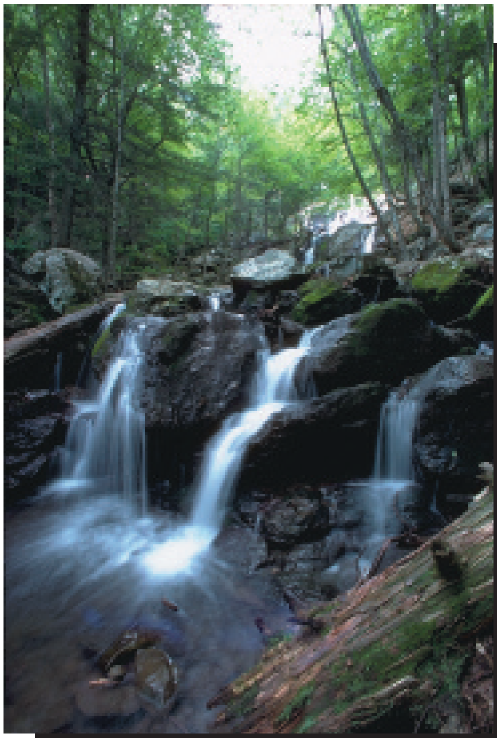
CHAPTER 5

Water Cycle



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National and International Partnerships

The water cycle is essential to life on Earth. As a result of complex interactions (see Figure 5-1), the water cycle acts as an integrator within the Earth/climate system, controlling climate variability and maintaining a suitable climate for life. The water cycle manifests itself through many processes and phenomena, such as clouds and precipitation; ocean-atmosphere, cryosphere-atmosphere, and land-atmosphere interactions; mountain snow packs; groundwater; and extreme events such as droughts and floods. Inadequate understanding of and limited ability to model and predict water cycle processes and their associated feedbacks account for many of the uncertainties associated with our understanding of long-term changes in the climate system and their potential impacts, as described by the Intergovernmental Panel on Climate Change (IPCC). For example, clouds, precipitation, and water vapor produce feedbacks that alter surface and atmospheric heating and cooling rates, and the redistribution of the associated heat sources and sinks leads to adjustments in atmospheric circulation, evaporation, and precipitation patterns.

Because water cycle processes occur, are observed, and are studied at a wide variety of scales (watershed, basin,continental, global), understanding of the water cycle is extremely challenging. Characterizing the interactions between the land and the atmosphere will require capabilities, such as improved observations and regional climate models, to scale down global climate model fields and to scale up the effects of land surface heterogeneity. The interactions between oceans and the atmosphere manifest themselves as the slower modes of climate variability, as described in Chapter 4.

Clean water is an essential resource for human life, health, economic growth, and the vitality of ecosystems. From social and economic perspectives, the needs for water supplies adequate for human uses—such as drinking water, industry, irrigated agriculture,

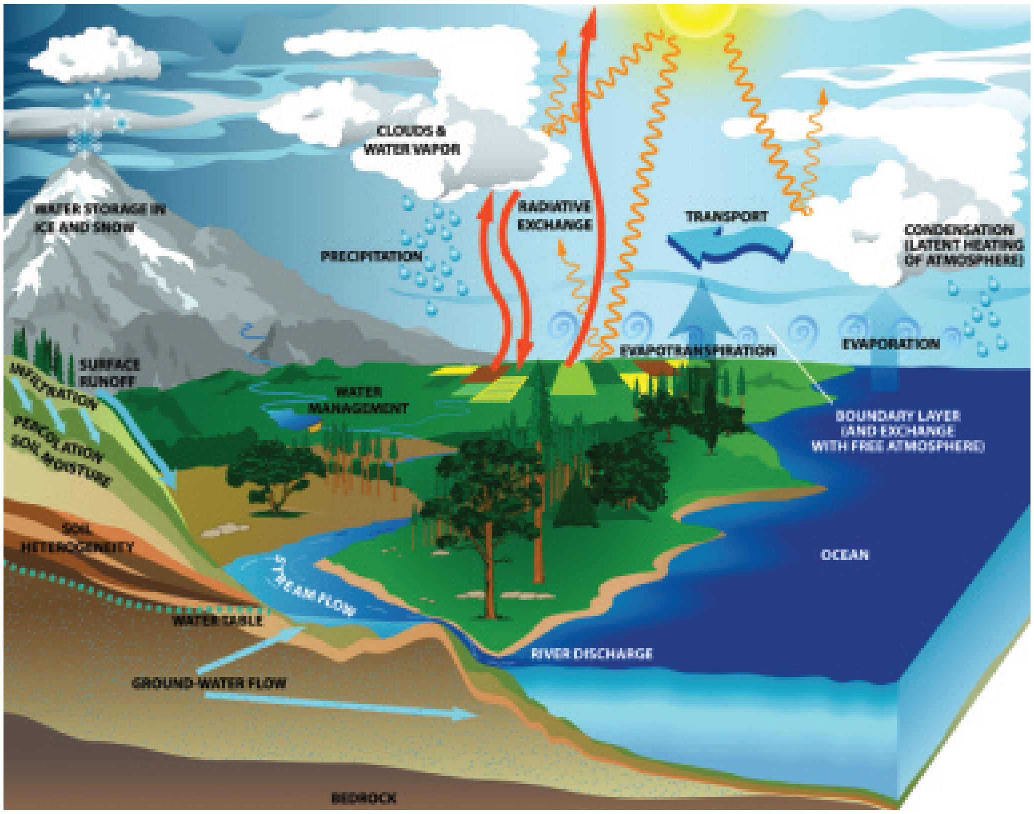

Figure 5-1: Conceptualization of the global water cycle and its interactions with all other components of the Earth-climate system. The water cycle involves water in all three of its phases [solid (snow, ice), liquid, and gaseous], operates on a continuum of time and space scales, and exchanges large amounts of energy as water undergoes phase changes and is moved dynamically from one part of the Earth system to another. These interactions with radiation and atmospheric circulation dynamics link the water and energy cycles of the Earth system. Source: Paul Houser and Adam Schlosser, NASA GSFC. For more information, see Annex C.

hydropower, waste disposal, and the protection of human and ecosystem health—are critical. Water supplies are subject to a range of stresses, such as population growth, pollution, and industrial and urban development. These stresses are exacerbated by climate variations and changes that alter the hydrologic cycle in ways that are currently not predicted with sufficient accuracy for decisionmakers. A number of these concerns and related questions and strategies are documented in a recent report on research needs and opportunities, *A Plan for a New Science Initiative on the Global Water Cycle* (USGCRP, 2001), which formed the basis for initial interagency planning related to the global water cycle.

Advances in observing techniques, combined with increased computing power and improved numerical models, now offer new opportunities for significant scientific progress. Furthermore, field studies and modeling initiatives like the Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project, observation systems such as the Tropical Rainfall Measuring Mission (TRMM, see Figure 5-2), and regional test beds such as the Cloud Atmospheric Radiation Testbed (CART)/Atmospheric Radiation Measurement (ARM) site have provided data and insights that accelerated improvements in model physics. Recently, for example, credible predictions of seasonal variations in the water cycle have been produced for the western United States and Florida. This activity has served as a basis for dialogue between the research community and decisionmakers on the latter's information needs and on opportunities for improving the adaptability of infrastructure and management practices to long-term changes and extremes. Along with the growing ability to provide advance notice of extreme hydrologic events, this forecast capability provides new options for social and economic development and resource and ecosystem management.

In addition, recently launched satellites such as Terra, Aqua, GRACE, and IceSAT, among others, will substantially increase the detailed data needed to better understand and model global and regional water cycle processes. The water cycle variables needed from satellite and *in situ* systems and field campaigns are included in the comprehensive list shown in Appendix 12.1. In addition, there are some central water cycle variables that will be featured in water cycle prediction efforts including clouds, precipitation, soil moisture, runoff, evaporation, and infiltration rate.

At the same time, considerable additional effort will be required to extract accurate regional and local climate predictions from global models. Furthermore, effective operational application of many of these new prediction and measurement capabilities is hampered by the lack of adequate networks for observing critical water cycle variables such as soil moisture, and the absence of effective coordination of terrestrial water observing activities.

To address the urgent need for better information on the water cycle, the Climate Change Science Program (CCSP) is planning its Water Cycle research program around two overarching questions:

- How does water cycle variability and change caused by internal processes, climate feedbacks, and human activities influence the distribution of water within the Earth system, and to what extent is this variability and change predictable?
- What are the potential consequences of global water cycle variability and change for society and the environment, and how can knowledge of this variability and change improve decisions dependent on the water cycle?

The following five questions address different aspects of these overarching questions. The first overarching question is dealt with in questions 5.1 to 5.3. Questions 5.4 and 5.5 relate to the second question. Further clarification of the science emphasis planned for each of the five areas is provided by the illustrative science questions. Linkages between the Water Cycle element and other CCSP elements are noted in parentheses after each illustrative question.

Question 5.1: What are the mechanisms and processes responsible for the maintenance and variability of the water cycle; are the characteristics of the cycle changing and, if so, to what extent are human activities responsible for those changes?

State of Knowledge

The global water cycle encompasses the distribution and movement of water in its three phases throughout the Earth system and includes precipitation, surface and subsurface runoff, oceans, cloud cover, atmospheric water vapor, soil moisture, groundwater, and so on. The *Third Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC, 2001a) cites evidence of possibly significant changes in critical water cycle and related climate variables during the 20th century. These include a 0.6 ± 0.2°C increase in global mean surface temperature, a 7-12% increase in continental precipitation over much of the Northern Hemisphere, massive retreats of most mountain glaciers, and later autumn freeze-up and earlier spring break-up dates for ice cover on many Northern Hemisphere lakes. Less certain, but potentially important possible changes, include a 2% increase in total cloud cover over many mid- to high-latitude land areas, increases in total area affected globally by combined extreme events including droughts and floods, and a 20% increase in the amount of water vapor in the lower stratosphere. Other studies suggest other conclusions, indicating that the question of significant changes may still be open for some water cycle variables.

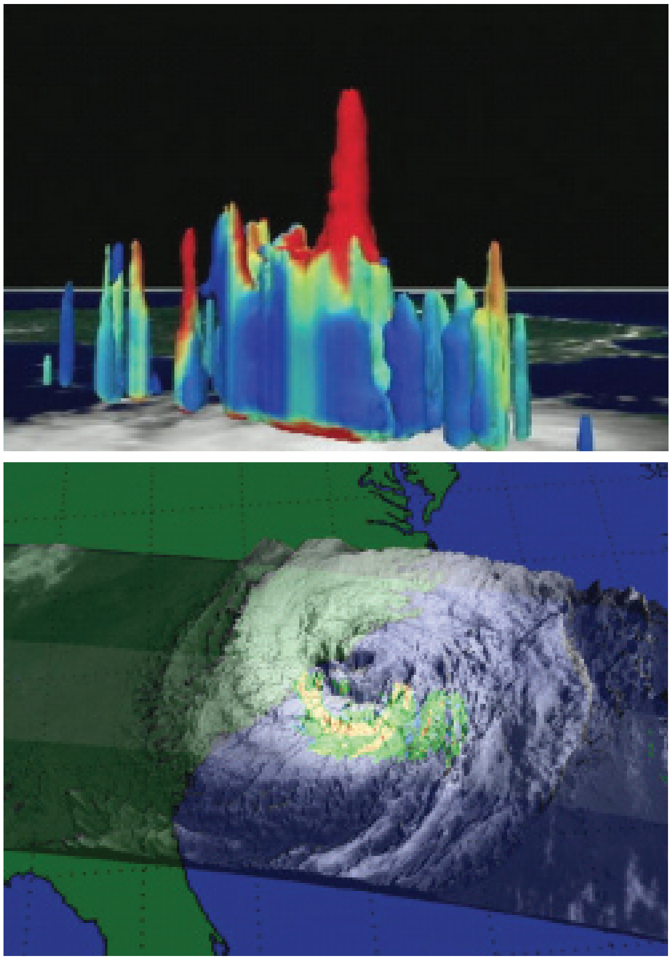

Figure 5-2: The TRMM Space-Based Observatory—a joint project of NASA and Japan's National Space Development Agency (NASDA)—monitors global tropical precipitation, sea surface temperature, hurricane structure, and other key aspects of the global water cycle. These particular renderings are visualizations of the vertical structure of a typical hurricane created using data from TRMM's Precipitation Radar (Hurricane Bonnie, August/September 1998). Source: X. Shiraz and Y. Morales, NASA Scientific Visualization Studio.

Because there is a substantial range of natural variability in the climate system due to internal processes alone, it is difficult to distinguish natural excursions from the "norm" from changes that might be the result of forcing due to human activities, such as land-use change and aerosols (see Figure 5-3). The distribution and nature of atmospheric aerosols have an effect on both cloud radiative properties and the generation of precipitation. Moreover, the impact of increased upper tropospheric/lower stratospheric water vapor on the radiative balance and cloud structure is potentially quite large. These effects are not yet well enough understood to accurately project their impact on water and energy cycles or to predict the effects of climate change on regional water resources. Although significant advances have been made in modeling moderately sized watersheds, current global climate models cannot properly simulate many aspects of the global water cycle, such as precipitation amounts, frequency, and diurnal cycle, as well as cloud distribution and its influence on climate. Without appropriate models to conduct tests, it is difficult to attribute observed trends to human-induced climate changes or natural variability.

Illustrative Research Questions

- How have the characteristics of the water cycle changed in recent years, and to what extent are the changes attributable to natural variability and human-induced causes (Chapter 4)?
- What are the key mechanisms and processes responsible for maintaining the global water cycle and its variability over space and time scales relevant for climate (Chapter 4)?
- How are regional groundwater recharge, soil moisture, and runoff affected by changing global precipitation and vegetation patterns, and cryospheric processes (Chapter 8)?
- How have changes in land use and water management and agricultural practices affected trends in regional and global water cycles (Chapter 6)?
- How do aerosols, their chemical composition, and distribution affect cloud formation and precipitation processes, patterns, and trends (Chapter 3)?
- With what accuracy can local and global water and energy budgets be closed?
- What is the relative importance of local and remote factors in extreme hydrologic events such as droughts and floods (Chapter 4)?
- What are the characteristics of upper tropospheric/lower stratospheric water vapor and clouds and how are they affected by deep convection (Chapter 4)?

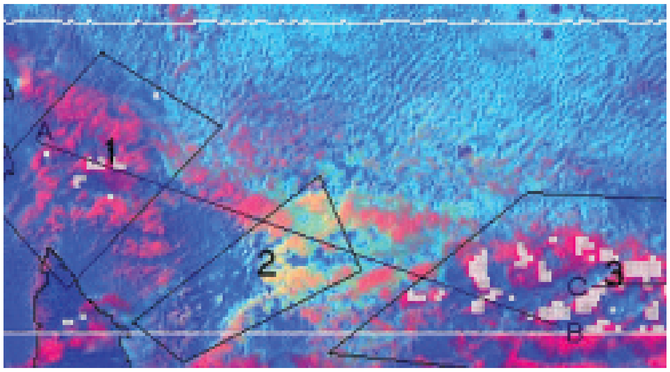

Figure 5-3: Observational evidence showing the effect of aerosols on cloud formation and precipitation processes over south Australia. The yellow patches within Area 2 have reduced droplet sizes, indicating the presence of pollution. White patches outside Area 2 indicate rainfall. Although measurements indicated ample water in the polluted clouds, the smaller droplet size may have prevented precipitation. Source: NASA GSFC (research results from Daniel Rosenfield, The Hebrew University of Jerusalem). For more information, see Annex C.

Research Needs

Although techniques for measuring water cycle variables have improved, the number of observations is limited and, in some cases, new sensors are needed. New satellite and *in situ* observing capabilities will be critical for detecting patterns and quantifying fluxes, especially in terrestrial variables such as soil moisture, and atmosphere-ocean fluxes. Existing *in situ* networks need to be maintained and enhanced, particularly those monitoring precipitation, river discharge, and snow pack. Data sets should be developed using historical and new observations to ensure consistency in the record and for sufficiently long time periods to assess climate variability. Network enhancements and open data access are needed to address water-related issues especially in areas that are currently underrepresented. Also needed are new data assimilation techniques to produce consistent data products for research and process studies from inhomogeneous and/or disparate observations. Appropriate paleoclimate data sets must be assembled to provide a long-term perspective on water cycle variability. New models are needed that can simulate critical water processes at resolutions that allow comparison with long-term data sets. Finally, a wide range of process studies must be conducted to provide understanding of the mechanisms that maintain the water cycle system.

Milestones, Products, and Payoffs

- In collaboration with the Observing and Monitoring research element, development of an integrated global observing strategy for water cycle variables, employing Observational System Simulation Experiments (OSSE) as appropriate [less than 2 years].
- Documentation of trends in key water cycle variables through data analysis and comparisons with model simulations to assess the mechanisms responsible for these trends [beyond 4 years].
- Planned satellite measurements and focused field studies to better characterize water vapor in the climate-critical area of the tropical tropopause (the boundary between the troposphere and the stratosphere) [2-4 years].
- Regional and global precipitation products that merge measurements from different satellite and other remote-sensing data streams to support joint Water Cycle/Climate Variability and Change studies of ocean- and land-atmosphere coupling and the global energy balance [2-4 years].
- Integrated long-term global and regional data sets of critical water cycle variables such as evapotranspiration, soil moisture, groundwater, clouds, etc., from satellite and *in situ* observations for monitoring climate trends and early detection of potential climate change [2-4 years]. The Ecosystems, Carbon Cycle, and other CCSP research elements will use these data sets as inputs for their analyses and model development studies.
- Results from process studies related to the indirect effects of aerosols on clouds will be available for future assessments of climate sensitivity to aerosols [2-4 years].
- Improved regional water cycle process parameterizations based on process studies conducted over regional test beds to improve the reliability of climate change projections [beyond 4 years].
- Development of analyses for a *State of the Water Cycle* evaluation [beyond 4 years].

Question 5.2: How do feedback processes control the interactions between the global water cycle and other parts of the climate system (e.g., carbon cycle, energy), and how are these feedbacks changing over time?

State of Knowledge

Feedback processes operating between the global water cycle and other components of the Earth/climate system represent the response to external forcing, such as increases in atmospheric carbon dioxide (CO_2). For example, results from climate models suggest there will be an increase in water vapor as the climate warms. Water vapor is the dominant greenhouse gas in the atmosphere; therefore, an increase would result in a strong positive feedback on temperature. Clouds strongly influence the energy budget because of their impact on the radiative balance, but the net cloud-radiation feedback is uncertain. Quantifying the water vapor-cloud-radiation feedback is key to understanding climate sensitivity and the factors governing climate change.

Because the physical processes responsible for the vertical transport of water vapor, cloud formation, cloud-radiation interactions, and precipitation occur at scales that currently are not resolved by climate models, they are parameterized. Although progress has been made in developing and applying high-resolution cloud-resolving models, to date the benefits of these developments for parameterizing three-dimensional cloud distributions in climate models have not been fully realized.

Climate model results also indicate that temperature increases will be amplified in the Arctic due to feedbacks involving permafrost, snow, and ice cover. Should these amplified increases occur, melting continental snow and ice may result in changes in northern river runoff and ocean salinity, while thawing permafrost may lead to increased releases of methane (a greenhouse gas) to the atmosphere. Given the same greenhouse gas increases, individual climate models produce different rates of warming and drastically different patterns of circulation, precipitation, and soil moisture depending on how feedback processes are represented in the models. Basic understanding of feedback processes must be improved and incorporated into models.

Illustrative Research Questions

- What is the sign and magnitude of the current water vapor-cloud-radiation-climate feedback effect (Chapter 4)?
- How do changes in water vapor and water vapor gradients, from the stratosphere to the surface, affect radiation fluxes, surface radiation budgets, cloud formation and distribution, and precipitation patterns, globally and regionally (Chapter 4)?
- How do freshwater fluxes to and from the ocean that affect the global ocean circulation and climate (precipitation, river discharge, sea-ice melt, evaporation) vary, and how may they be changing (Chapter 4)?
- How do changes in global and regional water cycles interact with evapotranspiration, vegetation and the carbon cycle and vice versa (Chapters 7 and 8)?
- What are the interactions between land surface changes and regional water cycles (Chapter 6)?
- How might an intensification of the hydrological cycle, warming in the Arctic, and melting permafrost affect the production of methane and nitrous oxide (Chapters 4 and 7)?

Research Needs

Model development can be accelerated by acquiring data from interdisciplinary field studies over regional test beds, such as those shown in Figure 5-4, to provide a better understanding of scaling effects and the best way to include them in parameterizations. New parameterizations of water cycle/climate feedbacks (e.g., cloud-aerosol and land-atmosphere) and sub-grid-scale processes (e.g., clouds, precipitation, evaporation) will have to be developed and validated, and the sensitivity of global climate models to these new parameterizations will have to be evaluated. Research on water and clouds will have to be closely linked to investigations of aerosols. The development and implementation of instrument systems over selected, globally distributed, test beds is essential. The data products must be comprehensive and include groundwater, and they should have sufficient resolution to assess optimal sampling strategies for future observational campaigns and field programs over larger regions. Where appropriate, data and experimental field sites will be shared with the Ecosystems and Carbon Cycle research elements.

Milestones, Products, and Payoffs

- New observationally tested parameterizations for clouds and precipitation processes for use in climate models based on cloud-resolving models developed in part through field process studies [2-4 years]. This will support Climate Variability and Change research element work on climate feedbacks.
- Incorporation of water cycle processes, interactions, and feedbacks into an integrated Earth system modeling framework [2-4 years].

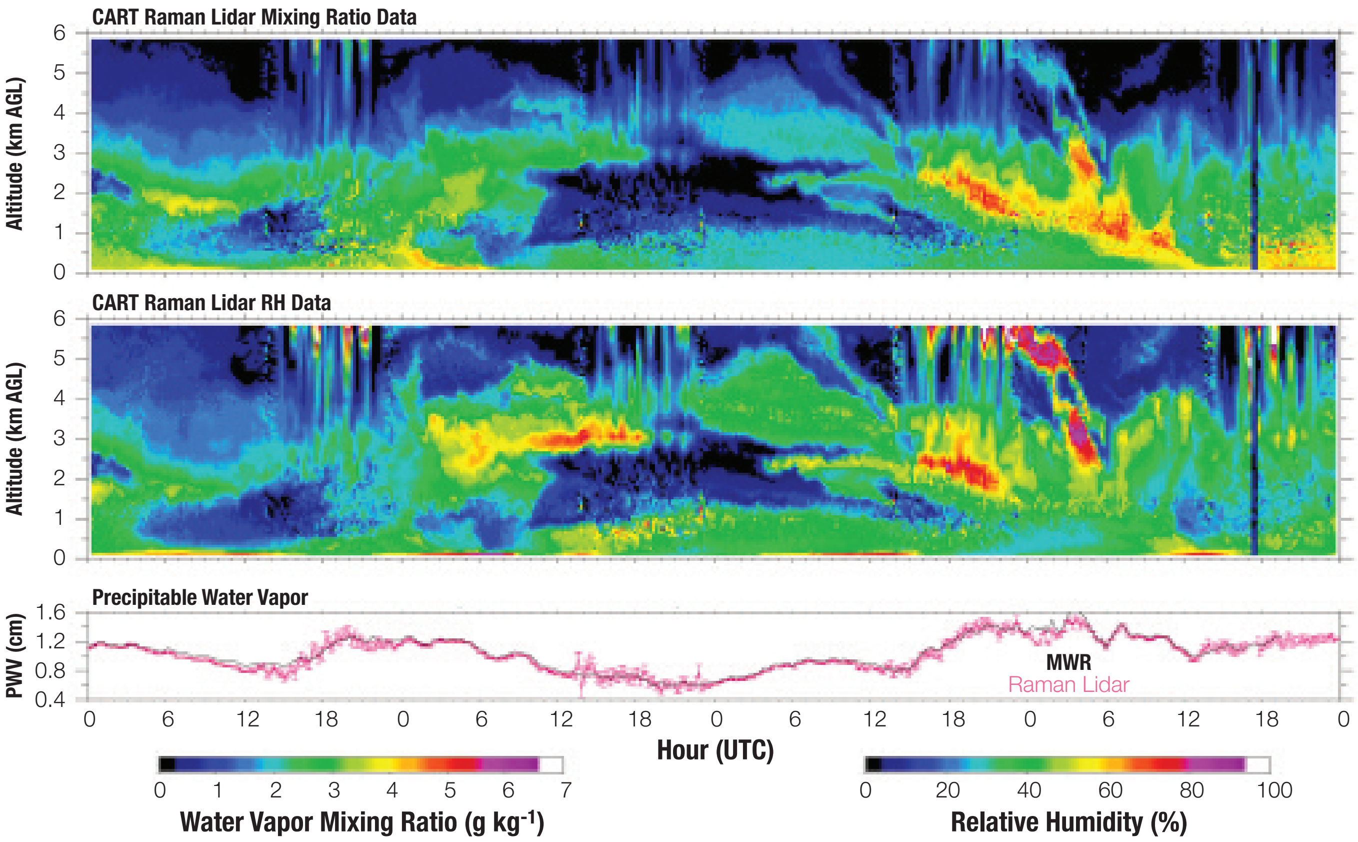

Figure 5-4: Water vapor measurements at the Atmospheric Radiation Measurement Program (ARM) Southern Great Plains (SGP) site from 29 November to 2 December 2002. *Top Panel*: Measured water vapor mixing ratio from the Raman lidar. These charts of the fundamental measured quantity from the lidar give unique information about the vertical and horizontal scales of turbulent fluxes that transport moisture. *Middle Panel*: Relative humidity calculated from the mixing ratio and associated temperature data at the SGP. *Bottom Panel*: Comparison between the integrated water vapor from the Raman lidar and the measured water vapor path from the microwave radiometer. Source: David Turner, University of Wisconsin, DOE ARM Program.

- Quantification of the potential changes in the cryosphere, including the effects of permafrost melting on regional hydrology and the carbon budget, and the consequences for mountain snowpacks, sea ice, and glaciers [beyond 4 years]. These efforts will complement those of the Climate Variability and Change and Carbon Cycle research elements in the area of cryosphere-atmosphere-ocean coupling and feedbacks.
- In collaboration with the Climate Variability and Change research element, sensitivity tests of global models to improve parameterizations of feedbacks and sub-grid-scale processes (land-cover change, land surface processes, precipitation, clouds, etc.) [beyond 4 years].
- Enhanced data sets for feedback studies, including water cycle variables, aerosols, vegetation, and other related feedback variables, generated from a combination of satellite and ground-based data [2-4 years]. These data sets will be critical for most CCSP research elements.
- Together with the Land-Use/Land-Cover Change and Carbon Cycle research elements, improved coupled land-atmosphere models and enhanced capability to assess the consequences of different land-use change scenarios [beyond 4 years].

Question 5.3: What are the key uncertainties in seasonal-to-interannual predictions and long-term projections of water cycle variables, and what improvements are needed in global and regional models to reduce these uncertainties?

State of Knowledge

Improved seasonal predictions of water resource availability and their application can have major economic benefits. For example, in 1999, if the experimental spring runoff forecasts for the Green River had been used, improved water management decisions could have resulted in more efficient use of stored water and yielded more than $3.1 million in additional revenues from power production and irrigation. While precipitation forecasts on "weather" time scales have improved, current global and regional models demonstrate limited skill in predicting precipitation, soil moisture, and runoff on seasonal and longer time scales. Water managers indicate this skill level to be inadequate for their needs.

Seasonal-to-interannual predictability is a function of local and remote influences involving various ocean and land processes. Enhanced predictability can result from persistence of specific phenomena or slowly varying boundary conditions (soil moisture/groundwater, snow/ice, vegetation/land cover, and ocean and land surface temperatures) that persist over periods of weeks, months, or even years. More accurate initial surface fields for prediction models produced by recently developed land data assimilation systems provide a basis for reducing prediction errors. Understanding of the El Niño/La Niña cycle has provided some predictive skill, particularly with respect to seasonal outlooks for floods and droughts (see Figure 5-5); however, the memory effects of land conditions on the atmosphere are not well enough understood. Cloud and precipitation feedbacks and the interactions of the lower boundary layer (lower 500 meters of the atmosphere) with land and ocean surface conditions also are not well understood.

A critical prediction problem involves advance warning for major flood and drought events. The ability to reliably assess whether hydrologic extremes will increase as greenhouse gas concentrations rise is also important. Extreme events arise from a combination of large-scale circulation patterns that enhance atmospheric conditions conducive to flood or drought, regional patterns and feedbacks that accentuate the larger scale factors, and preconditioning of the system to increase the impacts of the flood or the drought event. Understanding the relative roles of remote and local factors in initiating, maintaining, and terminating extreme events will require the Water Cycle and the Climate Variability and Change research elements to work collaboratively on this topic.

Illustrative Research Questions

- How predictable are water cycle variables at different temporal and spatial scales over different regions of the Earth's surface (Chapter 4)?

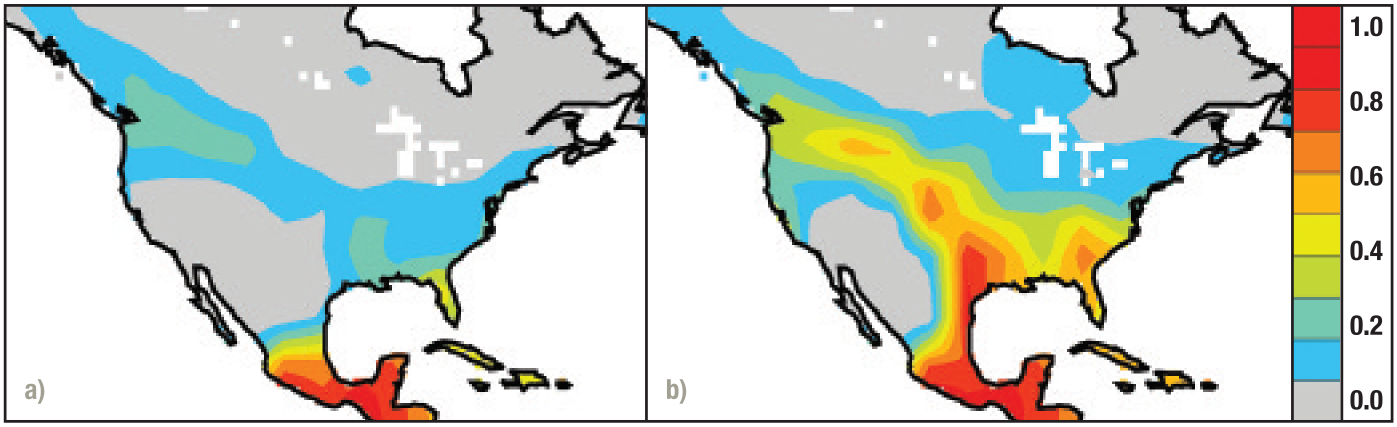

Figure 5-5: Predictability of precipitation in summer (June, July, and August) on seasonal time scales, through analysis of an ensemble of multi-decadal coupled land-atmospheric model simulations. In map (a), values close to 1 indicate areas where precipitation is strongly determined by sea surface temperature (SST) and therefore is predictable when SST is predictable; values close to 0 indicate where foreknowledge of SST may not lead to useful seasonal precipitation predictions. Map (b) shows the same information for SST and land surface moisture state. The addition of land surface information appears to improve predictability. Source: R.D. Koster, M. Suarez, and M. Heiser, NASA. For more information, see Annex C.

- For different model resolutions, how can key water cycle processes be better simulated, in order to enhance the capability of producing more accurate seasonal-to-interannual predictions of water cycle variables (Chapters 4 and 8)?
- How can the representation of water cycle processes in climate models be improved to reduce uncertainties in projections of climate change (Chapter 4)?
- What are the critical hydrological and atmospheric factors present in major flood and drought events that can be isolated, quantified, and incorporated into water cycle prediction methodologies (Chapter 4)?
- What model improvements are needed to assess the changes in seasonality, intensity, and variability of high-latitude freshwater fluxes (precipitation, evapotranspiration, runoff) and stores (soil moisture, snow/ice, permafrost) that may result from climate change, specifically in large basins covering a range of climate regions?
- What processes and model resolutions are needed to improve regional models used to downscale global predictions to local and watershed scales? Are there other downscaling techniques (e.g., statistical approaches) that can be equally effective (Chapter 4)?
- How can the uncertainty in the prediction of water cycle variables be characterized and communicated to water resource managers (Chapter 11)?

Research Needs

Advances in prediction capabilities will depend on improvements in model structure and initialization, data assimilation, and parameter representations. Predictability studies will be required to determine the regions, seasons, lead times, and processes most likely to provide additional predictive skill. Better understanding and improved model representations of less well-understood processes—such as the seasonal and longer term interactions of the atmosphere with vegetation, soils, oceans, and the cryosphere—are needed. The modeling of regional feedbacks leading to extreme events also requires a better understanding of land-atmosphere interactions, while the modeling of antecedent conditions requires hydrologic and biospheric models and monitoring programs that will account for the effects of prolonged rainfall, or lack thereof, in a given region. The goal of better predictions must be achieved by accurate representations of precipitation processes in climate models. The role of mountains in the annual water cycle also needs to be better understood. Data sets are needed for the calibration and validation of global coupled climate models and the development of regional downscaling and statistical forecasting techniques. In addition, model evaluation studies with enhanced data sets are needed to improve models and to characterize and reduce uncertainties.

Milestones, Products, and Payoffs

- Regional reanalysis providing a wide range of high-resolution, daily water cycle analysis products for a 25-year period, for use in analyzing features absent in global climate data assimilation products [less than 2 years].
- Observational data sets to initialize and test boundary layer and other components (including parameterizations) in mesoscale, regional, and global models [2-4 years].
- Results from field and modeling experiments to study the role of mountain environments on precipitation and runoff production [2-4 years].
- New drought monitoring and early warning products based on improved measurements of precipitation, soil moisture, and runoff, and data assimilation techniques to inform drought mitigation planning [2-4 years]. This initiative will be undertaken in collaboration with extreme event activities in the Climate Variability and Change and Ecosystems research elements.
- Metrics for representing the uncertainty in predictions of water cycle variables and measurably improved forecast products for water resource managers [2-4 years].
- In collaboration with the Climate Variability and Change research element, the capability for long-range prediction of drought and flood risks (seasonal-to-interannual time scales) [beyond 4 years]. The Water Cycle research element will focus on the role of terrestrial feedbacks to extreme events while the Climate Variability and Change research element will address the seasonal and longer term changes in remote influences such as sea surface temperatures.
- Downscaling techniques, such as improved regional climate models, that bridge the disparate spatial and temporal scales between global model outputs and atmospheric, land surface, and river basin processes, for improved evaluation of potential water resource impacts arising from climate variability and change [beyond 4 years].
- New space-based systems for measuring global precipitation will be developed and implemented to support the needs of the Climate Variability and Change, Carbon Cycle, and Land-Use/Land-Cover Change research elements [beyond 4 years].

Question 5.4: What are the consequences over a range of space and time scales of water cycle variability and change for human societies and ecosystems, and how do they interact with the Earth system to affect sediment transport and nutrient and biogeochemical cycles?

State of Knowledge

Variability and changes in the water cycle have been shown to have profound impacts on human societies (including human health) and ecosystems, but many of the linkages between these changes and their outcomes are not yet understood in the detail needed to inform policy and management responses. In addition, the strategies used for water management throughout the last century to adapt to climate variability have had impacts on water availability and water quality that must be identified and evaluated as part of the process of separating climate change effects from other forms of global change arising from factors such as industrialization and population growth. Furthermore, the ability to simulate variations in water availability and quality and their consequences for agriculture, wetlands, energy production and distribution, urban and industrial uses, and inland shipping, among others, should be further developed and integrated into a common modeling framework.

Many of the impacts of water variability arise because of its effects on sediment loadings and the transport of nutrients and sediments. As water cycles through the environment, it interacts strongly with other biogeochemical cycles—notably carbon, nitrogen, and other nutrients. Flowing water also erodes, transports, and deposits sediments in rivers, lakes, and oceans, altering water quality and affecting agricultural production and ecosystem functioning, among other socially relevant impacts. Yet our ability to quantify the role of flowing water as the primary agent for sediment transport that reshapes the Earth's surface, and for nutrient transport that feeds riparian (relating to rivers) habitats and degrades water bodies, is inadequate. Currently, we do not have the monitoring framework needed to generate a database to support research on these processes. The priority challenges are to quantify water flow and the various transport rates, biochemical transformations, and constituent concentrations and feedbacks whereby the water cycle alters media and ecosystems.

Illustrative Research Questions

- How does the water cycle interact through physical, chemical, biophysical, and microbiological processes with other Earth system components at the watershed scale (generally 50 to 20,000 km^2) (Chapters 6, 7, and 8)?
- How do changes in climate, land cover, and non-point waste discharges alter water availability, river flows, water quality, and the transport of sediments, nutrients, and other chemicals, and how do these changes affect human and ecosystem health (Chapters 6 and 8)?
- How do surface and subsurface processes change the quantity and quality of water available for human and environmental uses (Chapters 6 and 8)?
- How might an intensification of the hydrological cycle enhance soil erosion and result in soil degradation, especially losses in soil carbon (Chapters 6 and 7)?
- How would ongoing systematic depletion of groundwater resources be influenced by climate change and how is this process affected by sea-level rise (Chapters 4, 6, and 8)?
- How might ongoing and potential future changes in hydrologic regimes, such as earlier melting of the snowpack and lake and river ice, affect the amount and timing of spring, summer, and fall flows, surface water temperatures, and their impacts on aquatic biota (Chapters 4 and 8)?
- How do variability and change in the water cycle affect riparian and estuarine environments in the United States (Chapters 6 and 8)?
- How might water cycle variability and change affect the spread of vector-mediated disease (Chapters 4, 6, and 8)?

Research Needs

Overall, there is a basic need to develop an integrated research vision (complete with hypotheses) for addressing multiple-process (hydrological, physical, chemical, and ecological) interactions between water and other Earth systems. Techniques that scale up processes active at watershed and sub-watershed scales to larger scales must be developed and tested. In addition, it is necessary to refine geophysical methods and the use of tracers, including isotopes, to determine subsurface paths, flow rates, and residence times, and to track pollution plumes. Experimental watersheds are needed to develop an understanding of these processes. Information on trends in land use and land cover will be needed to assess consequences for water supply. It also will be essential to work closely with social and ecosystem scientists to develop understanding of impacts of water cycle variability, and social and biological responses and feedbacks arising from that variability.

Milestones, Products, and Payoffs

- Reliable, commensurate data sets at the watershed scale that scientists from various disciplines will use to examine critical water-Earth interactions for improved integrated watershed management [2-4 years].
- Development and application of better methods for monitoring subsurface waters for inventorying current and future water availability, including tracking aquifer storage and how it responds to water withdrawals and climate change [beyond 4 years].
- Development of data sets and analyses of spatial and temporal trends in stream flow and water quality (including sediments and chemicals) for a range of watershed conditions including watersheds with minimal effects from human activities, agricultural watersheds, sensitive ecosystems, and large river basins [2-4 years]. These activities will address the needs of the Ecosystems research element for baseline water cycle information.
- Evaluations of the effects of water cycle variability and change on trends in water-quality conditions [2-4 years]. Information from these evaluations is needed for studies by the Ecosystems research element.
- Improved modeling and remote-sensing methods for scaling up from individual pathways and mixing zones to the scale and complexity of watershed systems [beyond 4 years].
- Models that partition precipitation among surface and subsurface pathways, route flows, and quantify physical and chemical interactions for evaluating climate and pollution impacts [beyond 4 years].
- Contributions of data and advice to Human Contributions and Response studies, including use of improved epidemiological models, to examine the potential for major water-mediated infectious diseases [2-4 years].
- Scientific capability to assess the climate-related consequences of water use trends and water management practices [beyond 4 years]. This capability is needed to evaluate the effects of water management on the health of ecosystems, and together with the Climate Variability and Change research element to examine the combined effects and relative contributions of groundwater pumping and climate change on sea-level rise and coastal flooding.

Question 5.5: How can global water cycle information be used to inform decision processes in the context of changing water resource conditions and policies?

State of Knowledge

Results of recent research on the water cycle can contribute to the capacities of decisionmakers in such sectors as water management, agriculture, urban planning, disaster management, energy, and transportation. Improved understanding of water cycle variability and trends at regional and watershed scales appears to benefit decisionmakers dealing with climate-sensitive issues (see Figure 5-6). Whether the water cycle is changing as a result of human activities or natural low-frequency variation, human societies will have to adapt, and focused scientific information must be provided to support their choices. The growing economic and social costs of extreme events indicate that there is need for improved responses to these disruptions, whether or not their frequency and intensity are changing. Currently, climate forecasts are often temporally or spatially too coarse to be of use for many water-dependent decision processes. In addition, factors such as regulatory inflexibility, institutional structures, and time pressures make it difficult to change established management and decision systems. Interactions between decisionmakers and research scientists are needed to make mutual adjustments as appropriate to match scientific information with decision processes. Efforts to eliminate the barriers between researchers and research users have been initiated and indicate that early collaboration and side-by-side demonstrations may be effective tools for speeding innovation.

Illustrative Research Questions

- How could climate variability and change potentially alter the effectiveness of current and future water management practices and their feedbacks on the climate (Chapter 9)?
- What are the consequences of demographic and land-use trends on groundwater and surface water supplies domestically and globally (Chapters 6 and 9)?
- What are effective means for transferring stochastic water cycle research products (e.g., hydro-climatological predictions, projections, and associated uncertainties) into the management, planning, and design of water decision systems and infrastructure (Chapters 9 and 11)?
- How can advance knowledge of water availability be used to manage conflicting demands on domestic and transboundary water resources for water consumption, ecological functions, industrial uses, and transport (Chapter 9)?
- How can changes in the quality and quantity of water flowing within riparian and coastal environments arising from land management and policy decisions affect the provision of ecosystem services (Chapters 8 and 9)?
- How have water consumption patterns and trends changed as a result of major climatic events, technological innovation, and economic conditions, and how are they likely to change as a result of projected changes in the same factors (Chapters 9 and 11)?
- What are the trends in agricultural, industrial, municipal, and instream water uses, and what implications do they have for adaptation strategies (Chapters 6, 8, and 9)?
- What are the economic implications of strategies for the application of improved capabilities to predict seasonal water cycle variability and change (Chapters 9 and 11)?

Research Needs

For scientific information to have an impact, it will have to rely on refined and extended research on the role, entry points, and types of water cycle knowledge required for water management and policy decisionmaking processes. In order to make rapid progress it will be necessary to integrate data from a broad range of sources and disciplines. A basic requirement for achieving this goal is the

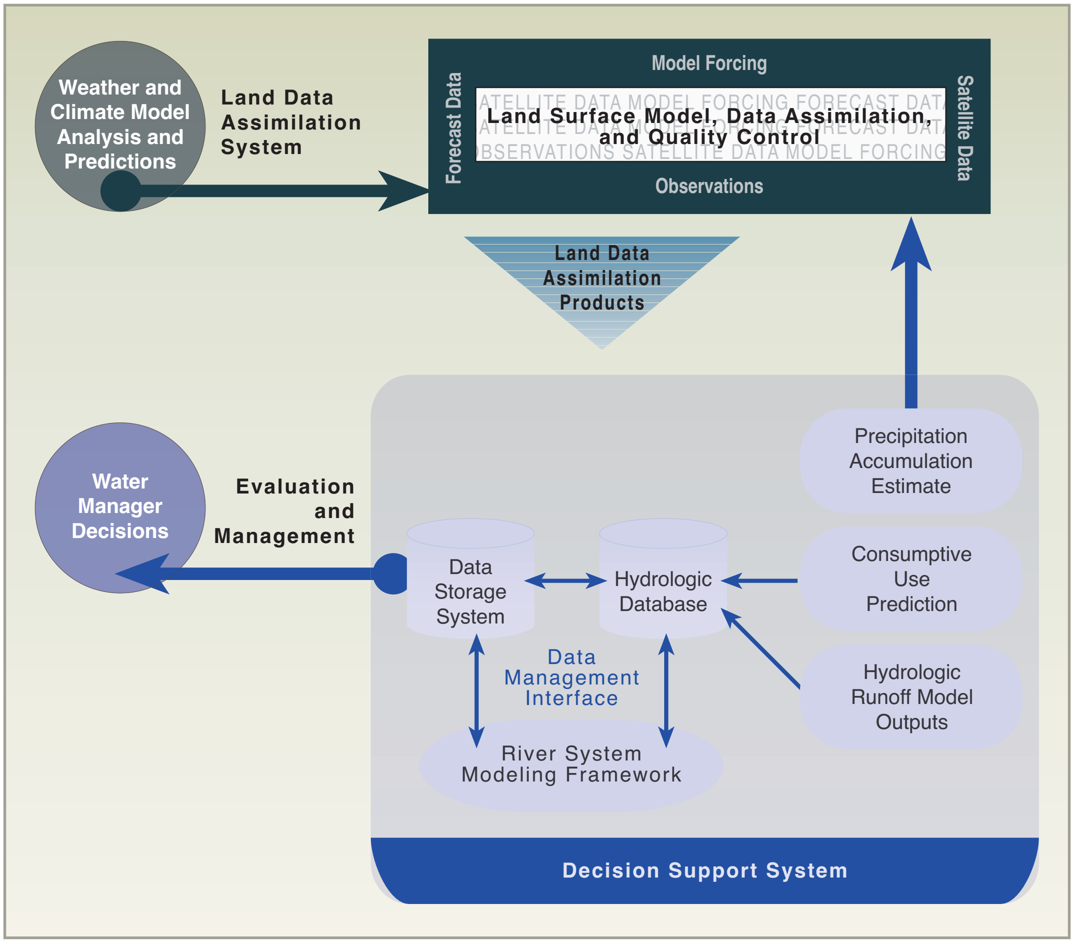

Figure 5-6: Schematic of the flow of data and information between land surface models, numerical forecasting products, and decision support systems used by water managers to operate reservoirs and river systems. Improved forecasts and data assimilation systems from water cycle research will lead to more equitable and sustainable management of precious water resources. Improved forecasts will lead to enhanced river system management, and increased water storage and efficient hydropower generation, while preserving flood control space.

development of frameworks for integrating the natural and social science information necessary for multiple-objective decisionmaking. Inputs should include research in remote sensing, uncertainty of predictions, data management for decision support, risk management, economic impact assessments, and water and environmental law, among many others.

An ability to assess the consequences of both historic and potential future water development paths is needed for assessing trends and variability in water resources. In addition, to determine patterns and trends, it will be necessary to inventory existing data sources and regional and sectoral studies, especially for data for which regional, national, and global repositories are rare or non-existent (e.g., water demand, diversion, use, and consumption). An integrated data system for collection, storage, and retrieval of these data would enhance national capacities for evaluating policy and decision options.

Milestones, Products, and Payoffs

A number of the following milestones, products, and payoffs will be developed in collaboration with the Decision Support Resources element.

- An experimental surface and subsurface moisture monitoring product for land resource management (e.g., fires or agriculture) [less than 2 years].
- An experimental online decision support tool designed to provide users with streamflow conditions and their accompanying probabilities in the Pacific Northwest arising from near- and far-term future climate predictions and projections [less than 2 years].
- Refinements of web-based tools that improve the communication and usability of climate/water forecasts [less than 2 years]. These developments will contribute to Human Contributions and Responses research element analyses of techniques for communicating and disseminating climate forecasts.
- Transfer to operations of capabilities to produce improved stochastic operational streamflow forecasts over a range of spatial and temporal scales (days, weeks, months, and seasons) to support water management decisions [2-4 years].
- Development of an ensemble forecast system to predict snowpack, streamflow, and reservoir storage over the western United States, based on information about global climate teleconnections, for lead times ranging from several weeks to 1 year for operational purposes, and from decades to a century for water resource planning [2-4 years].
- Demonstration of system simulation and forecasts using advanced watershed and river system management models and decision support systems, to facilitate acceptance and utilization of these advanced technologies for improved hydropower production and river system management [2-4 years].
- Assessment reports on the status and trends of water flows, water uses, and storage changes for use in analyses of water availability [2-4 years].
- Integrated models of total water consumption for incorporation into decision support tools that identify water-scarce regions and efficient water use strategies [beyond 4 years]. The Human Contributions and Responses research element will supply inputs on the effects of climate on human drivers of water demand.

National and International Partnerships

As indicated throughout this chapter, the Water Cycle research element will have strong ties to many of the other components of the CCSP. It will also contribute to water initiatives that may be forthcoming from the newly formed Subcommittee on Water Availability and Quality (SWAQ) and the hydrologic aspects of the U.S. Weather Research Program.

The Water Cycle research element has strong links to the World Climate Research Programme (WCRP) and its Global Energy and Water Cycle Experiment (GEWEX). In particular, the activities outlined in this chapter will use data sets from the Coordinated Enhanced Observing Period (CEOP) in model development. The Water Resources Applications Project (WRAP) will provide a framework for studies to assess the benefits of improved hydrological forecasts in decisionmaking. The Earth System Science Partnership's Global Water System Project will be a partner for studies of the feedbacks of water management practices and infrastructure to regional and global climate. Water cycle observational issues will form the basis for activities under the water cycle theme of the International Global Observing Strategy (IGOS) Partnership and related observational activities, namely the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the Global Terrestrial Observing System (GTOS). Improved coordination of terrestrial observations is a critical need of the Water Cycle research element that will be addressed at the international level in the IGOS Water Cycle theme report. The Water Cycle research element also has developed strong linkages with the Hydrology and Water Resources Programme of the World Meteorological Organization (WMO), the International Hydrology Programme of the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the joint UNESCO/WMO Hydrology for Environment, Life, and Policy (HELP) initiative. Water Cycle efforts also will contribute to observational programs and research developed through bilateral treaties, particularly with countries such as Japan that have placed a priority on water cycle research, and with Canada through the International Joint Commission, the Great Lakes Commission, and the Great Lakes Environmental Research Laboratory.

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