DRAFT WHITE PAPER:

THE GLOBAL WATER CYCLE AND ITS ROLE IN CLIMATE AND GLOBAL CHANGE

In support of Chapter 7 of the

Strategic Plan
for the
Climate Change Science Program

Draft dated 26 November 2002

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Preface

On 11 November 2002, the US Climate Change Science Program issued a discussion draft of its *Strategic Plan*. The strategy for each major area of the program is summarized in specific chapters of the draft plan, and for four chapters is described in greater detail in white papers. The white papers, including this one focused on the water cycle, represent the views of the authors and are not statements of policy or findings of the United States Government or its Departments/Agencies. They are intended to support discussion during the US Climate Change Science Program Planning Workshop for Scientists and Stakeholders being held in Washington, DC on December 3 – 5, 2002.

Both the chapters of the plan and the white papers should be considered drafts.

Comments on the chapters of the draft *Strategic Plan* may be provided during the USCCSP Planning Workshop on December 3 – 5, 2002, and during a subsequent public comment period extending to January 13, 2003. The chapters of the *Strategic Plan* will be subject to substantial revision based on these comments and on independent review by the National Academy of Sciences. A final version of the *Strategic Plan*, setting a path for the next few years of research under the CCSP, will be published by April 2003. Information about the Workshop and opportunities for written comment is available on the web site www.climatescience.gov.

Comments that are specific to this white paper – and that are not already conveyed through comments on the related chapter of the plan – should be directed to: Susanna Eden [seden@usgcrp.gov].

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In this paper…

1. Introduction

The Global Water Cycle (GWC) determines the amount of water that is available for human uses such as municipal and industrial supply, irrigation and agriculture, hydropower, waste disposal, protection of human and ecosystem health and a wide range of societal and environmental benefits. The GWC is an integral part of the Earth/ Climate system; water vapor constitutes the Earth's most abundant and important greenhouse gas, and water is its most active solvent. The interactions of the GWC and the climate system manifest themselves through many processes and phenomena, such as cloud formation, precipitation, groundwater recharge, accumulation and ablation of snow packs and glaciers, droughts and floods. Furthermore, water regulates the Earth's energy balance because energy is absorbed (or released) when liquid water is converted to or from water vapor and the energy stored in water is transferred from one location to another through water transport. These properties account for the critical role that the cycling of water plays in climate variability and its feedback effects that have a strong influence on the rate of climate change. The Global Water Cycle program forms a distinctive element within the CCSP that focuses research towards a more coherent view of the movements, transformations, and reservoirs of water, energy and water-borne materials throughout the Earth system and their interactions with ecosystems and human systems. In particular, the GWC element contributes to climate science by providing research on critical areas of uncertainty in climate change science and building the scientific basis needed by water users and managers to adapt to climate variability and change in a sustainable way. Although the GWC operates on a continuum of space and time scales, this document places more emphasis on the time and spatial scales relevant to climate issues.

The water cycle is now widely recognized as one of the dominant causes of uncertainty in climate change projections. Moreover, most major impacts of climate variability and climate change on human activity and natural ecosystems directly involve precipitation processes or water and energy cycles. Precipitation projections have been very uncertain; climate models have produced contradictory projections for the central USA–whether it will experience drying or wetting as atmospheric carbon dioxide concentrations increase. Because the availability of water for human uses and ecosystem functions in this area (as is the case in most land areas) is more sensitive to precipitation changes than changes in temperature, these uncertainties are important to resolve. Furthermore, the responses of vegetation and ecosystems to precipitation have implications for carbon sequestration. Increases in carbon sequestration in northern hemisphere forests are being attributed to changes in regional precipitation regimes. Furthermore, the changing evapotranspiration rates associated with changing vegetative cover arising from land use change complicates the interpretation of the warming trends that have been observed over the USA during the past century.

The Earth's water cycle is driven by processes that force the movement of water from one reservoir to another. Evaporation from the oceans and land is the primary source of atmospheric water vapor, which is transported, often over long distances, and eventually condenses into cloud particles, that in turn develop into precipitation. Precipitation over land finds its way into rivers, aquifers, and eventually oceans. Globally, there is as much water precipitated as is evaporated, but over land precipitation exceeds evaporation and over oceans evaporation exceeds precipitation. The excess precipitation over land equals the flow of surface and groundwater from continents to the oceans. This natural cycling of water is now perturbed by human activities. Together with changing vegetation patterns due to land management practices, these factors complicate the prediction of the consequences of climate change on the Global Water Cycle.

The water cycle is coupled with biogeochemical cycles that control the movement if nutrients, waste products and even toxic chemicals, in aquatic-land and coastal ecosystems. These linkages directly affect water quality and the availability of potable water and industrial water supplies. Water supplies are subject to a range of stresses, such as population growth, pollution and industrial and urban development. Furthermore, water has been identified as a major factor in the occurrence and transmission of a number of vector-borne diseases (e.g. West Nile virus). These issues lead to public concerns about water quality and efforts to improve the management of fresh water resources. Accordingly, the global water cycle is an issue of central concern in the USA and in every other country of the world. The needs for adequate supplies of clean water pose major challenges to social and economic development and to the management of natural resources and ecosystems. These challenges grow ever greater as variations and changes in climate alter the hydrologic cycle in ways that are currently unpredictable.

Extremes in the surface water cycle, in terms of droughts and floods, have major implications for the security of life and property and for economic activity. Floods are the most important natural hazard for the USA in terms of loss of life and property, with annual average losses now approaching $10 billion per year. Although drought losses are more difficult to quantify, the 1988 central US drought impacts have been estimated at more than $20 billion.

A recent report to the federal government by a group of leading atmospheric and hydrologic scientists, “A Plan for a New Science Initiative on the Global Water Cycle.” (Hornberger *et al.*, 2001) highlights the need for water cycle research. The authors emphasized that the water cycle is changing in ways that we have never experienced, and consequently, we must develop the knowledge base, information and decision support resources needed to deal with these emerging realities. This report identified three major areas that require more research over the next decade. The three areas include documentation and understanding of trends and variability in the GWC, improving the accuracy of water cycle predictive capabilities, and developing a better scientific understanding of the linkages between the water cycle and other biogeochemical cycles, especially the carbon cycle. These three areas form the basis for discussions in this white paper related to climate change and water cycle trends, prediction and the linkages between water and nutrients cycles in terrestrial and freshwater ecosystems.

The emerging capability to predict GWC variations at seasonal to interannual time scales provides a basis for dialog between the scientific community and water system and land managers. This dialog is enabling the program to provide the scientific underpinnings for improving the adaptability of existing infrastructure and management practices. Potential changes in water cycle variables such as precipitation, evaporation and runoff have critical implications for agriculture, water supply and hydropower managers, and other sectors that are affected by long-term water cycle changes.

To address the urgent need for better information on the water cycle, the USGCRP/CCSP is planning its Global Water Cycle research program around two overarching questions, namely:

1. How do water cycle processes (including climate feedbacks) and human activities influence the distribution and quality of water within the Earth system, to what extent are changes predictable, and how are these processes and activities linked to ecosystem and human health and the cycling of important chemicals, such as carbon, nitrogen, other nutrients, and toxic substances?
2. How will large-scale changes in climate, demographics, and land use (including changes in agricultural and land management practices), affect the capacity of societies to provide adequate supplies of clean water for human uses and ecosystems and respond to extreme hydrologic events?

The above questions define the scope of a science-driven Water Cycle program focused on the needs of society. To address these questions in a comprehensive way, the program elements developed in this document deal with:

1) long term trends in the global water cycle and the internal water cycle processes responsible for these trends;
2) links between the water cycle and the climate system and controls that the water cycle places on climate variability and change;
3) development of a capability to predict water cycle variables;
4) linkages between variations in the water cycle and variations in other connected cycles such as carbon and nitrogen and in reservoirs such as the cryosphere, ecosystems and coastal areas; and
5) information on the impacts of water cycle variability and change and its use in planning and management decisions that affect the use of the Nation's water resources.

USGCRP water cycle research, therefore, directly intersects all of the focused research required by the CCSP, especially in the context of delivering scientific results, observing and attributing trends and variability, assembling sets of integrated data and information, and improving prediction products, as needed for the development of decision support tools for water management.

Impacts of global change on water resources will be complicated and interactions will involve feedbacks likely to produce surprises and unusual events. Advances in GWC research require a mix of observational program enhancements, field experiments and process studies, model development and testing, and modeling studies. The development of better models deserves particular attention, as models are the key building block for improving the accuracy of water cycle predictions. To address the breadth of water cycle issues arising in the program, a mix of models is needed, some within linked model hierarchies for prediction purposes and some that would be run offline to build understanding of processes and provide the linkages with biogeochemical cycling and decisions support. Models will be used in both simulation and prediction modes. A suite of models and modeling strategies will be needed ranging from small area process models operating in stand-alone fashion to regional models nested in a hierarchy of partially- and fully-coupled models, to global Earth system models that include the representation of all elements of the GWC. The following pages outline the five questions that constitute the core of the CCSP water cycle element, as well as the associated research needs and expected results.

2. Elements of the CCSP Global Water Cycle Component

2.1 INTERNAL WATER CYCLE MECHANISMS

QUESTION 1: WHAT ARE THE UNDERLYING 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

Water strongly influences the Earth's radiation balance. Clouds reflect short wave radiation (thereby cooling the atmosphere) and absorb terrestrial outgoing long-wave radiation (warming the atmosphere). The nature and magnitude of the cooling/heating is a function of the areal coverage, height, structure and optical properties of the clouds. Water molecules are strong absorbers of infrared radiation and water vapor is, by far, the most effective of the "greenhouse gases". Water vapor concentrations in the upper troposphere and lower stratosphere are very critical in determining the rate at which radiative energy emitted by the atmosphere escapes to space.

The water cycle plays a key role in the maintenance of the climate system as a moderator of the Earth's energy cycle. It is through the water cycle that incoming solar energy is redistributed through the Earth system via the atmosphere and oceans. Latent heat exchanges occur as water changes phases from solid or liquid to vapor and vice versa. Water cools its surroundings when it evaporates or sublimates, usually at the land or ocean surface, and warms the surrounding air when vapor condenses as clouds and precipitation. Water vapor is transported by the wind from its source to other regions. Because of the large amount of heat released by the condensation of water molecules (latent heat), water vapor is a very effective means of storing energy and the latent heat flux in the atmosphere is a major component of the overall transport of energy from equator to poles. Furthermore, latent heat is the principal source of energy that drives cyclogenesis and sustains weather systems.

Recent observations suggest that there have been significant changes in a number of water cycle components – precipitation intensity, distribution and types; surface and subsurface runoff; cloud cover properties; atmospheric water vapor; and river discharge. For example, U.S., precipitation is characterized by more high intensity events than occurred in the past. According to current climate model predictions, the most significant manifestation of global warming could be an acceleration of the rate of the global water cycle. However, current climate models do not make consistently accurate predictions, and these critically important projections are very uncertain.

Within any part of the climate system, there is a substantial range of natural variability due strictly to internal processes. It is extremely difficult to distinguish between the natural excursions from the "norm" and changes that might be the result of forcing caused by human actions. Major improvements in observations and models of the water cycle are required in order to distinguish "natural" variability from change. Once models can successfully simulate past water cycle behavior, they can be used to assess potential changes due to human activity, such as anthropogenic emissions of greenhouse gases, land use change or aerosol production.

Current models do not simulate many aspects of the global climate well, and many of the model shortcomings are related to poor representations of the GWC. For a given increase in CO_2 , different climate models produce vastly different cloud, precipitation and soil moisture (both in magnitude and sign) depending on their parameterizations of basic water cycle processes. Furthermore, as global temperatures warm, the atmosphere becomes capable of holding more moisture and the warmer temperatures normally increase evaporation rates and the amount of water vapor throughout the atmosphere. This basic knowledge, however, does not reveal whether the increased atmospheric water vapor will lead to the formation of more extensive cloud covers and will enhance, reduce or counteract global warming.

Other external factors must also be considered in these models. Atmospheric aerosols affect cloud condensation nuclei concentrations, the radiative properties of cloud particles, and precipitation processes. Changes in land cover and land use have been extensive in the U.S. and in the rest of the world, and these changes have local, regional, and even global impacts on the hydrological cycle. Among other things, they can dramatically alter surface properties, affecting the surface heat budget and the partitioning of precipitation into surface storage or runoff.

Other factors also affect model performance. One is the inhomogeneous distribution of water vapor. For example, major transports of water vapor from the oceans to terrestrial regions occur in narrow streams of moisture that vary geographically and with height, making them difficult to measure, let alone model. Another is the dependence on timescale. Soil moisture, vegetation, and snow cover can influence the flux of moisture and energy into the atmosphere depending on the nature of the atmospheric flow, the surface radiation budget, and surface properties. To improve the reliability of climate projections a better understanding is needed of which are the key processes to represent and how processes that occur at scales smaller than the model grid squares interact. In particular, while some progress has been made in cloud parameterizations, the representation of clouds and cloud/ precipitation processes remains the greatest uncertainty in climate models. Furthermore, since cloud processes are inextricably linked to other critical water cycle processes, improved representation of clouds will be key to improved simulations as well as climate projections.

Because the set of observations available to answer questions about the natural variability and change in the water cycle are generally limited in both time and space, new observing technologies and creative data fusion and assimilation methods will have to be developed to combine inhomogeneous data with hugely varying temporal and spatial characteristics into physically and dynamically consistent data sets. This will be true both for existing and future data sets.

Draft Research Questions

- How have the characteristics of the water cycle changed in recent years and is the number of extreme hydrologic events (droughts, floods, high intensity rain events) increasing?
- To what extent are changes in the water cycle attributable to natural variability as opposed to human induced change?

- How are the rates of regional groundwater recharge, soil moisture availability, and runoff production affected by changing global precipitation patterns, vegetation distributions and cryospheric processes?
- What are the average regional water fluxes between surface and subsurface arising from recharge and discharge processes and their seasonal and interannual variability?
- What are the factors that control evaporation and evapotranspiration on local and regional scales, and how are they affected by climate variability and change?
- What are the characteristics of, and processes governing, water vapor distribution and transport in the lower atmosphere and how do they affect precipitation patterns on short- and long-term scales?
- How do aerosols, their chemical composition, and distribution feed back on cloud formation and precipitation processes and patterns?
- What are the characteristics of upper tropospheric water vapor and clouds and how are they affected by deep convection?
- What is the relative importance of local and remote factors in extreme hydrologic events such as droughts and floods?
- In what ways do aerosols affect the hydrologic cycle, particularly the space-time distribution of precipitation over land?

Products and Payoffs

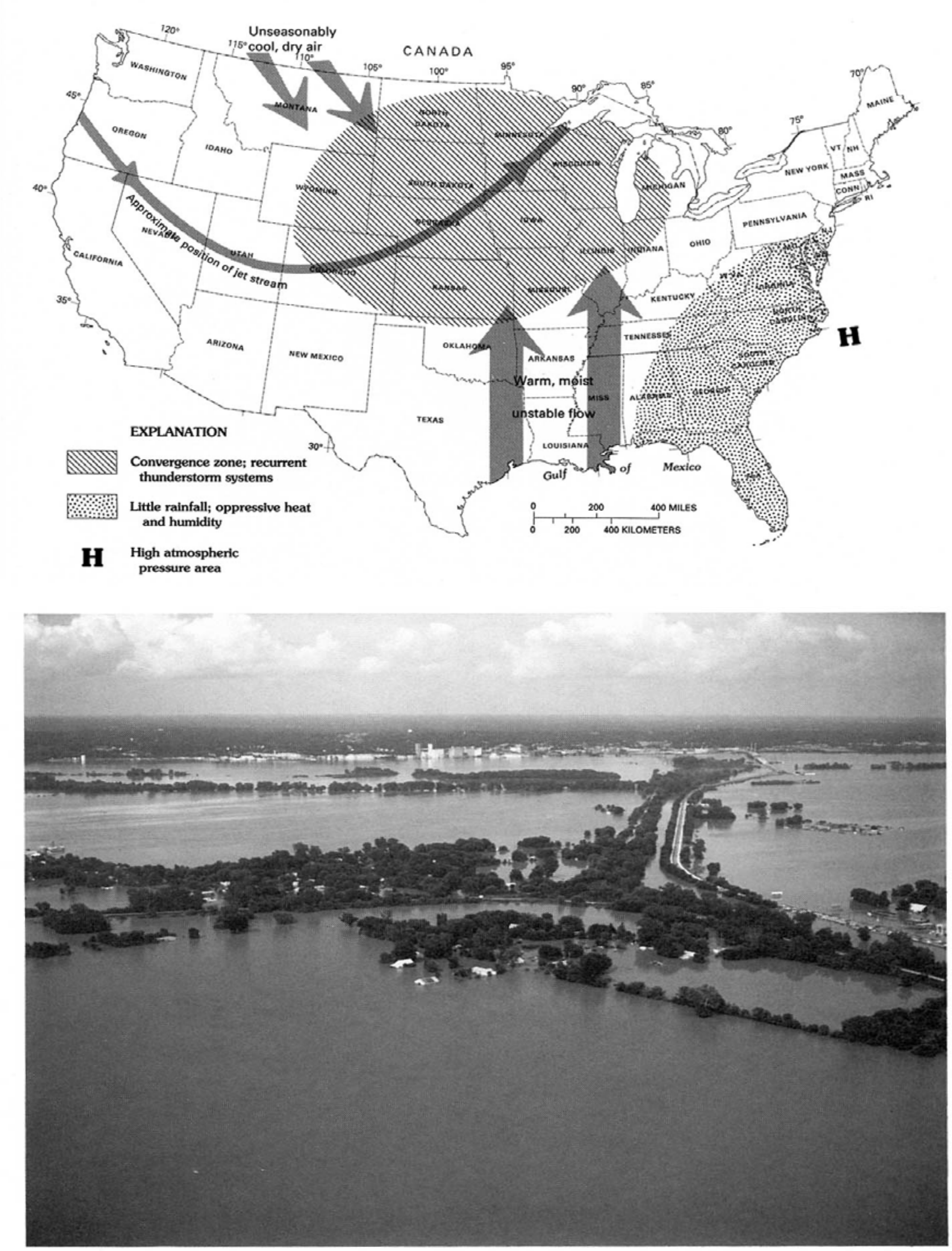
- Documentation of trends in key variables through data analysis and comparison with model-simulated trends to assess natural variability versus human-induced changes (5-10 yr.)
- Integrated long-term global and regional data sets of critical water cycle variables from satellite and *in situ* observations for monitoring climate trends and early detection of climate change. (2-5 yr.)
- Improved regional water cycle process parameterizations based on process studies conducted over regional test beds to improve the reliability of climate change projections. (5-15 yr.)
- Long term records of flood/drought frequency and intensity from proxy data such as tree ring data (5-10 yr.)
- 10-year data set of assimilated estimates of soil moisture and evapotranspiration rates (2 to 5 yr.).
- High-resolution data sets of precipitation amounts, distribution, and intensity over a regional testbed to be used to develop improved parameterizations of precipitation processes (5 yr.)
- New methods for measurement and estimation of subsurface fluxes (5-15 yr.).

Readiness and Feasibility

Techniques for measuring many of the water variables have improved, but the number of observations is limited and, in some cases, new sensors are needed. A number of new satellite-based sensors are just now or shortly will be available and will provide data on a number of key variables. In some cases, such as the current soil moisture measurements, new retrieval methods have produced more accurate estimates. Even with the potential for global coverage via satellite and ground based remote-sensing platforms, there remains a critical need for *in situ* observations of many GWC variables at higher spatial resolution and at more frequent intervals. Generally, *in situ* networks are declining and deficiencies in these networks will inevitably affect the ability to advance the GWC agenda. Thus, remotely sensed data must be supplemented with data from appropriate ground-based systems.

Box 1. The 1993 Mississippi River Floods

In the summer of 1993, the Mississippi River basin experienced anomalously high rainfall, following a winter and spring in which precipitation was generally above normal. During June and July, an unusually persistent branch of the jet stream was positioned over the



Dominant weather patterns over the United States for June-July 1993 (top panel) and flooding near West Alton, Illinois, during July 1993 (bottom panel) (USGS, 1993).

Box 2.1 (continued). The 1993 Mississippi River Floods

upper Mississippi and Missouri River basins. This phenomenon was caused by a low-pressure system over the southwestern United States, combined with a stalled high-pressure system over the southeast, which created an anomalous low-level flow of warm, moist air from the Gulf of Mexico that collided with cool, dry air from Canada over the central states. The result was two months of much above average precipitation. The combination of the high rainfall with wet antecedent conditions resulted in mean monthly discharges of the Mississippi River at its mouth during August and September that exceeded the largest values for the previous 63 years. At 45 USGS stream-gauging stations over a wide area of the central United States, peak discharges exceeded the 100-year flood. Damages exceeded $20 billion, making this one of the most costly natural disasters in U.S. history. Although the conditions that led to the 1993 flood have been quite well documented, what is much less well known is the likelihood of similar large-area flooding in the future. The 1993 flood was especially notable because it occurred during what is normally the low-flow period. Better understanding of the global water cycle will help to predict the possible occurrence of rare events like the 1993 flood, and thus to mitigate future flood damages.

Data assimilation is an advanced method for using measurements and models in combination to provide internally consistent data for analysis. For example, recent research has produced more effective methods of assimilating remotely sensed data and of predictions of some GWC variables such as evaporation at regional scales. Newly developed procedures for assimilating precipitation data for use in land-surface models are being used to produce experimental high-resolution soil moisture and other land surface data products on a routine basis. Further advances in data assimilation for other variables are needed because future large-scale or global observational networks will consist primarily of remotely sensed data that are augmented with limited *in situ* measurements, and there is much promising work going on in this area.

Many of the processes involved in the water cycle occur on scales smaller than are currently measured on a routine basis or are represented in numerical models. For instance, cloud formation is a small-scale process that cannot be explicitly represented in a climate model. Moreover, a full understanding of cloud formation, and all the processes involved, remains elusive. Model development can be accelerated by interdisciplinary field studies over regional testbeds that provide much needed understanding of scaling effects. New parameterizations of water cycle/ climate feedbacks (e.g., cloud-aerosol and land-atmosphere) and sub-grid scale processes (e.g., clouds, precipitation, evaporation, etc.) can be developed and validated on a regional scale. The sensitivity of global models to these new parameterizations can then be evaluated. In addition, cloud resolving models are proving to be a useful tool in ascertaining which processes are important in cloud and precipitation processes.

Research Needs

New observing capabilities, both satellite and *in situ*, will be critical to detecting patterns and quantifying fluxes, especially instruments for global measurement of water vapor, precipitation, and terrestrial water cycle variables such as soil moisture. The decline of *in situ* networks needs to be reversed and data sets developed to ensure consistency between historical and new observations. Network enhancements are needed to obtain data on critical quantities such as river discharge, precipitation and snow pack in mountain regions, as well as estimates of the fluxes between the surface and subsurface and recharge rates at the basin scale. There is a need for new data assimilation techniques that combine different kinds of data and data with varying spatial and temporal characteristics to produce consistent data products for research and process studies of key water cycle variables, such as clouds, precipitation and soil moisture. New models are needed that can simulate the critical water cycle processes at resolutions that will allow comparison with long-term data sets. Critical processes include precipitation, water vapor fluxes and transport at a variety of scale, coupled atmosphere – surface (both land and ocean) interactions, runoff, subsurface water, etc. Finally, process studies to investigate cloud and radiation processes at small scales will allow development of sub-grid parameterizations for climate models.

Linkages

National

As with all parts of the climate system, the factors affecting the water cycle variability in any location will be a complex combination of local and remote forcing mechanisms operating on a variety of timescales. Within the CCSP, these water cycle studies will need to be coordinated with those under the Climate Variability and Change element. Improvement in parameterizations of water cycle processes will provide input for the Climate Models and Simulation and Applied Modeling elements.

Other CCSP component programs that will contribute to and/or benefit from these research efforts include Atmospheric Composition; Ecosystems; Land Use/Land Cover Change; and Grand Challenges in Modeling, Observations and Information Systems.

International

Key programs with which linkages are being forged include the World Climate Research Programme (WCRP) (including GEWEX and CLIVAR); the International Geosphere-Biosphere Programme (IGBP); various programs of the United Nations (WMO, FAO and others). In particular, on-going collaborations will lead to development of an IGOS-Partners Water cycle theme report to guide the evolution of integrated global water cycle observing systems.

2.2 WATER CYCLE FEEDBACK EFFECTS ON THE CLIMATE

QUESTION 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 are interactions between components of a system as it responds to inputs. When the global water cycle is considered as a component of the Earth/ Climate system, feedback processes transmit external drivers, such as the increase atmospheric CO_2 through the system. An input provides a response in one component that, in turn, triggers a response in another. Mutual adjustments continue to occur and reverberate through the system. The system may return to equilibrium, develop a new cycle or cycles, or continue to exhibit chaotic behavior.

Feedbacks can be positive or negative, with positive feedbacks enhancing the initial response and negative feedbacks inhibiting or counteracting it. In the case of the feedbacks between the water cycle and the carbon cycle, a positive feedback could increase the accumulation of carbon dioxide in the atmosphere while a negative feedback with slow the growth of atmospheric CO_2. For interactions with the climate system, a positive feedback would enhance the global warming effect while a negative feedback would either slow the effect or produce a cooling. Understanding feedbacks between the water cycle and other component of the climate system is critical for climate modeling. There is a great deal of fundmental research to be done in this area.

Depending on time-scale, elements of the global/regional water cycle can act as either “forcings” or “feedbacks” on/within the Earth/Climate system. While all “feedbacks” are mechanisms not all water cycle mechanisms (discussed in Question 1) are feedbacks. For example, the release of latent heat during the formation of precipitation may be considered as a mechanism or internal process as opposed to a feedback. However, an initial change in land cover (vegetation, snow cover) due to a forcing, which then causes an additional change in land cover via the water cycle would be a feedback effect.

One major feedback involves the linkages between the global water cycle and the greenhouse gas warming. A small incremental increase in temperature will result in greater rates of evaporation, as a warmer atmosphere is capable of holding larger amounts of water vapor. The increases in water vapor, a very effective greenhouse gas, lead to a further increase in temperature. Water vapor, the most important greenhouse gas in terms of energy absorption (as measured in Watts/m^2) and long-wave heating of the planetary surface, is a major contributor to the net warming effect following an increase caused by anthropogenically emitted greenhouse gases such as CO_2 and CH_4. However, there are serious uncertainties in the vertical and spatial distribution of water vapor that might result from an initial CO_2 (plus other greenhouse gases) warming, and consequently the net resultant effect of the water vapor feedback. This is a positive feedback that could continue unchecked if there were no counterbalancing effects in the atmosphere. However, with increasing water vapor content from increased temperature, the potential for cloud production increases. Clouds have several impacts. Most significantly, during the day, they reflect incoming short-wave radiation back to space, thereby reducing the amount of radiation reaching the surface to warm it. Under these conditions, clouds have a negative feedback effect. However, under other conditions, the cloud may be trapping outgoing radiation, leading to a positive cloud feedback. Over the globe, depending on cloud types, the net feedback effect may be positive or negative. There is evidence to suggest that the treatment of clouds in climate models is one of the major determinants of their temperature sensitivity to greenhouse gases. These feedback effects are complicated by the presence of aerosols in the cloud that act to change the albedo of the cloud and reduce the likelihood that the cloud's moisture will rain out. At present, it is generally believed that there is insufficient observational evidence to determine whether clouds have a positive or negative net feedback effect on the climate.

Another important feedback comes from the linkage between the water cycle and the carbon cycle. Observational evidence indicates that transpiration rates for plants are high at the same time that carbon dioxide fixing by the plants and hence carbon dioxide flux from the atmosphere to the plant canopy is large. This connection between transpiration and the carbon flux suggests that many of the same processes must be controlling the rates of transfer. It also suggests that common approaches to measuring and parameterizing water vapor and carbon fluxes may exist. There are other feedbacks between the carbon cycle and the water cycle. For example, when an environment is humid, plants will grow more rapidly and draw carbon dioxide from the atmosphere and release more water to the atmosphere. The addition atmospheric moisture can enable the production of more clouds and rain, which will continue to moisten the ground and prolong the growth of plants and the continued transpiration of moisture to the atmosphere. This positive feedback is one that has not been examined in detail, but may lead investigators to identify of areas where terrestrial carbon sequestration would be particularly effective.

Another important feedback effect between greenhouse gas cycles and the water cycle is expected to unfold when increases in temperature and land use and vegetation cover changes affect the hydrology of sensitive regions. For example, melting permafrost could lead to larger areas of standing water at higher latitudes that could increase the rate of methane production. Methane, a very active greenhouse gas, could lead to further warming if present in sufficient quantities.

In current global and regional coupled models, feedback processes are typically poorly represented or accounted for. This difficulty arises from a lack of observations to provide for a basis for parameterizing these processes and partly due to the complexities involved in modeling them. In addition, there is a need conduct studies that will clarify the significance of the various feedback processes and to clarify how the ones that have the most significant effects for the CCSP operate.

There are also major uncertainties in the cloud/precipitation response to forcings on the Earth system and in cloud radiation feedback effects. The response of the atmosphere to increased evaporation at the ocean surface is expected to be an increase in cloudiness. The effect of clouds on the radiation balance depends on whether the clouds form in the upper or lower troposphere and whether they form near the equator or the poles. Furthermore, it is not clear how these clouds will be distributed over the planet nor is it clear how the production of precipitation from these clouds will be altered as a result of forcing. The vertical distribution of precipitation formation can have important effects on the atmospheric heating profiles and on patterns of storm development.

Water has an important influence on atmospheric circulation. Water cools its surroundings as liquid and solid water are converted into water vapor. Without this cooling the land surface would warm, much like hot pavement or the sand of deserts. On the average, this latent cooling is balanced by the latent heat released when water vapor is converted to liquid and solid cloud particles. Because of the large latent heat involved in the condensation of water molecules, water vapor is a very effective means of storing energy and the latent heat flux in the atmosphere is a major component of the overall transport of energy from equator to poles. In general, latent heat is the principal source of energy that drives cyclogenesis and sustains weather systems like convective cells that generate tornadoes and tropical storms that evolve into hurricanes.

Water molecules are strong absorbers of infrared radiation and the resulting greenhouse effect of atmospheric water vapor is, by far, the strongest determinant of the Earth's surface climate. Furthermore, atmospheric humidity is highly variable and responds to changes in atmospheric temperature, thus providing the most effective feedback mechanism tending to amplify global climate changes induced by other factors. Furthermore, clouds contribute about 50% of the planetary albedo, and absorption of terrestrial radiation by clouds is equivalent to that of all "greenhouse gases" other than water vapor. Radiative heating or cooling is a major contribution to the diabatic processes that cause air parcels to rise or sink in the atmosphere and, in general, power weather systems. The net radiant energy that reaches the Earth surface is the source that controls temperature, drives evaporation, and feeds photosynthesis and the Earth's primary biological productivity. Being able to measure and to forecast the evolution of the spatial and temporal patterns in water vapor and clouds is a key to applications of science to climate, water resources, and ecosystem problems.

Draft Research Questions

- What is the sign and magnitude of the cloud-radiation-climate feedback effect and how does it vary with latitude and season?
- How is the water vapor-climate feedback signal changing, and how can these feedback processes be better represented in global models?
- How do changes in water vapor and water vapor gradients, from the stratosphere to the surface, affect climate variables, such as radiation fluxes, surface radiation budgets, cloud formation and distribution, and precipitation patterns, globally and regionally?
- What are the variations and changes in freshwater fluxes to the ocean that could affect the ocean thermohaline circulation and feed back on global/regional climate?

- How do changes in the global/ regional water cycle feed back on vegetative growth and carbon sequestration?
- How do changes in water cycle processes in cold regions feed back on climate change? In particular, how would warmer temperatures in the Arctic affect regional hydrology and methane production over northern land areas?

Products and Payoffs

- New parameterizations for water vapor, clouds, and precipitation processes for use in climate models, using new cloud resolving models created in part as a result of field process studies (2-5 yr; Next generation improvements: 5-15 yr).
- Integrated water cycle time series data sets (derived from satellite and surface-based remote sensing, combined with *in situ* measurements) of tropical and extra-tropical precipitation, clouds and cloud properties, aerosols, short wave and long wave radiation, and water vapor (Initial: 2-5 yr; Periodic improvements and updates: 5-15 yr)
- Enhanced, integrated data sets (remote sensing and *in situ*) for correlated and co-located studies of the feedbacks and interactions between changes in water cycle parameters and biogeochemical cycles. Examples include carbon sequestration, ecosystem impact, and land-use change feedbacks. (Initial: 2-5 yr; Improvements and updates: 5-15 yr)
- 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 to evaluate the role of human influences in climate change. (5-15 yr).
- New models capable of simulating the feedbacks between the water cycle and the climate system (including biogeochemical cycles) to improve predictions of climate change and support the development of carbon management strategies (5-15 yr).
- Analyses to identify the variability of cloud and radiation fields and atmospheric conditions that could be important for cloud feedback research (2-5 yr)Methods to estimate cloud condensation nuclei (CCN) concentrations.
  (2-5 yr)
- Studies of the impact of aerosols on cloud drop distributions and the assessment of the "indirect" effect. (5 yr)

Readiness and feasibility

Considerable research has been conducted on improving observations of key parameters of the intertwined global and regional water and energy cycles, as well as research into improving skill in predicting changes in the variability of water resources and water availability, including precipitation, evaporation and soil moisture, on time scales up to seasonal and annual as an integral part of the climate system. Efforts include those of NASA's EOS program, GWEC, NASA's NSIPP (seasonal-to-interannual prediction) and DAO (data assimilation and modeling) programs (among others), DOE's ARM program (observations, process studies, and modeling), GEWEX/GAPP and GAPP-LDAS programs (NOAA in collaboration with NASA), a broad range of research sponsored by the NSF, and the efforts of other agencies involved in research and the operational monitoring of basic land surface and hydrological parameters (USGS, USDA, USFS, USBR, others).

Activities are ongoing to quantify and improve the understanding and modeling of key elements and processes of the global and regional water/energy cycles. Measurement techniques have been developed and/or improved. For example, more accurate measurements of water vapor were developed through joint NASA/DOE (ARM) campaigns. Global measurements are available from NASA's satellites. These include the EOS Terra and Aqua, TRMM (precipitation radar), QuickSCAT (measuring surface ocean winds—important for estimates of ocean evaporation, and GRACE (global surface and sub-surface water availability/resources). Important next generation follow-on missions include: GPM (Global Precipitation Measurements), Soil Moisture Mission, and others. Also important are the planned transition of EOS measurements to the NPOESS system of operational satellites.

The CCSP also supports a number of field testbeds and research basins. They include the USDA facilities, USGS stream gauge networks, and the DOE ARM sites. Collaborative efforts are being planned to combine the capabilities of agency resources to provide an enhanced research capability at existing sites.

Many of the uncertainties in the projections of the warming effects of increasing atmospheric carbon dioxide arise from the inability to adequately represent the cloud and water vapor radiative feedback processes in models. Advances have been made in measuring the Earth's surface energy and describing the interactions of water and energy (heat) in the water cycle. Studies show that in the tropics a decrease in cloud cover accompanies a warming trend in the region. Studies have provided insight into the relationship between the physical properties of cirrus ice crystals and meteorological factors, such as temperature and water amount, and the ability of cirrus clouds to reflect and absorb energy

Research Needs

Many of the uncertainties in the impacts of changes in climate variability and long-term global change that have been identified in IPCC reports arise from our inadequate understanding and inability to adequately model GWC processes as they feed back on the climate system. The current inability to adequately represent these complex multi-scale processes in climate models is a major source of uncertainty in long-term climate change projections, seasonal-to-interannual climate forecasts and their impacts. Model improvements will be accelerated by interdisciplinary field studies over regional testbeds that provide much needed understanding of scaling effects. New parameterizations of water cycle/ climate feedbacks (e.g., cloud-aerosol and land-atmosphere) and sub-grid scale processes will have to be developed and validated to improve the accuracy of precipitation predictions and projections generated by climate models.

Examples of key research needs:

- Development and implementation of satellite based global measurement systems for precipitation.
- New validated parameterizations of feedback processes that affect precipitation such as cloud-aerosol, land-atmosphere interactions, and cloud-radiation-climate change.
- Sensitivity tests of global models to improved parameterizations of feedback and sub-grid scale processes (e.g., clouds, precipitation, land surface processes, etc.)
- Scaling results from interdisciplinary field studies over regional testbeds for use in the development of models.
- Development of new observing system capability on a research/experimental basis to measure global/regional water cycle feedback parameters, including *in situ* and space-based and surface-based remote sensing instruments and platforms.
- Satellite-based global scale measurements of other key GWC variables including water vapor profiles, soil moisture/ wetness, and sediment transport. Transition of proven research/experimental observing instruments/platforms to operational systems (both remote sensing and *in situ* observing systems). This includes ensuring that the measurement of key variables is maintained through transitions in observing systems (globally and locally).
- Development of an integrated Earth system modeling infrastructure relevant for the testing, validation and use reducing uncertainties in climate change (and variability) predictions and projections.

Linkages

National

To address GWC feedbacks it will be necessary for this element to work closely with other CCSP Programs including Climate Variability and Change, Climate Models and Simulation (including Applied Climate Modeling), Atmospheric Composition, Carbon Cycle, Ecosystems, Land Use/Land Cover Change, Grand Challenges in Modeling, and Observations and Information Systems.

International

Key linkages for the GWC program include: the World Climate Research Programme (WCRP) (particularly GEWEX, CLIVAR, SPARC and CLiC) and the International Geosphere-Biosphere Programme (IGBP) (particularly the emerging iLEAPS project).

2.3 PREDICTING WATER CYCLE VARIABILITY AND CHANGE

QUESTION 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

Seasonal-to-interannual variability in the global water cycle is largely determined by ocean and land processes and their impacts on the atmosphere. The prediction of this variability relies on the persistence or memory in surface conditions that tends to provide the atmosphere with consistent anomalies in fluxes over periods of weeks or months or even years. Again, the time scale of "memory" in the atmosphere is fairly short, but due to the atmosphere's connection to the land and ocean, each of which is characterized by a much longer memory. As a result current dynamic global and regional models demonstrate limited skill in predicting precipitation and GWC variables that strongly depend on precipitation, such as soil moisture and runoff, on time scales beyond a few days. Droughts in particular and pluvial periods to a lesser extent can be extended and maintained at seasonal-to-interannual time scales, with potentially severe consequences for agriculture and water resources. The El Niño / La Niña cycle is the most obvious example of a coupled phenomenon that produces significant seasonal-to-interannual variability. Over land, it is known that soil moisture, groundwater, snow processes, and vegetation can also contribute to the memory effect. While the large-scale influences on the atmosphere by major anomalous oceanic variations such as El Niño events have been well documented, memory effects of land conditions and their consequences for evapotranspiration and albedo are not fully quantified. In addition, climate models exhibit serious bias in precipitation due to their inability to fully represent small-scale cloud and precipitation processes. However, much work remains to determine which variables can be predicted and which ones cannot. Furthermore, in the context of climate change issues, the relevant scales are larger and the issues more complex, especially considering the additional effects of increasing populations, rising standards of living and competition amongst the users of water.

Due to the large uncertainties associated with the outputs of climate models representing conditions up to 100 years in the future and the practice of using them as scenarios, the term "projections" is used to distinguish such outputs from "predictions." One of the most critical deficiencies in climate change projections involves precipitation and soil moisture—essential parameters for assessments of the nation's future water availability.

Advances in land surface models have led to a much improved capability of simulating coupled atmosphere-land system. When forced by observed precipitation and radiation data, today's land models are capable of simulating realistic land surface conditions on time scales much longer than a few days. Using this approach land data assimilation systems now can produce both real time and retrospective analyses of land surface variables that can be used for diagnostics, initialization, and validation of coupled atmosphere-land models for climate prediction and projections. Some improvements have been realized through the development of precipitation assimilation capabilities. These successes suggest that more realistic specification of land surface conditions can lead to better precipitation predictions and increase confidence that improvements in the land components of models will contribute to better water cycle predictions at daily, weekly and seasonal time scales. Studies based on both observations and model simulations also have shown potential linkage of land surface conditions, primarily soil moisture, on seasonal climate anomalies over the US, such as the major drought in 1988 and the Mississippi floods of 1993.

Many uncertainties in seasonal to interannual climate predictions and climate change projections will only be reduced when better representations of GWC processes can be incorporated into climate models. At seasonal time scales, predictions rely on accurate specification of the initial conditions and characterization of the boundary layer conditions that control surface-atmosphere interactions. In particular land surface and ocean feedbacks to the atmosphere, cloud and precipitation processes, and hydrologic surface processes need to be addressed. Projections at decadal to centennial time scales require representations of the boundary that can evolve over time. Surface boundary forcing changes are particularly important in sensitive areas such as the cryosphere (permafrost, snow cover and ice cover) and for vegetation conditions and water cycle variables such as soil moisture.

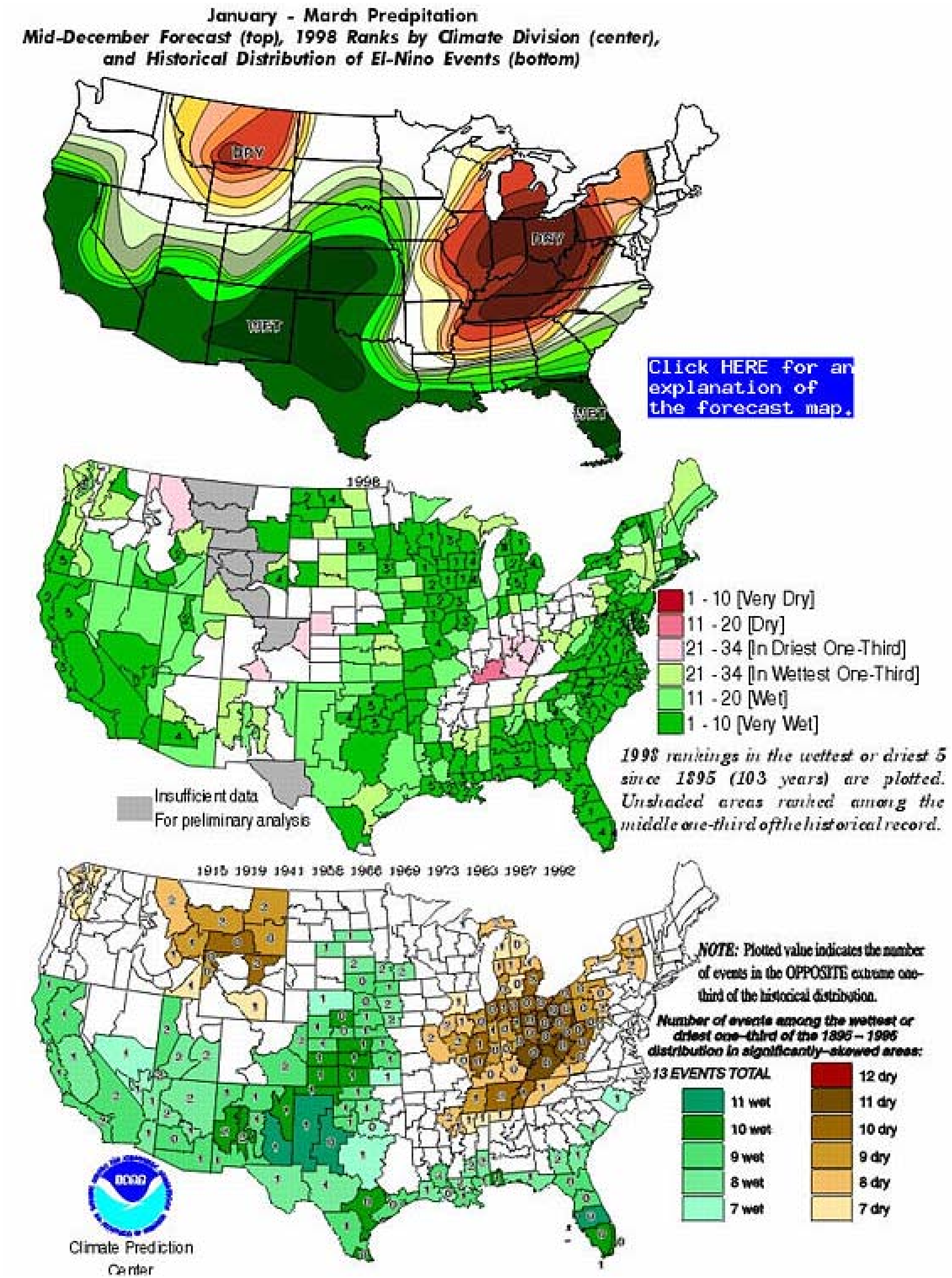
A critical prediction problem involves advance warning for major flood and drought events. The development of a capability to reliably assess whether hydrologic extremes will increase as greenhouse gas concentrations increase is also important. The increasing property damages from floods suggests that two factors may be at work, namely the tendency for more people to locate in flood plains and, possibly, a trend towards the intensification of the hydrological cycle. In order for an extreme event to occur the following factors are usually be present:

1) large-scale circulation patterns that enhance vertical atmospheric uplift for floods or increase the stability of the atmosphere for droughts;
2) regional patterns and feedbacks that accentuate the larger scale factors contributing to floods and droughts;
3) preconditioning of the system to increase the impacts of the flood or the drought event. For example, antecedent wet soils will leads to enhanced floods for a given rainfall, while antecedent low water tables and desiccated vegetation prior to the drought will cause the drought impacts to be much greater.

The prediction of large floods and droughts requires attention to each of these factors. Through global and regional climate models, it is possible to have good predictive skill for some areas, because the atmospheric flow patterns that are frequently associated with heavy rains or drought events can be identified. However, the modeling of regional feedbacks requires a good 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. Regional feedbacks and the role of antecedent conditions are two aspects of extreme events that are poorly understood.

Box 2. The Importance of Predicting the Effects of El Niño on North America: the 1997-98 ENSO Event

Among the largest El Niño events of this century, the winter of 1997-98 saw nearly unprecedented rainfall in several parts of the southwestern and southeastern United States, rainfall attributed directly to the effects of extremely warm sea surface temperature (SST) in the tropical Pacific. Unlike other such events, however, the 1997-98 event was relatively well predicted, both the SST anomaly in the Pacific and its remote effects, especially in the United States. The figure shows the precipitation prediction for January through March 1998 made by the U.S. Climate Prediction Center (top) three months in advance of the winter season as well as the observed precipitation (middle) and the historical expectation based solely on the presence of El Niño conditions in the tropical Pacific (bottom). As the figure shows, the CPC forecast was based on the expectation that El Nino would have a major effect on winter precipitation, and their predictions were quite accurate for many regions of the country. Individuals and organizations in climate-sensitive locations across the country made use of the forecast information, taking steps to mitigate the potential costs of El Nino, and thereby substantially reducing El Niño's actual costs.


January - March Precipitation
Mid-December Forecast (top), 1998 Ranks by Climate Division (center), and Historical Distribution of El-Nino Events (bottom)
DRY
DRY
WET
WET
Click HERE for an explanation of the forecast map.
1998
1 - 10 [Very Dry]
11 - 20 [Dry]
21 - 34 [In Driest One-Third]
21 - 34 [In Wettest One-Third]
11 - 20 [Wet]
1 - 10 [Very Wet]
1998 rankings in the wettest or driest 5 since 1895 (103 years) are plotted. Unshaded areas ranked among the middle one-third of the historical record.
Insufficient data
For preliminary analysis
1915 1919 1941 1958 1966 1969 1973 1983 1987 1992
NOTE: Plotted value indicates the number of events in the OPPOSITE extreme one-third of the historical distribution.
Number of events among the wettest or driest one-third of the 1895 – 1996 distribution in significantly-skewed areas:
13 EVENTS TOTAL
11 wet
10 wet
9 wet
8 wet
7 wet
12 dry
11 dry
10 dry
9 dry
8 dry
7 dry
Climate Prediction Center

Draft Research Questions

- How predictable are water cycle variables at different temporal and spatial scales?
- For different model resolutions, how can key water cycle processes be better simulated in current climate models in order to enhance their capabilities to produce more accurate seasonal to interannual predictions of water cycle variables?
- How can the representation of water cycle processes in climate change models be improved to reduce uncertainties in climate change projections of hydrologic variables? Variations of water cycle on longer time scales are associated with changes in slowly varying components of the Earth system, such as deep oceans, glaciers, ice sheets and sea ice, land cover and land use, and atmospheric composition. The challenge for prediction of these variations depends on our ability to understand and model the fundamental processes that affect climate change.
- How can GWC subgrid scale processes best be characterized in climate models being integrated over long time intervals?
- To what extent will the seasonality, intensity and variability of high latitude freshwater fluxes (evapotranspiration, runoff) and stores (soil moisture, permafrost) change as a result of climate warming? How well do climate and hydrologic models simulate these changes? How sensitive are climate change projections to errors in represented the processes causing these changes in climate models?
- What are the critical hydrological and atmospheric factors that are present in major flood and drought events that can be isolated, quantified and incorporated into water cycle prediction methodologies?
- How well do current global climate models simulate individual components of the global water cycle and what are the consequences of the model's weaknesses for current climate projections?
- What is the optimum structure for ensemble forecasts (in terms of members, models, start times) that produce the best seasonal precipitation, streamflow and soil moisture forecasts?
- How can the uncertainty in the prediction of water cycle variables be characterized and communicated to water resource managers?

Products and Payoffs

- New drought monitoring and early warning tools based on improved measurements of precipitation, soil moisture and runoff and data assimilation techniques to use in the implementation of drought mitigation plans. (2-5 yr).
- A regional "reanalysis" providing a wide range of daily analysis products at 32 km resolution for a 25 year period for use in analyzing many features that are absent in global climate data assimilation products. (2-5yr).
- Metrics for quantifying the uncertainty in predictions of water cycle variables and progress in improving their accuracy and for making forecasts more useful in water resources management. (2-5 yr)
- 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 change. (5-15 yr)

- Field and modeling experiments to study the role of mountain environments on precipitation and runoff production (2-5 yr)
- Improved global and regional climate models with improved representations of the key processes in the models (5-15 yr)
- Improved data assimilation which is benefited from the synergy of improved model and observations and improved assimilation techniques (5-15 yr)
- A long-range prediction capability of drought and flood risk (seasonal to internannual time scales). (5-15 yr)

Readiness and feasibility

Some effort is being directed currently at the seasonal prediction of the GWC's variability, mainly in conjunction with climate modeling and numerical weather prediction centers. Improvements made over the past decade to models, have advanced the ability to close regional water budgets. For example, when combined with new data assimilation capabilities the annual water budget for the Mississippi basin can now be closed to within 15 - 20%. While this progress is encouraging for climate applications, it indicates that more work is needed on predicting critical variables such as evapotranspiration before predictions will be adequate for the needs of water resource managers. The development of a Land Data Assimilation System (LDAS) at both the regional and global scales has allowed a significant reduction in the errors arising in initial fields due to the way traditional coupled land-atmosphere 4-D data assimilation systems (4DDA) in soil moisture, soil temperature, and surface energy fluxes. Another key to these developments are continued improvements in our understanding of land surface processes, particularly soil moisture, snow cover and frozen ground effects and their contributions to the memory effects that are evident in droughts and anomalously wet periods. However, there are reasons to believe that a modest increase in investment in this area could accelerate the development of a seasonal prediction capability.

Progress on long-term projections (decadal to centennial) of GWC variability have not matured as quickly, partly because the long model time integrations required to make such projections do not allow for the complexities of land surface processes to be fully incorporated into these models. However, recent advances in the national climate model development strategy are expected to provide a more efficient structure for improvements on these time scales. It is anticipated that, with a modest shift in emphasis by both the climate modeling and GWC communities, it would be possible to make significant progress in improving the representation of key water cycle processes in global climate models. However this will need to be a focused effort giving priority to those hydrometeorological processes (including clouds) to which climate models are most sensitive.

Research Needs

The major requirements for improved water cycle prediction capability lie in three areas, namely: 1) improved specification of initial conditions (including boundary conditions), 2) improved parameterization of relevant physical and biological processes and the land surface condition, and 3) improved model structure. The third area is addressed in the Climate Modeling section. Addressing land surface-atmosphere interactions will require research on the entire coupled system including cloud and precipitation feedbacks, the interactions of the lower boundary layer with land and ocean surfaces, and the role of groundwater- surface water and biospheric interactions. In addition, data sets are needed for evaluating and testing the water cycle components of coupled models, especially soil moisture and regional evaporation and for the improvement of regional downscaling and statistical forecasting techniques. Advances in prediction capabilities will depend on improvements in model structure and initialization, data assimilation, and representations of the key water cycle processes in models.

In summary the following developments are needed:

- Observations: Improved observations (both ground-based and satellite) of water cycle variables and fluxes (such as temperature, precipitation, snowpack, soil moisture, vegetation properties, radiation, wind, evaporative flux and humidity) will provide the foundation for improved predictions of water cycle variables. Enhanced data sets are needed to evaluate models, to characterize and reduce uncertainties of model predictions, to improve model initializations and to improve process understanding.
- Predictability studies: Predictability studies will be required to determine the regions, seasons, lead times and processes most likely to provide additional predictive skill, and to guide the development of models on all scales.
- Process studies and model improvements: Better understanding through field experiments and modeling studies of less-well-understood processes, such as the seasonal and longer term interactions of mountains, oceans, the cryosphere and soil-vegetation with the atmosphere are needed. In addition, these processes must be more realistically represented in models at appropriate scales.

Linkages

National

Seasonal water cycle variability over the US is influenced by both the land and ocean surface conditions. The relative roles of these influences depend on location and season. Consequently, the GWC program in collaboration with the Climate Variability and Change element must address both ocean-atmosphere coupling and land-atmosphere coupling in order to develop reliable water cycle predictions on seasonal and longer time scales. In addition, the hydrologic aspects of these predictions require a focused effort that will involve joint studies with the land use change and ecosystems groups.

International

The GWC research on prediction and predictability also needs to maintain close linkages with the International GEWEX program and CLIVAR under WCRP and the land components of the IGBP, as its new research agenda is consolidated. Some of the hydrological data and modeling issues may also be developed in collaboration with UNESCO's hydrology program.

2.4 THE CYCLING OF WATER AND OTHER BIOGEOCHEMICAL CONSTITUENTS

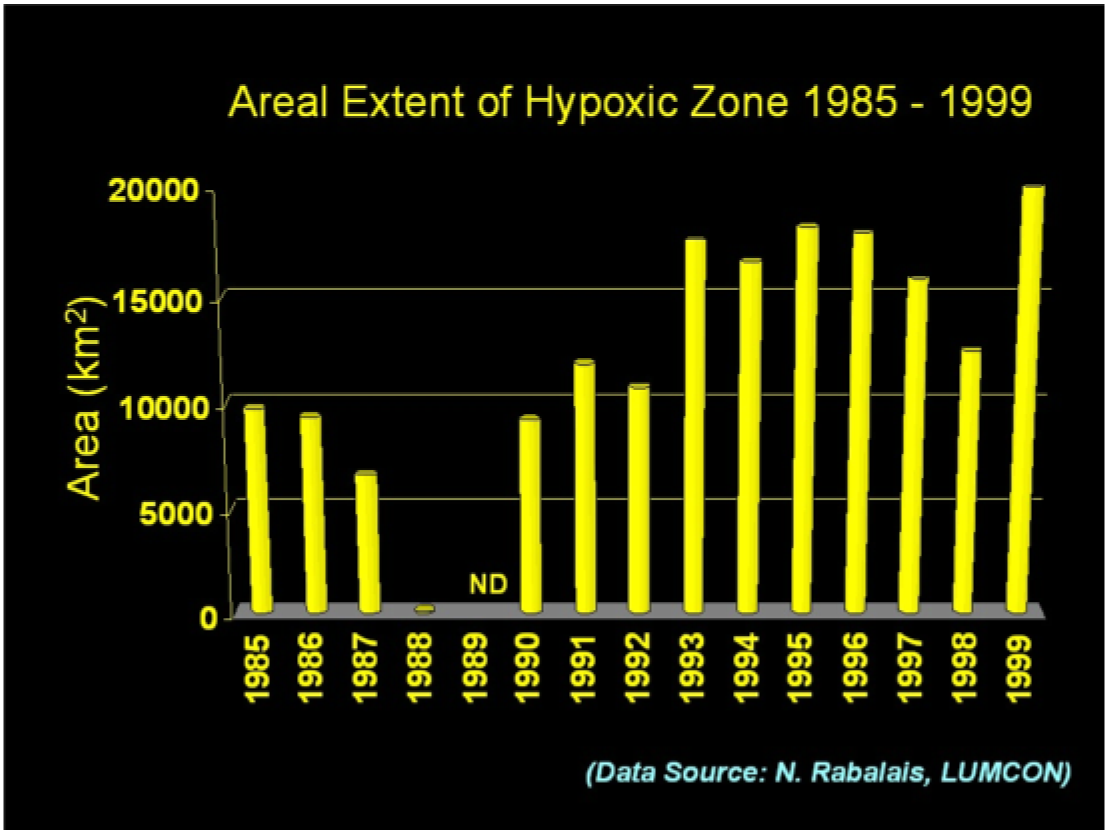
QUESTION 4: HOW DO THE WATER CYCLE AND ITS VARIABILITY AFFECT THE QUALITY OF AVAILABLE WATER FOR HUMAN CONSUMPTION, ECONOMIC ACTIVITY, AGRICULTURE, AND NATURAL ECOSYSTEMS; AND HOW DO THE VARIABILITY AND INTERACTIONS WITHIN THE WATER CYCLE AND BETWEEN THE OTHER BIOGEOCHEMICAL CYCLES AFFECT SEDIMENT AND NUTRIENT TRANSPORT, MOVEMENTS OF TOXIC CHEMICALS, AND OTHER BIOGEOCHEMICAL SUBSTANCES?

State of Knowledge

The essential role of water in sustaining all forms of life (plant, animal, and human) and the enormous contribution of water to economic development throughout human history have been recognized for millennia. During the past century, major advances have been made in quantifying the cycling of water between the atmosphere, land areas, oceans, lakes and streams, and groundwater aquifers. However, there is a consensus in the scientific community that the current level of understanding of the fate and movement of water and sediment in watersheds remains inadequate. The many societal problems that we face related to water availability, use, control, and management are not new. In the context of climate change issues, though, the relevant scales are larger and the issues more complex considering the additional stresses of increasing populations, rising standards of living, and the many diverse and competing demands for fresh water.

As water cycles through the environment, it interacts strongly with other biogeochemical cycles, notably the carbon, nitrogen, and other nutrients. Flowing water also erodes, transports, and deposits sediment in rivers, lakes and ocean, affecting the quality of the water. Soil erosion may result in degradation of farmland through loss of organic soil material, soil salinization, and gully formation, loss of aquatic habitat, and lost water storage capacity due to the sedimentation of reservoirs. Soil erosion and sedimentation of our rivers, deltas and channels also may lead to increased flooding and costs associated with dredging and maintaining shipping lanes. Toxic chemicals, pesticides, and agricultural fertilizers in water are detrimental to the health of inland aquatic ecosystems and coastal zones. The transport by water of bacterial contaminants from sewage and agricultural waste systems, often under the stress of flooding conditions, exacerbates human health problems and stresses water management and treatment systems.

Box 3. Recent Notable Oxygen Losses from Important Coastal Waters



Oxygen depletion results from the combination of several physical and biological processes. In Gulf of Mexico waters (graphed above), hypoxia results from the stratification of marine waters owing to Mississippi River system freshwater inflow and the decomposition of organic matter stimulated by Mississippi River nutrients. As a general rule, nutrients delivered to estuarine and coastal systems support biological productivity. Excessive levels of nutrients, however, can cause intense biological productivity that depletes oxygen. The remains of algal blooms and zooplankton fecal pellets sink to the lower water column and seabed. The resulting depletion of oxygen during decomposition of the fluxed organic matter exceeds the rate of production and resupply from the surface waters, especially when waters are stratified. Stratification in the northern Gulf of Mexico is most influenced by salinity differences year-round, but is accentuated in the summer due to solar warming of surface waters and calming winds. Oxygen depletion follows a fairly predictable annual cycle, beginning in the spring, and becoming most widespread, persistent, and severe during the summer months.

Midsummer coastal hypoxia in the northern Gulf of Mexico was first recorded in the early 1970s. In recent years (1993-1999), the extent of bottom-water hypoxia (16,000 to 20,000 km^2) has been greater than twice the surface area of the Chesapeake Bay, rivaling extensive hypoxic/anoxic regions of the Baltic and Black Seas. Even in 1998, the hypoxic area covered 12,400 km^2, an area about the size of Connecticut. Prior to 1993, the hypoxic zone averaged 8,000 to 9,000 km^2 (1985-1992).
Source: Nancy N. Rabalais, Louisiana Universities Marine Consortium, 8124 Highway 56, Chauvin, Louisiana 70344 (http://www.csc.noaa.gov/products/gulfmex/html/rabalais.htm)

Water conservation, water use efficiency, and watershed management play critical roles in the development of cost-effective solutions to social, economic, and environmental problems caused by water scarcity, water stress, and extreme climatic events. An improved understanding of the hydrologic processes that determine the fate and movement of water in watersheds is critical to the development of effective strategies for water management in a changing environment.

Reliable techniques are needed to quantify water resource responses to climate forcing and to use this information to predict the hydrologic consequences of climatic change. This research would require a major long-term commitment of resources to monitor water and energy fluxes over a range of scales and to develop accurate, cost effective methods to characterize watersheds and simulate their integrated responses at the regional and continental river basin scales. Currently available water cycle predictions and projections are inadequate for such assessments.

Watersheds are the fundamental landscape units used to determine direct and off site impacts of agricultural food and fiber production systems, soil and water conservation, climatic variability and watershed management practices. Watershed responses (e.g., hydrologic, riparian, water quality) to management and climatic inputs result from the complex interactions among numerous watershed factors and attributes (e.g., soils, vegetation, land use, management practices) and vary across geographic regions. Many of the major challenges in scientific hydrology and watershed management relate to quantifying the space-time variability of both weather and climate data, watershed characteristics, and tracking the ever-changing land use and management practices within the Nation’s agricultural and natural watersheds. However, science has not reached the point where these complex responses can be fully quantified and predicted at the temporal and spatial scales necessary to provide information with the accuracy desired by water resource managers and policy makers. Furthermore, the responses of basins to water cycle variability is also dependant on the basin characteristics such as topography, land cover, soils, and the types and level of socio-economic activity within the basin.

In order to gain the understanding needed to integrate water resource and water quality management under conditions of climatic change, researchers need to focus on how processes within this interactive system affect water availability and water quality and how these impacts vary over time. Systematic monitoring of flows and the fate and transport of nutrients, chemicals, and pathogens within our Nation’s rivers and aquifers is needed to acquire the basic information necessary to understand and predict the effect of climatic change on our water resources. Effective use of this information will require research on the causes for observed patterns. Past researchers have lacked access to spatially and temporally distributed data and have been forced to combine multiple pathways and reservoirs of many sizes and shapes in "lumped" models to simulate watershed responses at regional and continental scales. These models are inadequate for predicting and simulating the fate and transport of nutrients, chemicals, and pathogens, because the hydrologic analysis needs to be connected with ecological, chemical, microbiological processes as well as social and economic processes. A new generation of distributed models that is able to utilize the full information content of distributed data is now in its early developmental stages. These models use characterizations of pathway types to capture chemical and biological processes that can scale from a farm field to a river basin. The next step is to develop methods for scaling up these processes so their cumulative impacts can be determined at watershed and larger scales.

At present, a major obstacle to distributed modeling advances is the absence of a monitoring framework needed to generate the data at sufficiently high spatial resolution to allow evaluation and testing of spatially distributed land surface models. The data bases that are needed include critical variables such as surface runoff, aquifer depth, chemical and biological processes that alter the quality of the flowing water, and factors leading to changes in water demand (associated with population growth and higher standards of living) and their hydrological impacts, land use, agricultural practices, and climate. Data are needed to quantify flows by pathway, to determine chemical and biological changes along pathways, and to assess how these changes, over time, alter the physical system as well as ecosystems the flows supports. Observational networks in the major hydroclimatic and agroecological regions of the country are required to make simultaneous uniform, long-term, consistent, high quality data sets for tracking the water, energy, and biogeochemistry cycles. These networks should have an oversight mechanism that builds upon existing experimental watersheds and provides a unified framework to understand how climate change will affect critical national resources of water (quantity and quality), carbon, and nutrients.

The data bases described here will enable the scientific community to address the following issues:

- Effects on water quality of atmospheric deposition. Land use changes alter loadings of atmospheric vapor, dust, and chemical and other aerosols that are later deposited on land to become major non-point sources of pollution.
- Loadings of non-point source pollution washed by storm runoff into streams and carried by infiltrating water from urban areas or from fields treated with agricultural chemicals into aquifers.
- Performance of soils, buffer strips, wetlands, detention ponds, and other natural environments in ameliorating pollutant loadings through diverse weather sequences.
- Determining if soil erosion rates exceed soil production rates, and whether current land management practices are sustainable.
- Transport of pollutants and nutrients through rivers, lakes and estuaries.
- Effects of deforestation, agricultural practices, fires, urbanization, and other land changes on sedimentation and on fresh water quality, quantity, and distribution.
- Subsurface changes in water chemistry related to climate and other stresses at the surface. Engineers can use information on change processes to contain and degrade toxic materials, reduce subsurface contaminant discharge into rivers and estuaries, and foster use of alluvium and riparian ecosystems in water pollution control.
- Effects of groundwater fluxes on terrestrial, riverine, and coastal ecosystems and ultimately on geochemical balances at all scales.

Draft Research Questions

- How does soil erosion and sediment transport from the farm field to stream to watershed scale and through entire river systems vary as function of hydrologic processes and basin characteristics?
- How do changes in climate and land cover alter runoff quantities and hence the transport of sediments, nutrients, and other chemicals?
- How do changes in climate, land cover, and nonpoint waste sources alter water quality in streams and aquifers?
- How do physical processes in streams and aquifers change the quality of water available for human uses and natural ecosystems?
- How does water cycle variability and change affect the transport of nutrients in major rivers and influence the formation of hypoxia zones in the estuary areas?
- How do physical, chemical, biophysical, and microbiological processes interact along upland and stream field pathways to alter water quality? Systems of primary interest for effects on stream chemistry are stream alluvium (the hyporheic zone) and hillslope soil (the vadose zone).
- How can the linkages between particle and chemical transport be quantified as chemicals are adsorbed and desorbed in mixing zones with a wide variety of characteristics?
- How do field scale interactions accumulate to change water quality and quantity at watershed and larger scales?

Products and Payoffs

- Protocols for establishing commensurate sets of reliable benchmark data on surface water, ground water, sediment, toxic substances, and biogeochemical constituents at watershed and river basin scales for multidisciplinary studies aimed at improved integrated watershed management. Existing protocols will be reviewed and modified as necessary, existing study areas will be considered for continuation and enhancement, and additional study areas will be selected. (2-4 yr)
- Nationally consistent assessments of the water-quality conditions in our Nation's most heavily used streams and aquifers, trends in those conditions, and the primary natural features and human activities that affect them. (2-4 yr)
- Intensive field- and watershed-scale investigations of distribution, transport, fate and effects on contamination by toxic substances at local releases and non-point sources in order to provide objective scientific information to improve characterization and management of contaminated sites, to protect human and environmental health, and to reduce potential future contamination problems. (2-4 yr)
- Long-term monitoring and analysis of stream flow and water quality in areas that have been minimally affected by human activities, in agricultural watersheds, and in the Nation's largest rivers in order to characterize time trends and spatial patterns of regional flow and water quality variability, as well as concentrations and fluxes of sediments and chemicals, associated with both natural processes and regional-scale societal impacts. (2-4 yr)

- Integrated remote sensing and ground-based observations of the water, carbon, energy and nutrient cycles to develop and validate remotely sensed algorithms to enable extrapolation to regional and continental scales. (2-4 yr)
- Improved distributed models that partition precipitation among evapotranspiration, surface, and subsurface pathways. Characterize water by its chemical and microbiological characteristics, route flows, and quantify physical and chemical interactions for evaluating impacts of climatic change on water quality and nutrient cycling. Programs for national water quality assessment and studies into the fates and effects of toxic substances will receive powerful new tools. (5-15 yr)
- Improved modeling and remote sensing methods for scaling up from individual pathways and mixing zones to collective performance in watershed systems. (5-15 yr)
- Methods for using ground and remotely sensed observations together with models to gain better understanding of watersheds as hydrogeochemical units. Progress will lead to feedbacks to refine and improve the database and the models and to establish more cost effective methods for sustaining water quality and water availability. (5-15 yr)
- Decision support systems and recommendations for sustainable management of water and land resources that account for changes in the environment, provided economy opportunities, and meet societal needs. (5-15 yr)

Readiness and feasibility

Numerous recent field and modeling studies have investigated the transport and accumulation of pollutants in streams and ponds, particularly in bed sediments, and subsequent movement of nutrients from land through coastal wetlands. Based on the field results, models are being developed that simulate how aeration, binding, pollution, and storm energy interact determining the contribution or river transport to pollution loading in coastal waters. Integrated field and modeling studies in hill-slope environments have elucidated flow paths and chemical reactions in the dynamic mixing zones near the soil surface. Water quality in streams and rivers is largely determined by chemical weathering and reactions along runoff flow paths down and through hillslopes and floodplains. Research producing better definition of these pathways and temporary storage locations; their physical, chemical and microbiological characteristics, is building the science needed to predict the impacts of land and its uses and of climate change on water quality and aquatic ecosystems. A strong base of data and information, including instrumentation and techniques for observation, sampling, and data dissemination, is being built by ongoing programs such as the National Water Quality Assessment (NAWQA), National Stream Quality Accounting Network (NASQAN), Water, Energy, and Biogeochemical Budgets (WEBB), and Toxics Substances Hydrology programs of the USGS and by similar programs of USDA and other federal agencies. The data and knowledge developed by these programs will serve as a sound foundation for development of research to answer the many remaining questions about the effects of water cycle variability and potential change on water quality. As the reliability of water cycle predictions and the resolution of climate change projections increase, the ability to assess the consequences of climate variability for the cycling of sediments, carbon, nitrogen and other biogeochemical constituents will increase.

Research Needs

Existing water cycle research largely utilizes estimates of precipitation over watersheds and stream flows recorded at gages. Simultaneously, basin water quality studies are largely based on data collected through field sampling over short periods (with the connections to precipitation and flow data often poorly defined). Measurement techniques, databases, and procedures for data analysis largely serve a particular discipline rather than support inter-disciplinary research. As a consequence, we lack reliable means to quantify associations between flow and water quality, evaluate threats to natural systems and the sustainability of water supplies, or determine the impacts of the many forms of global change on water, land, or people.

Better and institutionalized coordination of inter-agency and inter-disciplinary activities and programs is needed to address this scattered approach. To make advances in our ability to effectively conduct watershed management assessments it is essential to maintain a geographically diverse, long-term experimental research and observational watershed programs.

The first step is adoption of a common vision of the research strategy needed to make progress in resolving the driving issues. That strategy will include:

- Continued maintenance and upgrading of existing hydrologic and geochemical monitoring networks. Enhanced availability of the resulting data streams to researchers and managers. Examples include the USGS Hydrologic Benchmark Network, the USDA-ARS watershed network, and the USGS National Stream Quality Accounting Network, all of which are being used to gain better information on time trends and spatial patterns of water quality and quantity variability, and how natural processes and regional-scale anthropogenic activity drive the variation.
- Expansion of monitoring networks into areas identified as particularly sensitive to climate variations and changes.
- Greater use of chemical and isotopic tracers to identify important flow paths (either in terms of volumes of water transported, contributions to sedimentation, or sources of pollution plumes). Tracers can also be used to estimate residence times and predict movements and composition changes in pollution plumes.
- A more distributed monitoring approach to catchment’s hydrology that captures both pathway flows and chemical and microbial characteristics of solid materials at boundaries. New instrumentation will need to be developed.
- Monitoring that records fluxes, properties of both the flow and the media, and changes to both systematically and in a framework with common spatial and temporal referencing.
- Hypothesis testing to determine how water flowing along characterized pathways changes in quality and how consequent feedbacks alter the properties of pathways themselves.
- Methods for scaling up from individual pathways and mixing zones to collective performance in watershed systems.

Linkages

National

GWC activities addressing this question will liaise closely with other integrated CCSP/GCRP components, especially Carbon Cycle; Ecosystems; Land Use/Land Cover Change; Observations and Information Systems programs. US Government agency programs with which linkages are maintained include the USGS, USDA, EPA, USACE, Bureau of Reclamation, NSF and others.

International

Critical international linkages for this research include programs under the IGBP (particularly the emerging land program), UNSECO and WMO (through Hydrology for Environment, Life and Policy), other programs under the United Nations including WCRP, FAO and others, and the Global Water Partnership.

2.5 MORE EFFECTIVE WATER MANAGEMENT THROUGH WATER CYCLE SCIENCE

QUESTION 5: WHAT ARE THE CONSEQUENCES, AT A RANGE OF TEMPORAL AND SPATIAL SCALES, FOR HUMAN SOCIETIES AND ECOSYSTEMS OF GLOBAL WATER CYCLE VARIABILITY AND CHANGE? HOW CAN THE RESULTS OF GLOBAL WATER CYCLE RESEARCH BE USED TO INFORM POLICY AND WATER RESOURCE MANAGEMENT DECISION PROCESSES?

State of Knowledge

Variability and changes in the water cycle lead to profound impacts on human societies and ecosystems, but many of the linkages between GWC changes and societal outcomes are not yet understood in the detail needed for formulation of policy and management responses. The ability to estimate and predict the quantity and timing of streamflow is essential to planning and operation of water supply, energy generation, irrigation, and transportation systems. Changes in water availability, water quality, and in some cases, water temperature, impact domestic, industrial, agricultural and recreational uses of water, as well as on habitat protection and conservation of ecosystem values. Planners and managers who must deal with these impacts will require information on the nature of the potential changes and consequent impacts. Extreme events, such as floods and droughts, have vividly demonstrated impacts on property, productivity and health. What will it mean locally, regionally, nationally and globally if the frequency and intensity of extreme event increases due to an intensification of the water cycle that some studies suggest? Water management issues frequently arise because of variability in the natural system or inadequate planning and management decisions by water resource managers or both. As global water cycle changes are added to the multiple stresses of other global changes that include a growing population and large-scale land use/cover change, “traditional strategies for managing water supply and related agricultural and natural ecosystem issues are becoming inadequate, and improvements in prediction are becoming critical." (Hornberger *et al.,* 2001)

To achieve optimal use of the Earth's vital freshwater resources under conditions of climatic change, scientifically based procedures are needed to assess the economic and environmental consequences of different water resource management strategies and policies at the farm, ranch, and regional river basin scales. Many individual impact studies have been undertaken, and significant progress has been made in some areas. For example, studies using projections of global warming to evaluate the impacts potential changes in the behavior of snow packs in the western U.S. have shown that current infrastructure and operating policies would be inadequate for dealing with the projected hydrologic regime. However, science is far from achieving the kind of comprehensive understanding needed to guide resource management and policy decisions.

For instance, a critical need for decision support guidance exists in the area of hydrologic design and water resources planning. Virtually all design and planning is now based on the use of statistical frequency analysis, critical period analysis and related methods that design or plan for the future based on what amounts to extrapolation of historic observations. Examples include estimation of flood plain extents (typically using 100 year recurrence intervals estimated solely from past observations), flood spillway design and redesign based on probable maximum flood analysis, and reservoir operating procedures based on, for instance, historic drought and/or flood occurrences. Long-term climate variability and potential change calls into question the practice of excluding information about likely future conditions that may well differ from what have been observed in the past. Although there have been numerous sensitivity studies demonstrating the likely impacts of climate change on the performance of water management systems, there are essentially no methods for including such information in practice. This disconnect is not limited to questions associated with long-term climate change. In the realm of seasonal to interannual forecasting, there now exists sufficient understanding to identify differences in short-term risk associated with, e.g., climate teleconnection information like ENSO, the Pacific Decadal Oscillation, and the North Atlantic Oscillation. This information is rarely included in water resources decisionmaking however, which instead typically utilizes seasonal operating methods that essentially weight all possible future conditions equally. The reason for these failures to incorporate scientific advances in planning and management of water resource systems is sometimes attributed to the "uncertainty" about future climate. However, water resource managers routinely incorporate other sources of uncertainty – about future demands, and hydrologic uncertainty within the range observed in the past – in their decision-making. Current water cycle research programs have the potential to break this logjam, but, as noted in the report by Hornberger *et al.* (2001), it will require implementation of a new knowledge transfer framework.

More generally, water management decisions are often constrained by laws, agreements and societal pressures such as stringent flood control standards, federal and state environmental regulations, hydropower production schedules, and increasing water demands for irrigation, urban, industrial and recreation. Recent research results indicate that water cycle information as well as predictions and analysis tools, can contribute to the decision-making capacities of water managers who must operate within these constraints. However, factors such as regulatory inflexibility, institutional structures, and time pressures make it difficult to change established management and decision systems to take maximum advantage of new products and tools. In addition, there is a mismatch between research products and operational information needs. Information is only of value (1) if decisionmakers understand the implications and uncertainties of the new information, (2) if they trust the information enough to incorporate it into their plans and decisions, and (3) if they have mechanisms for responding to the information.

Efforts to eliminate the barriers between research and research users have been initiated and indicate that early collaborations and side-by-side demonstrations may be effective tools for speeding innovation. Collaboration is essential to ensure that learning occurs on both (or all) sides of the research development process. Decisionmakers need to be able to understand the value of the new information and how it is likely to improve their decisions. In addition, they must develop an understanding of uncertainty and its implications. They also need to understand the limits of water cycle science and the kinds of questions for which it can provide answers. Studies have shown that decisionmakers are more likely to use water cycle change information if they gain experience with the use of shorter-term hydro-climate predictions and are provided with mechanisms for incorporating the information into decision processes. Development of these mechanisms and experience in their use requires close interactions between the hydro-climate scientists and resource managers. For their part, scientists should learn from these interactions about the system of constraints under which decisionmakers operate. A better understanding of the applications environment can lead to modifications in research design that speed the adoption of results without detracting from the science.

A major deficiency precluding the use of water cycle predictions is that many of the water cycle related forecasts are either temporally or spatially too coarse and lack accuracy. It is essential that interactions between decisionmakers and research scientists identify effective methods for providing this uncertain information in a tractable manner for decisionmakers. In some cases, more finely detailed climate information or predictions may be possible; in others, decision-makers may need to work with water-cycle researchers to reframe methods and issues in forms that can plausibly be addressed. The advances needed to overcome the above deficiencies and limitations have been outlined in the previous four questions.

Another problem limiting our capability to fully assess the adequacy of water resources for the next ten to fifty years arises from the gaps in socio-economic data such as historical sequences and patterns of water use and consumption and their responses to historical ranges of price and water law scenarios, the impact of alternative water law and water trading strategies on regional development. While the development of models to assess vulnerabilities arising from changing demands patterns and climate variability have been developed elsewhere, the US is lagging other developed countries in this area. Creation and use of models that combine physical data and processes with behavioral and social factors and processes are hampered by the lack of an integrating framework for currently incommensurable measures. Furthermore, as Hornberger *et al.*, (2001) noted, a research effort is needed that integrates advances in physical water cycle science with social science research to determine how the new information can be of value in policy makers and operational water managers.

Draft Research Questions

- What are the consequences for existing water management infrastructure of variability and change in key water cycle variables such as evaporation and streamflow?
- How have water consumption patterns and trends changed as a result of major climatic events, technological innovations and economic conditions? How are patterns in water consumption likely to change as a result of projected changes in temperature, land cover/ land use, demographics, water policies, and economics?
- To what extent can changes in the management of water resources increase the adaptability of existing infrastructure to the effects of variability and change in key water cycle variables?
- What are the limits of accuracy for water cycle predictions at spatial and temporal scales required for water resource management?
- To what extent can improvements in seasonal precipitation and streamflow forecasts improve the management of water reservoirs?
- How can water cycle research products, such as the hydro-climatological projections and forecasts from global and regional climate models, remote sensing data streams, meteorological and hydrologic monitoring, and snow pack information, be deployed to improve policy decisions and water resource management?
- How can the procedures used to develop design statistics be modified to accommodate the non-stationarity of the climate?
- 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 environmental services?
- What institutional and technical issues limit the use of hydroclimatic predictions by current water resource agencies? What technical or institutional changes are needed to encourage improved use of predictions of water cycle variables?
- How do variations in water-resource availability over a range of temporal and spatial scales affect the suitability of existing institutional arrangements, management practices and the ability to meet existing and planned water allocation commitments? How can institutions incorporate projections of water cycle change during the next century in their planning and operations?
- How can water cycle, climate information, and predictions be designed and communicated to be of the most relevance, usefulness, and benefit to decision and policy makers?

Products and Payoffs

- Technology transfer and enhanced capability to produce operational streamflow forecasts over a range of spatial and temporal scales (days, weeks, months and seasons), for more effective water management decisions. (2-5 yr)
- Assessment reports on the status and trends of water flows, water uses, and storage changes for use in analyses of water availability. (2-5 yr).
- Improvements access and availability of water cycle and climatic monitoring data series and climate-change projections at the finest temporal and spatial scales available for use by land and water management agencies, with improved tools for analysis and use of these products. (2-5 yr)
- Report for stakeholders and decisionmakers on general conclusions, recommendations about information needs and research gaps regarding measures to mitigate climate change impact (2-4 yr).
- Decision support tools integrating historic climate variability, water cycle predictions and socio-economic analyses to produce planning and management tools that include these major decision factors. Decision-tree analyses of current decision-making in selected key water and land management institutions to reveal opportunities and limitations for the use of water cycle and climatic information. Forecast evaluations that link levels of error and uncertainty with potential consequences for specific water use sectors. (2-15 yr)
- Integrated models of total water use and consumption for incorporation into decision support tools that identify water scarce regions and efficient water use strategies. (5-15 yr).
- Development of tools and applications to enable the analysis of impacts of climate change on water resources and their management. Near term studies include assessments of climate change on 1) sea level rise impacts on drinking water systems in Florida; and 2) wastewater treatment costs in the Great Lakes region. (2-4 yr).
- Decision support tools for water management decisions such as web-based calculator for estimating soil retention potential of riparian buffer strips in different locations, soil types, and plant communities. (2-5 yr).
- Watershed and River System Management decision support systems to help resource managers achieve an equitable balance among competing uses: municipal, fish and wildlife, agricultural, recreational, hydropower, and water quality. Payoffs include improved methods and tools for integrating meteorological data (both *in situ* and remotely sensed), hydrologic observations, and watershed and river models, for water-supply management simulations and decision-making for major river basins in he western U.S. (5-15 yr).
- Observing system simulation and forecast demonstrations 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. (5-15 yr)

Readiness and Feasibility

This area of research is ready for development and implementation, particularly in the area of decision support tool development and application. Seasonal forecasts with useful skill are available for the western USA to be used in demonstration projects. Some studies demonstrating the usefulness of these forecasts and how they need to interact with decision support tools have been carried out and show considerable promise. Results to date have shown that the methodologies and priorities are strongly regional and require continued development on a regional basis.

Collaborative exercises were developed whereby water managers and water users test experimental products developed by the Water Cycle program in parallel with normal operations to evaluate product utility. In particular, experimental Land Data Assimilation System (LDAS) products have been developed that will be compared with traditional algorithms used to determine releases from multipurpose reservoirs in the Upper Columbia Basin. Other test sites include the Madison and Jefferson headwaters basins of the Upper Missouri. In addition, a framework for scientist-stakeholder interaction to improve water management was designed for the headwaters of the Red River in southwest Oklahoma in conjunction with the Hydrology for Environment, Life and Policy program.

Research Needs

In order to make accurate assessments of the consequences of GWC variability and change for water resources, it will be necessary to integrate data from a broad range of sources and disciplines. Frameworks such as data assimilation and fusion techniques, Geographical Information System capabilities, and decision support tools are needed to integrate this information for water resource managers. It will also be necessary to inventory existing data sources and regional and sector studies, especially for data for which regional, national, and global repositories are rare or non-existent, such as for water demand, diversion, use and consumption. A more scientific basis and method for estimating and predicting water demands is a particularly pressing need.

A critical need for decision support guidance exists in the area of hydrologic design and water resources planning. Virtually all design and planning is now based on the use of critical period analysis and related methods. Examples include estimation of flood plain extents (typically using 100 year recurrence intervals estimated solely from past observations), flood spillway design and redesign based on probable maximum flood analysis, and reservoir operating procedures based on, for instance, historic drought and/or flood occurrences.

Although there have been numerous sensitivity studies demonstrating the likely impacts of climate variability and change on the performance of water management systems, there are essentially no methods for including such information in an operational system. In the realm of seasonal to interannual forecasting, there now exists sufficient understanding to identify differences in short-term risk associated with teleconnection patterns such as ENSO and the Pacific Decadal Oscillation. However, this information is rarely included in water resources decision-making. Current water cycle research programs have the potential to connect researchers with users, but, as noted in Hornberger *et al*. (2001), it will require implementation of a new knowledge transfer framework. Furthermore, for scientific information to have an impact, it must be adaptable and timely in the user's decision-making process.

Linkages

National

To address the issues that are raised when the basic science research and results begin to be translated into innovations in water management there will be a need to extend and enhance the ongoing linkages between the several federal programs that are addressing and improving the climate-society connections. Linkages between NOAA's Hydrology research efforts and stream flow forecasting centers, and Regional Integrated Sciences and Assessments teams (RISA) with NASA's Regional Earth Science Applications Centers (RESACs), the National Science Foundations (NSF) Science/Tech Centers, the United States Geological Survey, the Bureau of Reclamation, the Department of Energy's (DOE) Accelerated Climate Prediction Initiative (ACPI) initiative, USDA-Natural Resources Conservation Service Hydrology research, and the United States Geological Survey are developing and will be further coordinated through the Water Resources Research Coordinating Committee. Potential for new collaboration exists between the Land, Sea, and Space Grant Extension and Research entities under the auspices of the recently developed Earth Grant initiative.

International

Bilateral collaboration is occurring between the USA and Canada and Mexico through studies with the International Joint Commission (IJC) related to the effects of climate change on water resources. In addition, the water cycle program will collaborate with the WCRP/ IGBP/ IHDP/ Diversitas Joint Water Project, with the WMO's Hydrology and Water Resources Programme, and with UNESCO through its International Hydrology Program and the Hydrology for Environment, Life and Policy (HELP), and the Dialogue on Water and the third World Water Forum. Also, the global water cycle program will contribute to work through bilateral treaties, particularly with countries like Japan, that have placed a priority on Water Cycle research.

3. Summary

Important and urgent problems face society as a result of decreasing access to fresh water arising to possible climate change impacts, increasing water consumption, changing land use and pollution effects. These problems are the Global Water Cycle are numerous and all interrelated through the physical processes that connect the storage of water in individual reservoirs and control the fluxes between reservoirs. Proper management of this resource is essential for all societies. The potential for better management lies in anticipatory and adaptive actions based on reliable medium and long term predictions and projections regarding the availability and use of water. Research on the Global Water

Cycle is an essential contribution to the development of such predictive systems and associated adaptive strategies.

Some of the challenges facing the global water cycle community will not be fully resolved in this decade. Well thought out, stable and adequately funded programs are needed to ensure that the activities will produce the needed results for the CCRI at the same time as they are developing longer term objectives connected with the USGCRP. This is possible because of the readiness of the science to take advantage of the new observational systems that are coming on line and to utilize the new modeling capability that is now becoming accessible to the water science community.

Water cycle research provides an excellent programmatic laboratory for exploring the potential interactions between scientists and land and water managers who deal with issues such as land, irrigation and fertilizer use and coastal zone protection. As this aspect of the program grows, the priorities for water cycle research will be expanded. In order to place the water cycle program in a position to deal with such growth issues, the physical and natural sciences must be linked with social, legal and political issues.

In order to achieve a primary goals of the CCSP, namely reducing the uncertainties in the global climate predictions/ projections, it is essential that the interactions between the global water cycle and the climate system be more fully understood and be more effectively simulated. The time is right to advance our understanding of many aspects of the global water cycle. Some federal programs related to land surface forcing have matured and are contributing many new insights regarding land surface process understanding and ways to simulate these processes in models, while other programs are receiving significant motivation and data sources through new technologies such as advanced satellites sensors and data assimilation systems. Global water cycle issues need to be addressed at a number of time and space scales. Hydrologic modeling is needed at catchment and continental scales supplemented by a capability to scale up to regional and continental scales. Atmospheric observational and modeling programs are needed to address the role of the global water cycle in climate change. A holistic perspective of the global water cycle needs to be developed through a strong Global Water Cycle program so the entire system can be understood and the interconnectedness of its various components can be properly addressed.

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