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

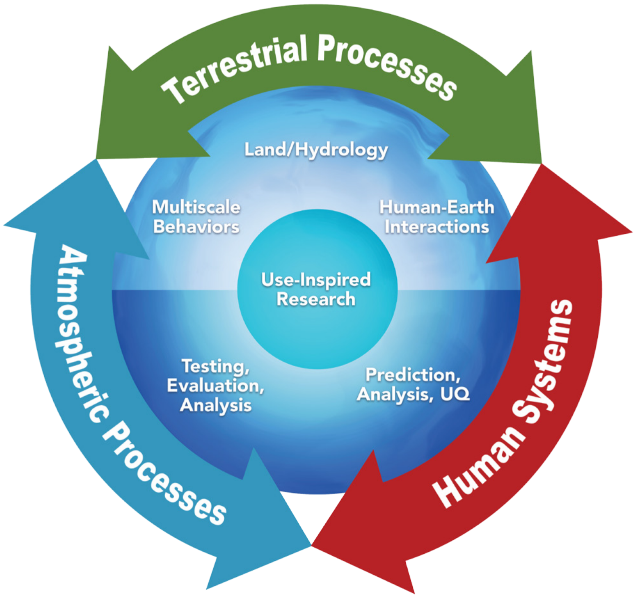
EXECUTIVE SUMMARY

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.

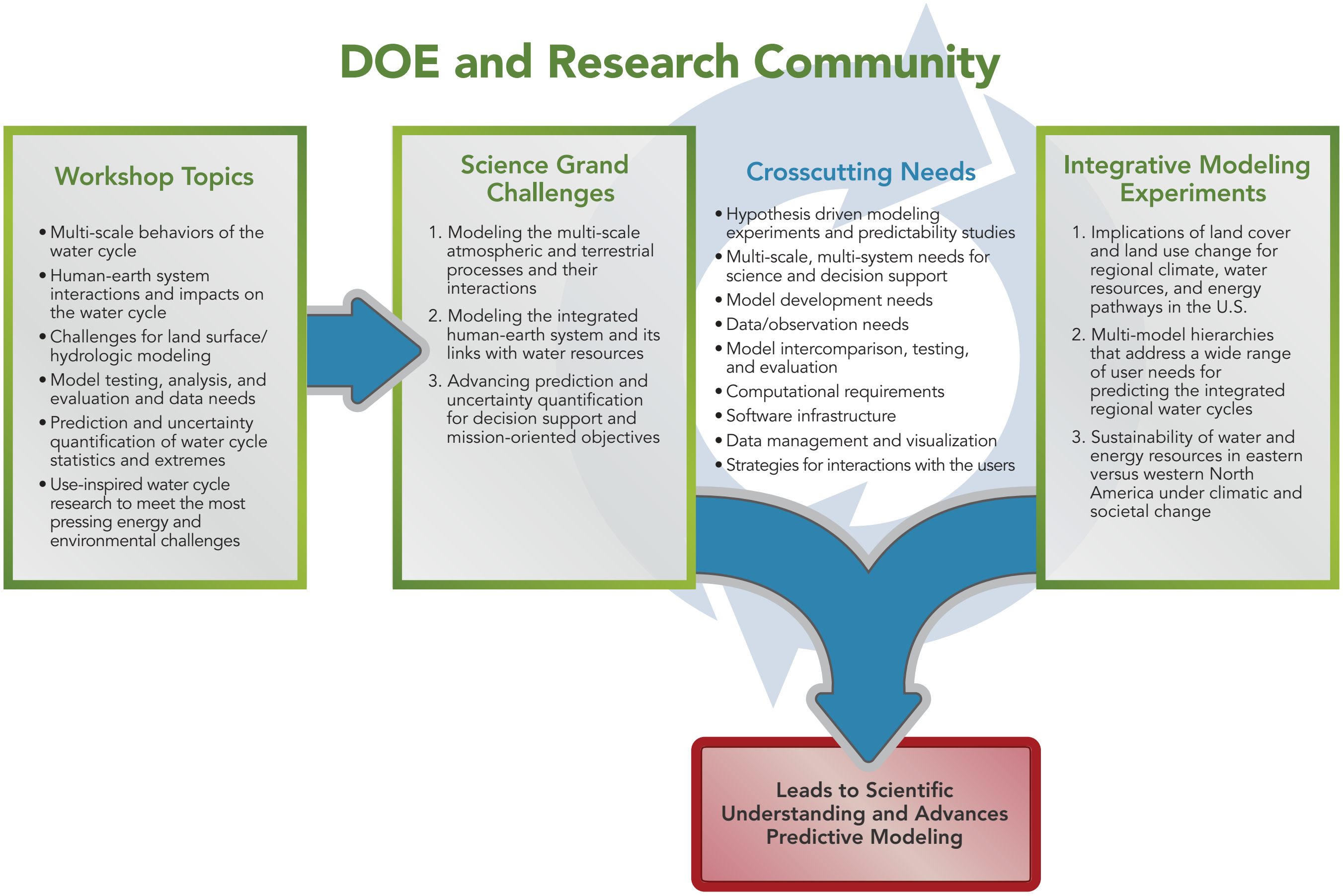
Modeling the fully integrated water cycle is a significant scientific challenge that is well aligned with the mission of the Department of Energy's (DOE) Climate and Environmental Sciences Division (CESD): "to advance a robust predictive understanding of Earth's climate and environmental systems and 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 next page. These challenges represent remarkable opportunities for interagency collaborations to improve predictions of the integrated water cycle for significant scientific and user impacts.



DOE and Research Community

Workshop Topics

- 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

Science Grand Challenges

1. Modeling the multi-scale atmospheric and terrestrial processes and their interactions
2. Modeling the integrated human-earth system and its links with water resources
3. Advancing prediction and uncertainty quantification for decision support and mission-oriented objectives

Crosscutting Needs

- 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
- Software infrastructure
- Data management and visualization
- Strategies for interactions with the users

Integrative Modeling Experiments

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

Leads to Scientific Understanding and Advances Predictive Modeling

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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ADDITIONAL INFORMATION

Workshop Website
http://climatemodeling.science.energy.gov/doe-workshops/water-cycle-workshop

Complete Report
http://science.energy.gov/ber/news-and-resources/