing an ad hoc collection of participating models, as is typical in current intercomparison studies, there are simply too many structural and implementation differences to meaningfully attribute the performance differences between any two models to specific individual components (Koster and Milly 1997). Second, the output of multi-component models conveys only limited information on the internal system states and fluxes. Hence, in studies where models are evaluated solely on the basis of aggregated output performance (e.g., goodness-of-fit of streamflow time series alone, the regional distribution of time-mean precipitation), the individual model components remain hidden from comparison and scrutiny (Kuczera and Franks 2002).

More specialized intercomparison studies do compare the behavior of individual modeling components by requesting detailed output of model processes for specialized modeling frameworks. An example is intercomparison of atmospheric parameterizations (e.g., cloud and convection parameterizations) in one-dimensional model when driven by observed large-scale state (the so-called "single-column model" approach [Randall and Cripe 1999]). However, even for these intercomparison studies, attribution of inter-model differences remains challenging. In sum, while intercomparison experiments are very useful document strengths and weaknesses of models, more controlled and detailed testing is necessary. This motivates the use of model testbeds.

A.4.2.2 Model Testbeds

Model testbeds are computational frameworks designed to systematically evaluate models and streamline processes for model evaluation, development, and parameter calibration. Existing testbeds described by Phillips et al. (2004), Fast et al. (2010), and the Fast-physics System Testbed and Research (FASTER) project focus on specific aspects of the atmospheric systems such as clouds and aerosols that are important for predicting the water cycle. However, while most testbeds aim to evaluate processes across a wide range of spatial and temporal scales, we are unaware of a testbed that specifically targets dynamical frameworks for high-resolution or multi-scale modeling, including scale interactions, or the dynamics of human-earth system interactions.

Despite this, testbeds that address some of these aspects are starting to be developed. For example, the UK Met Office and the NOAA/NCAR Development Testbed Center (DTC) both integrate in real-time regional non-hydrostatic models with horizontal resolution of ~3–5 kilometers. These simulations are used for prediction of precipitation (among other things) at regional scales but also are used as testbeds for any new parameterizations of atmospheric physical processes that are intended to be incorporated into their models. These model "testbeds" could be very valuable for real-time evaluation of the regional-scale water cycle, and human-earth system models could be coupled to them.

Very recently the DOE Office of Science has initiated the CSSEF project, which uses a variable-resolution version of the CESM with fine resolution in a regional patch to test how well high-resolution models simulate the regional-scale water cycle. An interesting aspect of this project is an extensive effort in UQ, whereby a perturbed-parameter ensemble technique is used to deduce the sensitivity of the system to uncertain constants in the parameterizations as well as to calibrate a model to a set of observations with consideration of observational uncertainty. Potentially regional- or small-scale human system models could be coupled with this new testbed and be used as a prototype of a modeling system sought for here.

A.4.2.3 Diagnostics and Metrics

It is worth distinguishing "diagnostics" and "metrics". Metrics refer to scalar measures that can be used to characterize model performance. They just answer how well a system performs. However, in order to build faith into the modeling systems we need to understand if the predictions are skillful for the right reasons and to be able isolate causes of model deficiencies. This is what "diagnostics" aim to do—to provide insight into the model behavior both good and bad.

Therefore, model evaluation must be "diagnostic" in the sense that the goal of model evaluation is to understand the reasons for modeling deficiencies rather than just report on model performance (e.g., Gupta et al. 2008). As discussed by Kuczera and Franks (2002), a major challenge "is to expose internal variables to scrutiny. This is not a trivial challenge, but one that must be vigorously pursued […] to avoid degenerating into a sterile curve-fitting exercise". Recent model benchmarking activities, such as the international land model benchmarking project (iLAMB) includes a wide range of model evaluation metrics (see *http://ilamb.org/benchmarks/*), which focuses attention on process representation and makes it difficult to "win the game" through calibration.

At the largest scale (i.e., global climate model scale), probably the most widely used metric of model performance of the hydrological cycle is the time mean of surface precipitation as a function of space and time. We have precipitation observations whose uncertainty is small enough to provide meaningful constraints on model behavior both for a climatological annual cycle (at the large-scale) and for aspects of interannual behavior. Due to their greater uncertainty, models are compared less often to estimates of evaporation from the surface and the horizontal transports of water vapor in the atmosphere. It should be noted that the climatological 3-dimensional distribution of water vapor is relatively well observed, but is by itself a relatively weak constraint on the transports of water of through the system (i.e., the water cycle).

A.4.2.4 Data Requirements

The data used in model evaluation efforts have typically been rather limited, where in hydrology it is common to evaluate model performance based on the sum of squared differences between simulated and observed streamflow. This historical practice has received widespread critique (e.g., Schaefli and Gupta 2007), and recent efforts to take account of multiple metrics in model evaluation (e.g., iLAMB) will help identify model shortcomings and accelerate model development efforts. However, there are still two major shortcomings. First, there is never sufficient data to scrutinize individual model components (e.g., consider the lack of reliable measurements of under-canopy turbulence). As such, there is a need to use data in creative ways for model diagnosis—for example, Yilmaz et al. (2008) use the runoff to precipitation ratio to diagnose model representations of regional evapotranspiration and the flow duration curve to diagnose partitioning between surface runoff and baseflow. Second, there are limited observations of hydrological states and fluxes at multiple spatial scales, making it difficult to evaluate the impacts of spatial heterogeneity on storage and fluxes of water at regional scales. Both of these shortcomings emphasize the need for a new multi-scale field experiment, measuring a complete suite of hydrological states and fluxes at multiple spatial scales.

From the atmospheric point of view, observations of the large-scale state (wind, temperature, humidity) of atmosphere are critical in order that the large-scale transports of water vapor to a region are accurately captured by analysis data. At the interface of the atmosphere and the land surface, high-quality observations of precipitation—probably from ground-based scanning precipitation radars calibrated to rain gauge stations—are needed. Unfortunately the transfer of water vapor to the atmosphere through evapotranspiration is not well observed. Such data are only routinely collected at a few sites. Also, process-level observations (e.g., cloud microphysics) of precipitation-related processes are not generally available, hindering efforts to understand how these processes work in nature as well as how to improve the representation of these processes in models.

Given the limited state of observations, closing the water budget of a region—which would seem to be an integral part of testing the water cycle representation of the combined land-atmosphere system—remains a very daunting challenge. Despite advanced data assimilation of precipitation and clouds, the analyses provided by Numerical Weather Prediction centers still come with significant uncertainties in closing the water budget of the atmosphere, much less the water budget and flows of the surface. Observations of the flow of precipitation from the atmosphere to surface may be in somewhat better shape due to the widespread use of precipitation scanning radars coupled with gauges, but there are significant uncertainties in both the horizontal transport of water vapor within the atmosphere (so key to driving anomalies in a regional hydrological cycle) as well as the evapotranspiration from the surface to the atmosphere. The observational limitations of closing the water budget of a region would seem to be a significant issue for model evaluation that should be given continued attention. New satellite missions to be launched in the next few years, such as NASA Global Precipitation Mission and the Soil Moisture Active-Passive satellite, do offer the potential to improve the ability to close the water budget of a region.

For models of the human systems, there are severe data issues regarding both the water supply and the water demand, as the data are lacking in general to represent all technologies and human activities that produce or consume usable water. For water supply, besides precipitation, information on the amount and cost of non-renewable groundwater and de-salinated water is needed. For water demand, information on water withdrawal and consumption and the associated costs and energy consumption stratified by technology and human activity is needed. Unfortunately, data of this type are only generally available for developed countries for recent years and may only have very coarse space and time resolution. As a result, efforts to evaluate models of human dimensions have been hampered, as properly defining a suitable hindcast test in light of these data restrictions remains difficult. Thus, any effort to use models of human dimensions for the water cycle must place a high priority on collecting and organizing data that can be used for model evaluation.

A.4.3 Research Gaps and Needs

A.4.3.1 Improve Model Evaluation Practices and the Diagnosis of Modeling Deficiencies

Incisive model evaluation metrics are necessary to diagnose model deficiencies. Two key challenges are (a) the difficulty of effectively discriminating among competing models, given the large uncertainties in model forcing data and a priori estimates of model parameters and (b) compensatory errors among different components of a model, creating difficulties in evaluating the fidelity of individual model components.

Some potential solutions include

- Include parameter estimation and parameter sensitivity analysis as part of the model evaluation effort, to avoid making incorrect inferences in cases where a priori parameter estimates are unrealistic.
- Account for uncertainty in forcing data as part of model evaluation.

- Develop modeling methods that isolate errors in different parts of the modeling system (provide insight into individual processes), through, for example, controlled component perturbation analyses.
- Use simplified and idealized simulations to diagnose the representation of processes within complex modeling systems.
- Analyze analysis increments in data assimilation systems to more precisely separate high-frequency errors from systematic biases.
- Use Bayesian methods to infer the extent to which the data conflict with our a priori expectations (insights into structural problems, parameter values).
- Use multiple data sets (including satellite data) to provide insight into individual processes and their interactions to avoid making incorrect inferences associated with compensatory errors caused by the reliance on inverse methods for model calibration.
- Include inter-variable relationships as part of model evaluation metrics (e.g., elasticities).
- Use a mix of model benchmarking and model diagnostics, to both document the overall model fidelity (PALS, iLAMB), and understand why models behave poorly.

A.4.3.2 Evaluate Coupled Systems (Including the Human Component)

Evaluating coupled systems is a very difficult challenge. In land-atmosphere coupling there is no direct way to evaluate if the coupling is "correct"—for example, whether precipitation causes soil moisture anomalies or soil moisture anomalies cause precipitation anomalies. Incorporating new processes (e.g., saturated flow processes in land models) can substantially alter the land-atmosphere feedbacks, and with no knowledge of the correct coupling, it is difficult to evaluate the realism of model advancements.

Some key model evaluation strategies:

- Evaluate the predictive skill of coupled systems.
- Define a set of simple experiments and basic test cases.
- Develop the testing environment to include hindcasting.
- Evaluate models across multiple modeling contexts—metrics for IAM include economics, consumption, and damages.
- Evaluate both the sensitivity to model inputs as well as the fidelity of the model itself.
- Consider elasticities.
- Give the model scenarios where you expect it to fail (e.g., drought of 2012).
- Evaluate coupled models with respect to contrasting extremes.

A.4.3.3 Develop Data Sets Necessary for Meaningful Model Evaluation

While it is relatively straightforward to evaluate aggregate model performance, there is never enough data to evaluate model representations of individual processes in order to constrain system-scale predictions.

Some key needs include the following:

- Coordinate the data that we do have (disparate data compilations, common data formats) and identify data gaps.
- Embark on a multi-scale field experiment to estimate regional ET (~100 kilometers). Consider establishing soil moisture arrays (including COSMOS), multiple eddy correlation sites, and aircraft campaigns.
- Identify different types of data that are meaningful at different scales. Get at the inherent variability of the system due to non-linear dynamics.
- Quantify data uncertainty, even for variables we think are "good" (e.g., streamflow).
- Improve assembly of global data sets to evaluate global-scale energy and water budgets.

A.5 Prediction, Analysis, and Uncertainty Quantification of Water Cycle Mean and Extremes

Patrick Reed, Chris Forest, and William Collins

Critical Research Gaps and Needs

- Validated observations of the water cycle/precipitation distribution and quantify uncertainty in the products as a function of space and time scale.
- A coherent strategy to advance high-resolution modeling that will resolve processes and scales for precipitation phenomena.
- Model-assimilation system for the water cycle will be critical for producing high-frequency/high-resolution water-cycle reanalysis required by user communities.
- Better decision-relevant extremes and distributions with a particular focus on the co-variation of extremes.
- More interaction with the user community – frame this in terms of functional impacts. Expand water cycle observations to include the evolving socio-economic systems.

A.5.1 Scientific Challenges

The DOE has an emerging suite of community models, primarily ESMs, which broadly offer the opportunity to bridge scientific communities that are currently exploring broad aspects of the water cycle. These tools bridge prediction-focused research related to climate change, hydrology, hydrogeology, biogeochemistry, ecology, and human social systems. In this thematic white paper, we explore the question:

"What does the goal of predicting mean and extreme hydrologic states as well as their associated uncertainties presume in terms of our theoretical, observational, and institutional understanding of the complex systems that compose the water cycle?"

At the coarsest level of addressing this question, we use the river basin scale to represent a fundamental organizing spatial unit of analysis (Reed et al. 2006, NRC 2012). To predict mean and extreme states at the river basin scale, we presume knowledge of the topography, geology, geomorphology, ecosystems, land use, and atmospheric states when simulating human and climate impacts on river systems. Together, this knowledge can be categorized into the geometrical, material, and forcing frameworks required for predictions. Moreover, to fully characterize a river basin, we require significant and relevant documentation of the watershed planning unit, including the following (NRC 2012):

- water use
- point source wastewater discharges
- water withdrawals
- inter-basin water transfers
- land use and land cover affecting non-point-source pollution
- stormwater storage and recharge facilities, surface reservoir developments, aquifer storage and recovery projects
- evolving water policies.

For credible predictions and in addition to the three physical frameworks previously discussed, we require a clear understanding of the interactions between the human and ecosystem components of a river basin. Knowledge or experience of extremes changes how agents within a river basin behave and potentially shapes the dynamics, morphology, and policy context that strongly govern its future. We must acknowledge the river basin as a multi-dimensional resource and economic system where hydrologic extremes will expose emergent multi-sector (i.e., industry, energy, agriculture, water supply, recreation, in-stream ecosystems, etc.) dependencies and potentially competitive needs across multiple sectors that have large economic impacts and a broad array of relevant timescales (i.e., minutes for controls/management and decades for planning). The integrated climate-terrestrial-human systems response is illustrated in Figure A10.

Figure A10 illustrates that despite its initial landfall in the gulf coast of the U.S., Hurricane Ivan subsequently strongly impacted the Susquehanna River basin as it exited the continental U.S. Figure A10a highlights the dramatic increase in sediment transport and flow within the mid-Atlantic where the response to the extreme forcing involves land cover, built system infrastructure, population centers, and ultimately the Chesapeake Bay ecosystem. Figure A10b shows that Conowingo Dam was limited to largely maximizing its releases to avoid structural damages, and consequently, the flood wave is largely unconstrained on its downstream impacts.

Within this broader context, we expand upon the initial framing question to pose the following questions:

- What are the skills of current models in predicting characteristics of the regional water cycle including its extremes?
- What are the critical missing capabilities or components in current modeling systems for predicting regional water cycle variability, change, and extremes?
- What improvements can be gained by quantitative assessment of uncertainty in the predictions? What methods are more suited to the particular challenges of the water cycle problem?
- What tools can facilitate integrative research in prediction, analysis, and UQ?

A.5.2 Current Status and Research Gaps

Broadly, two research areas must be bridged to improve hydrological predictions of means and extremes. On longer timescales, there are the projections from climate models that are now developing higher-resolution versions, which must provide inputs to hydrologic models (or couple directly) (NRC 2006, NRC 2009). On short timescales, there are high-resolution hydrologic models that provide process-level understanding of specific systems and require scaling-up to the global domains in the ESMs. In short, the gaps between these two modeling paradigms must be identified and addressed.

On the process-level side, the ability to predict long-term hydrologic response to climatic, land-use, and land cover changes at the basin scale is limited by the significant uncertainty associated with the paths and residence times of water within the tributary watersheds that compose river basins. Most hydrologic models only represent the pressure response of the system and do not attempt to explicitly represent flowpaths or residence times. Reproducing the main system modes with respect to the pressure response can often be achieved with very parsimonious models, but new modeling approaches are required to advance our understanding of surface-atmosphere-groundwater interactions as well as solute transport. Advancing our understanding of flowpaths and residence times will require that significant effort be invested in developing integrated observations of the hydrologic and human processes shaping a river basin (NRC 2012).

On the climate modeling side, our ability to predict future climates and extremes is limited by model structure (parameterizations, grid size, etc.) and the ability to characterize the uncertainties through ensembles based on parametric and initial condition uncertainties. Model parameterizations must include assumptions that govern the model behavior and thus require calibration of parameters based on observational data. Representative observational data (with respective uncertainties) are required on the spatial and temporal scales of the predictions, and calibration/data assimilation framework provides prediction uncertainty estimates (NRC 2006, National Science and Technology Council Committee on Environment and Natural Resources 2007, NRC 2008). In both hydrologic and climate

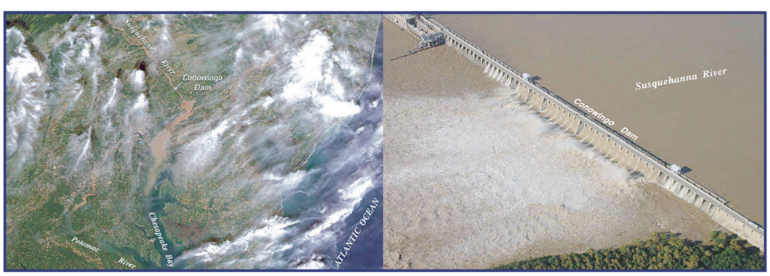

Figure A10. (a) Conowingo Dam and (b) Susquehanna River basin after Hurricane Ivan in 2004. This figure demonstrates the connectivity of landscape and climate across time and spatial scales, human dimensions, etc. (Image from Reed et al. 2006.)

modeling, deep uncertainty exists where model predictions are beyond the scope of the observational data that are required to evaluate the model response. We note that assessment of model errors at "short" time scales is not guaranteed to characterize the errors at long, climatic time scales. We also note that initial condition ensembles used to sample internal variability must be large enough to establish adequate signal-to-noise ratios for identifying model errors and that for highly variable time series (i.e., precipitation) this requires significantly more computational power. Overall, the demand for higher complexity, larger ensembles, higher resolution, and observational diagnostic data (for model assessments) provides a clear trade-off in computational resources that needs to be considered in the design of future prediction systems.

Short- and Long-Term Needs

By monitoring the quantity and quality of atmospheric, surface, and subsurface waters over large, mixed land-use watersheds, we can assess the cumulative and integrated impacts of environmental and anthropogenic change and evaluate the effectiveness of controls. Having identified the river basin as a natural scale for designing observatories, we must work in parallel with operational monitoring efforts (such as the water quantity and quality networks of the USGS) to provide integrated and regular sampling of key indicator nutrients, pollutants, and related parameters for the atmosphere, surface water, and groundwater. Within urban systems, the policies and actions related to water supply development, wastewater treatment, stormwater management, wastewater recycling, and land-use and land cover changes will have a profound effect on water quantity and quality.

Furthermore, we must understand both how policies related to water management are adopted and implemented at the grass-roots level and how they relate to projecting future trends. Only by carefully documenting changes in water management policy and implementation can we properly interpret future hydrologic data trends on these watersheds. Consequently, to understand coupled human-watershed dynamics, we also demand socio-economic monitoring that introduces a broad range of deep uncertainties (e.g., population changes, water demands, economic incentives, institutional/legal context, etc.).

A.5.3 Research Gaps and Needs

- Validated observations of the water-cycle/precipitation distribution and quantify uncertainty in the products as a function of space and time scale.

- High-quality observational data are required to assess predictions relevant for modeling at the watershed scale. These data are required for testing models of the climate system, natural and managed ecosystems, and hydrologic and water resource management systems.

- A coherent strategy to advance high-resolution modeling that will resolve processes and scales for precipitation phenomena.

- The goal is to produce accurate precipitation predictions from ESMs that provide inputs into catchment-scale hydrologic models. This would be for decadal or longer timescales and approaching spatial scales at < 10 meters. Fidelity across the model hierarchy is expected as scale-aware precipitation modeling is developed.

- Model-assimilation system for the water cycle will be critical for producing high-frequency/high-resolution water-cycle reanalysis required by user communities.

  Data assimilation techniques must adapt to the higher resolutions needed by the community. Developing this system will span multiple agencies with the goal of producing long-term data sets of state variables with analyzed uncertainty estimates.

- Better decision-relevant extremes and distributions with a particular focus on the co-variation of extremes.

  Decision support systems are typically focused on low probability, high consequence events for single variables. Decision questions are changing to include extremes of multiple variables and thus requiring adequate data sets.

- Facilitate and improve interactions with the user community—frame this in terms of functional impacts. Expand water cycle observations to include the evolving socio-economic systems.

The stakeholder community must be part of the development process and engaged in the design of decision support tools. The socio-economic systems are tightly connected to the water cycle as being both driven by water availability and quality and driving changes in the natural and managed water-cycle systems.

A.6 Use-Inspired Water Cycle Research to Meet Pressing Resource Challenges

Vincent Tidwell, Dan Cayan, Phil Mote, and Anthony King

Critical Research Gaps and Needs

- A hierarchy of modeling tools for policy-relevant analysis spanning global to regional issues. Design must encourage transparency and broad stakeholder engagement.
- Focused analysis on the climate-water-energy-food nexus. Effort must consider both the physical dynamics along with the social, cultural, and institutional aspects of the allocation and demand of these natural resources.

A.6.1 Scientific Challenges

With the growing realization that stationarity is dead (Milly et al. 2008) comes the need for a new paradigm in water resources management and planning. While recourse to the historical record may have provided predictable bounds on the uncertainty and variability of water supply in the past, that appears to no longer be the case (Schwalm et al. 2012). Confidence in bounding uncertainty in the face of climate change is complicated by uncertainties in future greenhouse gas and aerosol emissions and other forcings, the uncertainty of the response of the climate system (which may be incompletely quantifiable by considering the range of responses of climate models) to forcings, and the inherent uncertainty of natural climate variability. Adding to this difficulty in quantifying climate uncertainty is the uncertainty of modeling hydrological and biological processes and the various interlinked systems and impacts under consideration. The process of downscaling coarse-grained (order of 100 kilometers) global climate model output to conform to complex regional and local settings intensifies the uncertainty. Design of infrastructure projects to account for the resulting broad tails of the probability density function of projected future conditions poises substantial challenges, particularly raising the financial and human capital necessary to achieve resilient planning.

On another level, planning for extreme events as well as the new normal must account for uncertainty in human response to problems such as impacted water supplies, floods, and human health. Resource demand characteristics vary significantly by region and water use sector (Figure A11). Variability is a function of regional physiography, economy, culture/tradition, and personal values. Infrastructural capacity also plays heavily in the water use culture, particularly through moderating impact of extreme events, whether flood or drought. Infrastructure operations generally require coordination across multiple institutions with jurisdiction divided according to source (surface water, groundwater), purpose (flood control, irrigation supply, energy generation), and/or multiple political boundaries. This variability in physical conditions, water demand structure, infrastructure, and regulating institutions gives rise to significant differences in the adaptive capacity and options available to any given region.

A further challenge of use-inspired water cycle research is the tight coupling between water and other critical resources, particularly the convergence of supply and demand issues related to energy, water, and land resources in a changing climate. Changes to one resource affect other resources, which in turn feed back to affect the initiating resource. Identifying and quantifying the linkages and trade-offs is central to informing planning and policy choices about climate mitigation and adaptation (Skaggs et al. 2012). Analyzing mitigation and adaptation through the lens of the energy-water-land interface facilitates not only the evaluation of the net impact of individual mitigation or adaptation measures, but also the compound effects when they are implemented together, either intentionally, or as is more likely, as an outcome of uncoordinated actions of independent parties. These compound effects may not always have positive synergies, and ignoring or failing to identify potentially negative interactions runs the risk of undermining planning and policy goals (Moser 2012).

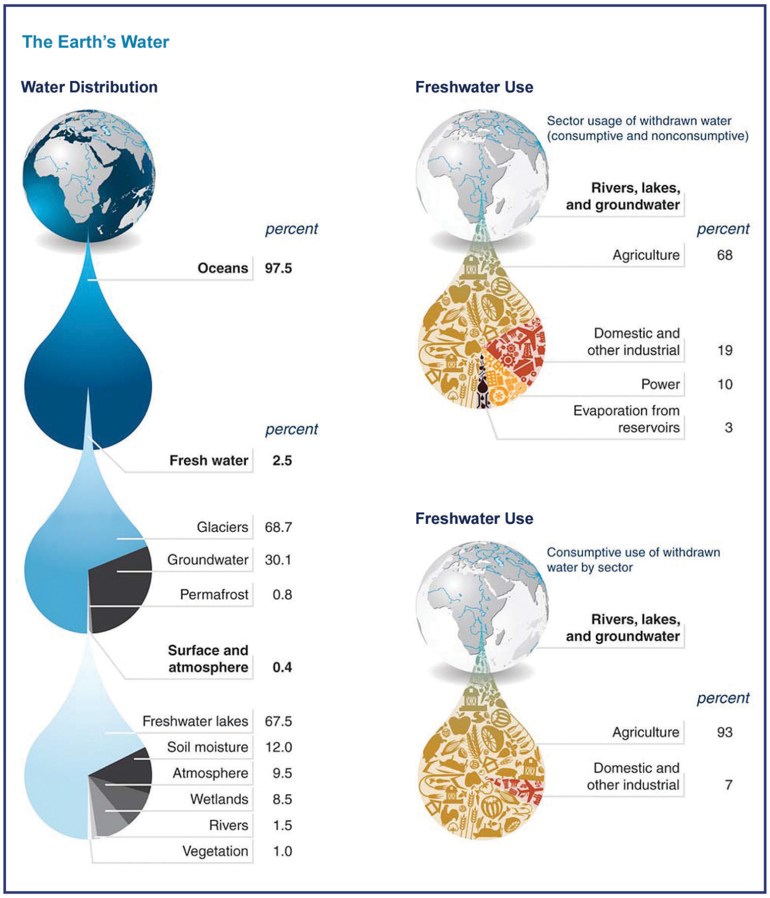

Figure A11. Global water distribution and its use. (Image from Intelligence Community Assessment 2012).

A.6.2 Current Status and Research Gaps

Resource management is generally approached through the lens of a dynamic water budget; that is, to develop a balance between variable supply and projected demand (Connel-Buck et al. 2011). The water balance construct is used here to explore the linkage between climate change, resource management and water use. Implicit in this view is the realization that water supply influences water demand and vice versa.

A.6.2.1 Climate-Water Supply Dynamics

Understanding Water-Cycle Related Linkages and Impacts

Downscaling of precipitation and other measures is necessary to understand how global changes will affect watershed and water-management responses in California and other regions (Dettinger et al. 2011a, Das et al. 2011). Many applications of downscaled climate simulations have employed statistical methods (Maurer et al. 2010, Pierce et al. 2012), which have mostly been limited to temperature and precipitation but now include additional variables like relative humidity and wind speed (Abatzoglou and Brown 2011). Because of the large volume of computer resources required, decades-long regional dynamical climate simulations have not usually been undertaken. In addition, each regional model contains some degree of bias, so bias adjustments are usually required, as they are with statistical methods. However, to provide more process-level insight into regional changes, continued development and longer simulations of high-resolution dynamical models is needed (Leung et al. 2004, Mearns et al. 2009).

Such tools could help better understand potential climate impacts on the incidence of wildfire. Increased wildfire in recent decades in some forested areas of the western U.S. is a multi-billion dollar per year issue that has been shown to be partly a response to drier forest fuels from warmer springs and summers and earlier snowmelt (McKenzie et al. 2004, Westerling et al. 2006, Westerling and Bryant 2008). Improved hydroclimate forecasts on seasonal and on longer multi-year time scales are needed to assist in planning and adaptation. At the same time, it is clear that wildfire risk assessment must consider changing human footprints, including population and land use (Bryant and Westerling 2012).

An experimental water management tool called INFORM (Integrated Forecast and Reservoir Management) (Georgakakos et al. 2007) is providing a way to use probabilistic forecasts and decision science, including forecast uncertainty, to reduce the effects of climate variability and extreme events on the water system. The project, which targets major water management agencies and their facilities in northern California, was implemented in cooperation with national and regional weather forecasting, along with the reservoir management agencies. Reservoir decisions are based on the best available forecasts and current data along with management objectives. Importantly, the INFORM system has been designed to run in parallel with existing conventional reservoir management procedure to compare and demonstrate performance. Significant legal and institutional barriers must be overcome before the benefits of an adaptive management system such as INFORM can be realized. Key reservoir management organizations were established years ago when forecasts had appreciably less skill, yet such organizations can be hesitant to change from the old tried-and-true ways even now that forecasts have improved.

Quantifying Human-Driven Climate

Climate change scenarios indicate a cascade of effects on water resources and ecosystems in the western U.S. (Mote and Redmond 2011), including the San Francisco Bay Delta (Cloern et al. 2011), indicating the need for multi-disciplinary assessment. Increasing duration and severity of drought conditions (Seager et al. 2010, MacDonald 2010) could have a particularly deleterious effect on water supplies. Because the water in the river is already completely allocated, this leads to questions of whether those allocations are sustainable. The early twenty-first century drought on the Colorado River was unusual in the context of the twentieth-century record, but model simulations suggest that it may be matched or exceeded by future dry spells as climate warms during the twenty-first century (Seager et al. 2010, Cayan et al. 2010, Vano et al. 2012). Climate change model ensemble projections indicate that mean temperature is highly likely to rise substantially (e.g. 1°C or greater by 2050), but changes in precipitation, both in magnitude and sign, are still uncertain. Narrowing the range of uncertainty and understanding how and why precipitation will change over the western U.S. is crucial to decision makers (e.g., Vicuna et al. 2008), including those who are grappling with long-term water planning (e.g., California Department of Water Resources 2009).

Weather-Climate

To better anticipate and prepare for extremes such as floods (e.g. Dettinger et al. 2011b), it is critical to understand and improve predictions of extreme precipitation events. In particular, landfalling atmospheric rivers along the west coast of the U.S. generate many of the region's great floods and flood losses (e.g., Florsheim and Dettinger 2007, Ralph and Dettinger et al. 2011) but also supply valuable water resources. Uncertainties in predicting these events are associated with a limited understanding of tropical-extratropical dynamics on synoptic to intra-seasonal time scales, a lack of precision in observing and modeling of the water vapor transport in these systems, and the lack of understanding of the meteorology in complex terrain.

On longer time scales, regions such as the southwestern U.S. exhibit a hydrologic environment that is greatly affected by variability on seasonal to multiannual time scales, whose effects cascade from

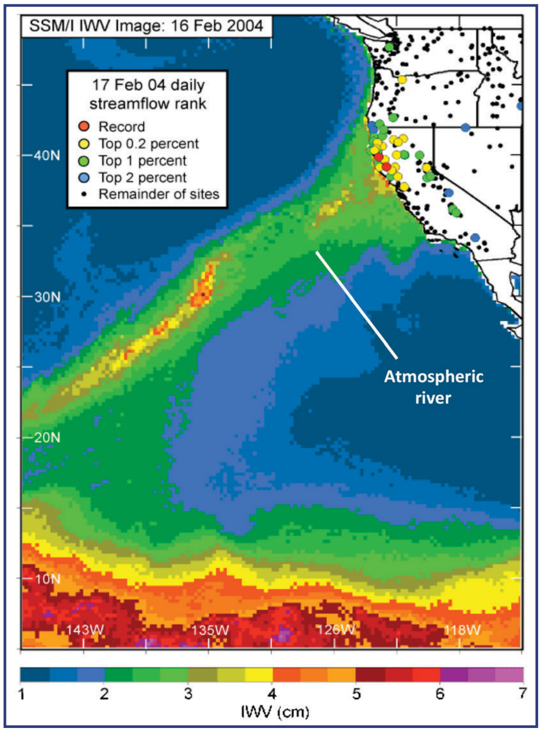

Figure A12. Atmospheric Rivers (ARs) are key drivers of floods and water supply along the West Coast. All major floods of the Russian River (central California coast) since 1997 have been ARs. The nine largest winter floods of the Carson River (west central Nevada) since 1950 have been ARs. ARs contribute greatly to California's water supply: 25%–50% of all precipitation and 20%–50% of all streamflow in central and northern California from 1998–2008 (Image from Ralph and Dettinger 2011, Dettinger et al. 2011a).

ecosystems, water supplies, agriculture and many other sectors (e.g., MacDonald, 2010). The nature and causes of seasonal decadal hydrologic variability are uncertain. In California, multi-year droughts occur more often than would be expected by chance, but wet years do not exhibit such persistence. A crucial aspect of California's climate stresses is that patterns that cause the state's climatic fluctuations typically reach well beyond its boundaries. When dry winters occur in the Sierra Nevada, they also tend to occur in the Columbia and Colorado basins (Cayan et al. 2003, Meko and Woodhouse 2005). This breadth affects California because much of the energy and water used there are supplied by distant parts of the state as well as from the Northwest and Southwest. But what causes multi-year precipitation anomalies? Can we anticipate spatial pattern–is it random or is it guided by governing dynamics? Changes in flood frequency and amplitude also may be affected by climate warming and other changes (Das et al. 2011). Paleoclimate evidence has proven useful in identifying past extremes and recurrence intervals (Woodhouse and Lukas 2006).

Managed and Regulated Water

Managed and Regulated Water (MRW) is an inseparable component of the water cycle of the twenty-first century. At least 90% of the river flows in the United States are managed for human use (Jackson et al. 2001). Much of this water is regulated to provide water for consumptive human uses such as irrigation for agriculture, drinking, sanitation, and industry. When precipitation and runoff are captured in regulated reservoirs and river systems, natural water is transformed into managed water. Any truly "integrated approach to modeling of the regional water cycle", particularly "in the context of a closely linked human earth system" (Jackson et al. 2001), must explicitly include MRW. As noted in Section A.3, there is ample opportunity to improve representation of MRW in large-scale terrestrial systems models. Addressing issues of water storage, management, distribution, and operations is necessary to achieve any realistic representation of past or future streamflow. Clearly, if next-generation models of the regional-scale integrated water cycle are going to address the scientific uncertainties "limit[ing] the Nation's ability to develop sustainable energy solutions" (Zimmer and Renault 2012), those models must address uncertainties in MRW.

A.6.2.2 Climate-Water Demand Dynamics

Modeling the human dimension of water use is mostly lacking (but see Payne et al. 2004) from large-scale terrestrial systems models (see Section A.3) and only recently have efforts been made to incorporate water in a more substantive manner in IAMs. Key to modeling demand dynamics is capturing the strong intersectorial trade-offs between energy, agriculture, and municipal water use (e.g., Skaggs et al. 2012). Additionally, demand-side modeling must go well beyond traditional constructs of per capita water use and crop coefficients to consider such issues as population dynamics, economic development, technology innovation/adoption, personal value/choice, and institutional/policy evolution. What may at first seem unnecessary detail is critical to modeling the adaptive capacity of a region to the combined effects of human development and climate change.

Sectorial Heterogeneity and Adaptive Capacity

Water demand is strongly sectorially dependent. For example, in the western U.S., agriculture accounts for roughly 84% of all withdrawals and 96% of water consumption (Kenny et al. 2009). The intensity of water use is a function of the arable land, crops grown, irrigation system efficiency, strategy of the farmer, and ultimately the availability of water. However, demands in the agricultural sector have seen little growth over the past 40 years (Kenny et al. 2009). In contrast, thermoelectric power generation accounts for roughly 2% of the withdrawals and less than 1% of the consumption in the West. This demand profile is a function of plant capacity, fuel/cooling type (Macknick et al. 2011), and water source (three times more seawater is withdrawn than freshwater in the West). Demand is expected to grow by 20–40% over the next 25 years (NETL 2008). Municipal water demand (which for purposes of the paper includes domestic, residential, commercial, and industrial) accounts for around 14% of withdrawal and 4% of consumption, expressing a strong function of population, personal use behavior, and industrial mix. Additionally, location exercises considerable influence on the demand mix. Specifically, agriculture accounts for less than 2% of withdrawals and 13% of consumption in the Great Lakes region, while thermoelectric power generation accounts for 76% of withdrawals and 13% of consumption (Kenny et al. 2009). The big difference is local dependence on dry-

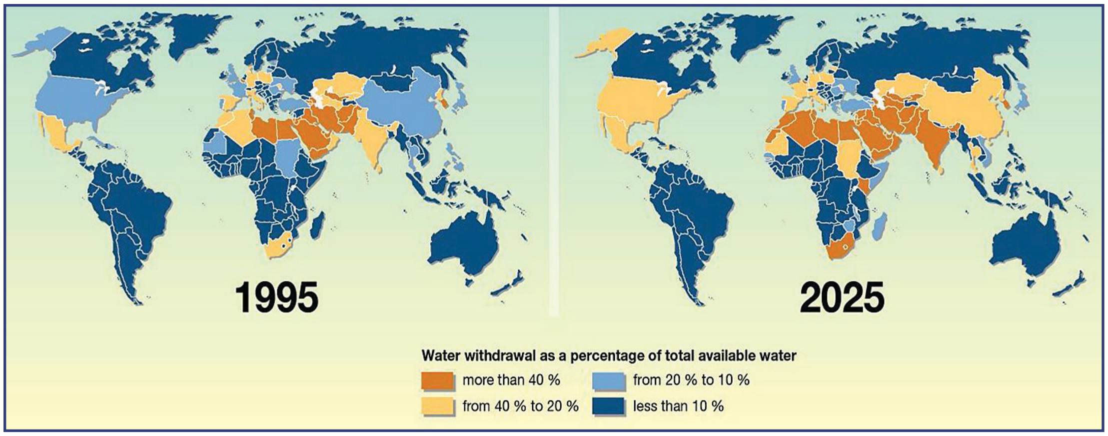

Figure A13. According to Population Action International, based upon the UN Medium Population Projections of 1998, more than 2.8 billion people in 48 countries will face water stress or scarcity conditions by 2025. Of these countries, 40 are in West Asia, North Africa or sub-Saharan Africa. Today, 31 countries, accounting for less than 8% of the world's population, face chronic freshwater shortages. (Image from UNEP 2012.)

land farming and extensive use of open-loop cooling by the electric power industry (EIA 2012).

Salient to integrated assessment modeling are the significant differences in how each sector is likely to evolve in response to human development/climate change, reflecting important differences in the adaptive capacity unique to each sector. Improved irrigation system efficiencies have been able to keep pace with the modest increase in irrigated acreage in the West over the last 40 years. Efficiencies have been realized through such improvements as lining irrigation canals, innovation in irrigation application, integrated soil moisture monitoring and weather forecasting, field practices, and crop innovation (e.g., Economic Research Service 2012). Technology adoption is required, which is not simply a matter of economics but also involves knowledge transfer, culture/tradition, and climate/economic forcings (Dinar et al. 1992, Deressa et al. 2008).

Significant changes in the energy sector are possible. Fresh water use could be totally avoided, as is now required by all new thermoelectric development in California (California Water Code, Section 13552), through adoption of wind/photovoltaics, use of treated waste/brackish water, or implementation of dry cooling (DOE 2006). Alternatively, carbon sequestration, adoption of electric hybrid cars, increased dependence on gas/oil shales, or expanded irrigation of energy crops could sharply increase water use characteristics (King et al. 2008). Water and energy conservation programs could yield significant improvements given the water use in energy production and conversely the energy use in water production.

The municipal water sector has significant adaptive capacity. Technology plays a potential role through low-flow appliances, efficient landscape irrigation, system water loss, and water re-use. In fact, combined water re-use and restricted outdoor landscape irrigation could alleviate the vast majority of municipal water consumption. However, adoption of such measures is influenced by pricing, public perception of water re-use, and community norms concerning home landscaping (Po et al. 2003, Dale et al. 2009). Nevertheless, significant change is possible as evidenced by Melbourne, Australia's shift from 132 gpd/person in the 1980s to 11 gpd/person today, following an extended drought (Melbourne Water 2012).

Institutions

Adaptive capacity in water use is also intimately related to the institutions that govern water allocation. Particularly insulated from change are treaties, interstate compacts, reservoir operations, and threatened/endangered species listings, which largely require congressional authorization to amend. States have primacy over water allocation, which in the West is administered according to the doctrine of Prior Appropriation (first in time to use has first priority to the water in times of shortage). Traditionally, such legal constructs have made it very difficult to move water (Squillace 2012) from senior water rights holders (usually irrigated agriculture) to junior users (municipalities). While adaptive reservoir management (Pahl-Wostl 2007), water markets (Adler 2008), and shortage sharing agreements hold promise, adoption requires considerable political will, stakeholder cooperation, and facilitating conditions (e.g., prolonged drought). Further complicating matters is growing public concern over stewardship of the environment as well as protection for traditional farming practices and rights of indigenous communities. Small changes in these institutions hold the potential for transformational change in the characteristics of water use.

Non-Locality

The link between changing climate and water demand is a strongly non-local problem depending on changes and adaptation at the regional, national and international levels. Specific are changes to irrigated agriculture with some regions requiring expanded irrigation to supplement traditional rain-fed cultivation practices. Other regions may see significant decrease in irrigation, resulting in water available for new development. Such a shift is currently evident in the High Plains and Central Valley of California where the aquifers are being exhausted, which could impact irrigation and the economy at large (Scanlon 2012). Migration is an equally important dynamic considering that immigration (immigrants and births to recent immigrants) fueled 82 percent of growth between 2000 and 2010 in the U.S. and could add another 100 million people in 50 years unless immigration—legal and illegal—is quickly returned to lower norms (Vaughan 2011).

A.6.2.3 The Evolving Landscape of Research

The domain of use-inspired water cycle research requires involvement not just of researchers but also of experts in the management and planning of water resources, and is often conducted in 'boundary organizations' which place a high priority on bridging the gap between research and applications. Some of these boundary organizations include:

- NOAA's Regional Integrated Sciences and Assessments (RISA) program, which dates to 1995 and currently funds 11 regional centers that cover most of the U.S.
- Department of Interior's eight Climate Science Centers, which cover all of the U.S. and focus on landscape, fish, wildlife, and habitat management (DOI 2012)
- Bureau of Reclamation's WaterSmart program
- State climatologists, some of whom are working deeply in water issues in their respective states
- The Water Utility Climate Alliance, a partnership of 10 large urban water utilities
- The 2013 National Climate Assessment that provides a status report on research pertaining to climate change science and impacts on our Nation's agriculture, water resources, energy supply and use, urban infrastructure to name a few
- The Environmental Protection Agency's Office of Water, in collaboration with NSF's Urban Long-Term Research Areas, is focusing on eight U.S. water utilities to identify vulnerability and opportunity to respond to climate change (EPA 2011).

A.6.3 Research Gaps and Needs

In the preceding sections several gaps and opportunities for improving understanding of use-inspired water cycle research were identified. Key physical and social processes were highlighted that are needed to improve modeling of climate impacts on the human dimension. A brief list of enabling steps would promote integration and enhance the resulting impact:

1. Development of a hierarchy of modeling tools is needed for policy-relevant analysis. It is unlikely that current global climate models will be able to incorporate key regional processes with the level of detail required to fully explore human related impacts. Additionally, analyses aimed at broad global policy issues will require fundamentally different tools than that required for much more specific regional analyses. Effective design should encourage transparency and extensive stakeholder engagement. Improved treatment and communication of risk and uncertainty is also required.
2. The climate-water-energy-food nexus provides a fertile environment for developing this hierarchy of models. Water availability impacts

the pathway along which both energy and agriculture evolve. More importantly decisions in one sector profoundly influence other competing sectors. While physical dynamics relating these sectors is complex, social, cultural, behavioral, and institutional dynamics also play critical compounding roles in defining climate-related impacts. The inter-sectorial dynamics, natural resource endowments, exposure to climate change and hence adaptive capacities vary greatly by region.

3. The concepts of risk and uncertainty need to be integrated into modeling and analysis in order to design climate resilient infrastructure and to adequately inform climate policy options.

Appendix B

B.1 Agenda

Day 1 (Monday): September 24, 2012

Plenary Session Chair: Jay Famiglietti,
University of California at Irvine

8:30 am–8:35 am	Workshop Logistics: Patrick Horan
8:35 am–8:55 am	Welcoming Remarks and Relevance to the DOE Climate and Environmental Sciences Division (CESD) and US Global Change Research Program (USGCRP): Gary Geernaert, CESD Director
8:55 am–9:05 am	Remarks from DOE sponsoring program managers: Renu Joseph, DOE CESD
9:05 am–9:45 am	Workshop Overview - The broad challenges of predicting the integrated water cycle and charge to the workshop participants: Workshop organizers (Ruby Leung, Bill Collins, Jay Famiglietti)
9:45 am–10:25 am	Keynote Talk - Use-inspired water cycle research: Kathy Jacobs, Office of Science and Technology Policy
10:25 am–10:45 am	Break
10:45 am–11:30 am	Presentations of White Papers: Topic leads for Topics 3, 5, and 6 (15 minutes per topic)
11:30 am– 2:00 pm	Topical Breakout Session 1 (Topics 3, 5, and 6 in parallel): Working lunch with discussion of science challenges and current gaps and limitations (includes short presentations by workshop participants)
2:00 pm – 2:15 pm	Break
2:00 pm – 4:00 pm	Topical Breakout Session 2 (Topics 3, 5, and 6 in parallel): Discussion of research needs and priorities
4:00 pm – 5:30 pm	Crosscutting Breakout Session 1 (Groups A, B, and C in parallel): Discussion of Integrative Modeling Challenges

Day 2 (Tuesday): September 25, 2012

Plenary Session Chair: Bill Collins,
Lawrence Berkeley National Laboratory

8:15 am–9:00 am	Keynote Talk – Multi-scale Water Cycle Characteristics: Graeme Stephens, NASA Jet Propulsion Laboratory
9:00 am–9:45 am	Keynote Talk – Model Prediction and Evaluation: Eric Wood, Princeton University
9:45 am–10:00 am	Break
10:00 am–10:45 am	Report From Topical Breakout on Day 1 (15 minutes per topic)
10:45 am–11:30 am	Presentations of White Papers: Topic leads for Topics 1, 2, and 4 (15 minutes per topic)

11:30 am– 2:00 pm	Topical Breakout Session 3 (Topics 1, 2, and 4 in parallel): Working lunch with discussion of science challenges and current gaps and limitations (includes short presentations by workshop participants)
2:00 pm– 2:15 pm	Break
2:15 pm–4:00 pm	Topical Breakout Session 4 (Topics 1, 2, and 4 in parallel): Discussion of research needs and priorities
4:00 pm–5:30 pm	Crosscutting Breakout Session 2 (Groups A, B, and C in parallel): Discussion of Integrative Modeling Experiments (IMEs)

Day 3 (Wednesday): September 26, 2012

Plenary Session Chair: Ruby Leung,
Pacific Northwest National Laboratory

8:15 am– 9:00 am	Keynote Talk – Modeling human-earth system interactions in the water cycle: Taikan Oki, University of Tokyo
9:00 am–9:45 am	Report From Topical Breakout on Day 2 (15 minutes per topic)
9:45 am–10:30 am	Report From Crosscutting Breakout on Day 1 and Day 2 (15 minutes each for crosscutting groups A, B, and C)
10:30 am– 11:15 am	Panel Discussion 1: Science panel, Moderator: David Lesmes, DOE CESD
11:15 am–11:55 am	Panel Discussion 2: Agency panel, Moderator: Bob Vallario, DOE CESD
11:55 am–Noon	Closing Remarks: Gary Geernaert, DOE CESD Director
Noon	Workshop Adjourns
Noon– 1:00 pm	Lunch
1:00 pm–3:00 pm	Follow-Up Discussion: Organizers and topic leads

B.2 Workshop Topics and Topic Leads

Topic 1: Multi-scale behaviors of the water cycle
Rob Wood, University of Washington
Xubin Zeng, University of Arizona

Topic 2: Human-earth system interactions and impacts on the water cycle
Tony Janetos, Pacific Northwest National Laboratory/Joint Global Change Research Institute
Ken Strzepek, Massachusetts Institute of Technology

Topic 3: Challenges for land surface/hydrologic modeling
Dave Lawrence, National Center for Atmospheric Research
Reed Maxwell, Colorado School of Mines

Topic 4: Model testing, analysis, and evaluation and data Needs
Martyn Clark, National Center for Atmospheric Research
Steve Klein, Lawrence Livermore National Laboratory

Topic 5: Prediction, analysis, and uncertainty quantification of water cycle mean and extremes
Chris Forest, Pennsylvania State University
Patrick Reed, Pennsylvania State University

Topic 6: Use-inspired water cycle research to meet the most pressing energy and environmental challenges
Dan Cayan, Scripps Institution of Oceanography/US Geological Survey
Phil Mote, Oregon State University
Vince Tidwell, Sandia National Laboratory

B.3 Workshop Participants

Last Name	First Name	Institution	Day 1	Day 2	Crosscutting
Averyt	Kristen	University of Colorado	Topic 6	Topic 2	Group B
Bacmeister	Julio	National Center for Atmospheric Research	Topic 5	Topic 1	Group C
Bales	Jerad	US Geological Survey	Topic 6	Topic 2	Group B
Barros	Ana	Duke University	Topic 5	Topic 1	Group C
Bosilovich	Mike	NASA/Goddard Space Flight Center	Topic 5	Topic 4	Group A
Calvin	Kate	Pacific Northwest National Laboratory/Joint Global Change Research Institute	Topic 6	Topic 4	Group A
Cayan	Dan	Scripps Research Institute	Topic 6	Topic 2	Group C
Clark	Martyn	National Center for Atmospheric Research	Topic 3	Topic 4	Group C
Collins	Bill	Lawrence Berkley National Laboratory	Topic 5	Topic 1	Group B
Crow	Wade	US Department of Agriculture-Agricultural Research Service	Topic 3	Topic 2	Group B
Diffenbaugh	Noah	Stanford University	Topic 5	Topic 4	Group B
DiLuzio	Mauro	US Department of Agriculture	Topic 3	Topic 4	Group A
Dole	Randy	NOAA Earth System Research Laboratory	Topic 5	Topic 1	Group A
Donner	Leo	Geophysical Fluid Dynamics Laboratory	Topic 5	Topic 1	Group B
Duffy	Chris	Pennsylvania State University	Topic 3	Topic 1	Group A
Easterling	Dave	NOAA/National Climatic Data Center	Topic 5	Topic 4	Group C
Faeth	Paul	CNA	Topic 6	Topic 2	Group A
Famiglietti	Jay	University of California, Irvine	Topic 6	Topic 2	Group A

Forest	Chris	Pennsylvania State University	Topic 5	Topic 4	Group B
Fung	Inez	University of California, Berkeley	Topic 3	Topic 1	Group B
Ganguly	Auroop	Northeastern University	Topic 6	Topic 4	Group B
Gentine	Pierre	Columbia University	Topic 6	Topic 2	Group B
Gochis	Dave	National Center for Atmospheric Research	Topic 3	Topic 4	Group C
Gutowski	Bill	Iowa State University	Topic 5	Topic 1	Group A
Hejazi	Mohamad	Pacific Northwest National Laboratory/Joint Global Change Research Institute	Topic 6	Topic 2	Group C
Hibbard	Kathy	Pacific Northwest National Laboratory	Topic 6	Topic 2	Group B
Hoffman	Forrest	Oak Ridge National Laboratory	Topic 3	Topic 4	Group A
Houser	Paul	George Mason University	Topic 6	Topic 4	Group C
Jacobs	Kathy	Office of Science and Technology Policy	Topic 6	Topic 2	Group C
Janetos	Tony	Pacific Northwest National Laboratory/Joint Global Change Research Institute	Topic 6	Topic 2	Group A
Kinter	Jim	Center for Ocean-Land-Atmosphere Studies	Topic 5	Topic 4	Group C
Klein	Steve	Lawrence Livermore National Laboratory	Topic 5	Topic 4	Group C
Koster	Randy	NASA/Goddard Space Flight Center	Topic 3	Topic 4	Group A
Lawrence	Dave	National Center for Atmospheric Research	Topic 3	Topic 4	Group A
Leung	Ruby	Pacific Northwest National Laboratory	Topic 3	Topic 4	Group C
Maxwell	Reed	Colorado School of Mines	Topic 3	Topic 1	Group A
O'Neill	Brian	National Center for Atmospheric Research	Topic 6	Topic 2	Group C
Oki	Taikan	University of Tokyo	Topic 3	Topic 2	Group C
Peters-Lidard	Christa	NASA/Goddard Space Flight Center	Topic 5	Topic 4	Group C
Reed	Patrick	Pennsylvania State University	Topic 5	Topic 4	Group B
Regan	Steve	US Geological Survey	Topic 3	Topic 4	Group C
Riley	Bill	Lawrence Berkeley National Laboratory	Topic 3	Topic 2	Group B
Salvucci	Guido	Boston University	Topic 3	Topic 1	Group C

Schlosser	Adam	Massachusetts Institute of Technology	Topic 6	Topic 2	Group B
Schubert	Siegfried	NASA/Goddard Space Flight Center	Topic 5	Topic 1	Group B
Sorooshian	Soroosh	UC Irvine	Topic 6	Topic 1	Group A
Stephens	Graeme	NASA/Jet Propulsion Laboratory	Topic 5	Topic 1	Group C
Strzepek	Ken	Massachusetts Institute of Technology	Topic 6	Topic 2	Group A
Swenson	Sean	National Center for Atmospheric Research	Topic 3	Topic 4	Group A
Tebaldi	Claudia	Climate Central	Topic 6	Topic 2	Group A
Thornton	Peter	Oak Ridge National Laboratory	Topic 3	Topic 2	Group B
Tidwell	Vince	Sandia National Laboratories	Topic 6	Topic 2	Group C
Trenberth	Kevin	National Center for Atmospheric Research	Topic 5	Topic 4	Group C
Wehner	Mike	Lawrence Berkeley National Laboratory	Topic 5	Topic 1	Group C
Weyant	John	Stanford University	Topic 6	Topic 2	Group A
Wilson	Cathy	Los Alamos National Laboratory	Topic 3	Topic 1	Group A
Wood	Rob	University of Washington	Topic 5	Topic 1	Group B
Wood	Eric	Princeton University	Topic 5	Topic 1	Group B
Xie	Shaocheng	Lawrence Livermore National Laboratory	Topic 5	Topic 1	Group B
Zamuda	Craig	DOE Energy Efficiency and Renewable Energy	Topic 6	Topic 2	Group B
Zeng	Xubin	University of Arizona	Topic 3	Topic 1	Group B
Zhang	Minghua	State University of New York at Stony Brook	Topic 5	Topic 4	Group A

B.4 Agency Representatives

Last Name	First Name	Institution
Anderson	Don	NOAA
Arnold	Jeff	Army Corps of Engineers
Arrigo	Jennifer	Consortium of Universities for the Advancement of Hydrologic Science, Inc.
Bamzai	Anjuli	National Science Foundation
Barrie	Dan	NOAA

Bayer	Paul	DOE
Cavallaro	Nancy	US Department of Agriculture
Considine	David	NASA
Entin	Jared	NASA
Ferrell	Wanda	DOE
Geernaert	Gary	DOE
Gregurick	Susan	DOE
Horan	Patrick	DOE
Jonhson	Tom	Environmental Protection Agency
Joseph	Renu	DOE
Katz	Arthur	DOE
Koch	Dorothy	DOE
Kuperberg	Mike	DOE
Lesmes	David	DOE
Mariotti	Annarita	NOAA
Petty	Rick	DOE
Philbrick	Mark	DOE
Rosen	Rick	NOAA
Rosum	Mary Ann	NOAA
Stover	Dan	DOE
Torgersen	Thomas	National Science Foundation
Vallario	Bob	DOE
van Oevelen	Peter	Global Energy and Water Cycle Experiment
Weatherwax	Sharlene	DOE
Weaver	Chris	Environmental Protection Agency
Williamson	Ashley	DOE

Appendix C

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Notes

More information about the workshop is available at
http://climatemodeling.science.energy.gov/doe-workshops/water-cycle-workshop.

The complete workshop report can also be downloaded from
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