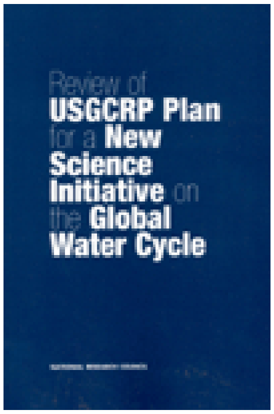

Review of USGCRP Plan for a New Science Initiative on the Global Water Cycle

Committee on a Review of A Plan for a New Science Initiative on the Global Water Cycle, Water Science and Technology Board,Board on Atmospheric Sciences and Climate, National Research Council

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REVIEW OF USGCRP PLAN FOR A NEW SCIENCE INITIATIVE ON THE GLOBAL WATER CYCLE

Committee on a Review of A Plan for a New Science Initiative on the Global Water Cycle

Water Science and Technology Board
Board on Atmospheric Sciences and Climate
Division on Earth and Life Studies
National Research Council

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Preface

The global water cycle is central to Earth's climate. It is a pervasive aspect of the physical, biological, and chemical processes and interactions of the coupled climate system. In addition, water exerts a profound influence on human activities and natural environmental processes. Global change related to anthropogenic effects on climate, land use, and water use increases the uncertainty in forecasts of the water cycle, especially as these forecasts relate to the management of water resources and mitigation of natural hazards. Study of the global water cycle transcends conventional discipline boundaries. Improved knowledge about land surface/atmosphere interactions, including more precise quantification of precipitation, soil moisture, evapotranspiration, river flow, groundwater storage and flow, and the movement of carbon and nutrients—particularly at the continental and global scales—has been recognized as critical to our ability to understand variability and changes in the Earth's climate system. Consequently, the U.S. Global Change Research Program (USGCRP) is planning to devote increased attention to improving knowledge of these phenomena. Last spring, the USGCRP produced the report *A Plan for a New Science Initiative on the Global Water Cycle* (USGCRP, 2001). This report was designed to represent a research strategy and scientific plan for investigating the global water cycle, and its interactions with climate and for developing an enhanced understanding of the fundamental processes that govern the availability and biogeochemistry of water resources. The USGCRP managers are currently considering how to move forward with implementation of this ambitious, broad, and potentially very fruitful plan on an interagency basis, and it requested that the National Research Council (NRC) advise them in this regard (see Appendix A).

In response, the NRC appointed a special committee for the purpose of this review. Our committee of 10 members was drawn from the mem berships of two NRC standing committees—the Committee on Hydrologic Science and the Climate Research Committee. These two standing committees have much experience relevant to global change science and some knowledge of the water cycle science plan. The members were selected from the two existing committees with an overriding aim of having an appropriately sized committee, with a proper disciplinary composition and free of conflicts of interest and inappropriate biases. As requested, our report provides comments on the water cycle science plan as related to its recommended scientific initiatives and goals, and it provides comments on the usefulness of the water cycle science plan to the USGCRP agencies in developing a coordinated global water cycle implementation plan. We recognize that the Water Cycle Study Group (WCSG), which performed the study for the USGCRP, has finished its work, and thus the usefulness of our review must be considered in the currently developing agency implementation plans.

In preparing this report, our committee sought to address the following statement of task:

The committee will review and provide guidance on implementation of the recent report *A Plan for a New Science Initiative on the Global Water Cycle* (USGCRP, 2001). The review will focus on a research strategy and help set scientific priorities for a proposed national program concerning the global water cycle. Specifically, the committee will assess and advise on:

- how well the water cycle science plan reflects the breadth and depth of water cycle research currently ongoing and planned in the United States, and the compatibility of this plan with USGCRP objectives, and
- coordination, collaboration, and implementation by the agencies.

In addressing this charge, we have found it useful to organize our advice in this report around four main issues: (1) assessment of the success of the water cycle science plan in addressing the charge to the WCSG, (2) evaluation of whether the water cycle science plan provides sufficient guidance to the USGCRP agencies for them to establish agency implementation plans, (3) assessment of the feasibility of the water cycle science plan's recommended research strategy and scientific plans, and, (4) recommendations on priorities for the USGCRP program and agency implementation activities.

Our study and the preparation of this report occurred on a rapid timetable of less than three months so as to accommodate the needs of the USGCRP. I appreciate the efforts made by the committee members and NRC staff in working on this tight timetable to produce a report that should be useful in advancing this important area of water science. The USGCRP initiative on the global water cycle is of vital importance to the nation. The potential disruption to our well-being is significant if anthropogenic climate change affects the water cycle, resulting in changing patterns of rainfall and related changes in river flows, soil moisture, and water quality. The committee recognizes the complexity facing the USGCRP in developing coordinated implementation plans but urges USGCRP to take all possible steps to assure the success of this initiative.

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscripts remains confidential to protect the integrity of the deliberative process. We thank the following individuals for their participation in the review of this report and for their many instructive comments: Alan K. Betts, atmospheric research consultant, Pittsford, Vermont; Kenneth R. Bradbury, Wisconsin Geological and Natural History Survey; Stephen J. Burges, University of Washington; Eville Gorham, University of Minnesota (retired); Upmanu Lall, Columbia University; and Margaret A. LeMone, National Center for Atmospheric Research.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Eugenia Kalnay, University of Maryland. Appointed by the National Research Council, she was responsible for making certain that an independent examination of the report was carefully carried out in accordance with the institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Eric F. Wood, Chair
Committee on a Review of a Plan for A New
Science Initiative on the Global Water Cycle

Contents

1
Introduction

In August 1999, the U.S. Global Change Research Program (USGCRP) commissioned a panel of experts (referred to in this report as the Water Cycle Study Group, WCSG) to advise the USGCRP agencies on "formulating a research strategy and scientific plan for investigating the global water cycle, its role in climate, and the fundamental processes that govern the availability and the biogeochemistry of water resources" (USGCRP, 2001). The charge to the WCSG listed six issues that the resulting research strategy and scientific plan should address:

1. quantitative understanding of atmospheric, terrestrial, and oceanic interactions that govern water and energy cycles on intraseasonal to centennial time scales and on regional and global scales, including, inter alia, the roles of water vapor, clouds, and precipitation processes; biogeochemical processes; terrestrial and aquatic ecosystem influences; and the roles of surface and subsurface waters within the overall hydrologic cycle,
2. an improved representation of these processes in climate and other models, across the relevant space and time scales, that will allow simulation of the hydrologic cycle and its interactions with the rest of the earth system,
3. an understanding of the response of the water cycle to environmental change and accompanying impact on water resources,
4. a capability to model and, where appropriate, predict variations in global and regional hydrologic processes and water resources on seasonal to interannual time scales and longer time scales,
5. the requirements for comprehensive, systematic space-based, ground-based, and in situ observations in support of the water cycle sci

ence objectives, with consideration of the compatibility of measurements across scales and processes, and

6. guidance on the linkages, areas of cooperation, and potential integration with other relevant national and international programs to make the initiative a success.

The WCSG provided its draft report to USGCRP in August 2000; a final report was issued by the USGCRP the following spring. In October 2001 (USGCRP, 2001), the cochairs of the Interagency Working Group for the USGCRP water cycle initiative requested that the National Research Council (NRC) review the water cycle science plan (see Appendix A for a copy of the letter request). This report provides that requested review.

The review focuses on (1) the responsiveness of the water cycle science plan to its charge, especially as it addresses the six areas identified in the August 1999 letter establishing the study group, (2) an evaluation of whether the water cycle science plan provides sufficient guidance to the USGCRP agencies for them to establish agency implementation plans, (3) an assessment of the feasibility of the water cycle science plan's recommended research strategy and scientific plans, and (4) recommendations concerning priorities for the USGCRP program and agency implementation activities.

2
Overview *A Plan for A New Science Initiative on the Global Water Cycle*

The global water cycle is central to the Earth's climate system. It transcends conventional disciplinary boundaries and is a pervasive aspect of the physical, biological, and chemical processes and interactions of the coupled climate system. In addition, water exerts a profound influence on human activities and natural environmental processes. Global change related to anthropogenic effects on climate, land use, and water use increases the uncertainty in forecasts of the water cycle, especially as these forecasts relate to the management of water resources and mitigation of natural hazards. Juxtaposed with increasing human demand for water, this increased uncertainty is cause for the concern among the USGCRP agencies that the existing scientific knowledge of the water cycle is insufficient. In response, the USGCRP empanelled the WCSG, comprised of 16 scientists under the chairmanship of Dr. George M. Hornberger (University of Virginia), to draft a plan for a coordinated research strategy on the global water cycle.

The WCSG structured its research strategy in a matrix-like format with three major science questions, each with three research goals, and three crosscutting pillar initiatives. These pillar initiatives are identified in the water cycle science plan as "research that should be given first priority" (USGCRP, 2001, p. 13). The science questions and related goals are as follows:

Science Question 1: What are the causes of water cycle variations on both global and regional scales, and to what extent is this variation induced by human activity?

Goal 1: Quantify variability in the water cycle.

Goal 2: Understand the mechanisms underlying variability in the water cycle.
Goal 3: Distinguish human-induced and natural variations in the water cycle.

Science Question 2: To what extent are variations in the regional and global water cycles predictable?

Goal 1: Demonstrate the degree of predictability of variations in the water cycle.
Goal 2: Improve predictions of water resources by quantifying fluxes between key hydrologic reservoirs.
Goal 3: Establish a systems modeling framework [i.e., all elements of the system— observing methods, models, risks and values—are evaluated within a common framework] for making predictions and estimates of uncertainty that are useful for water resource management, natural hazard mitigation, decision making, and policy guidance.

Science Question 3: How are water and nutrient cycles linked in terrestrial and freshwater ecosystems?

Goal 1: Develop observations and experiments that characterize the coupling of water, carbon, and nitrogen cycles.
Goal 2: Develop a quantitative predictive framework for water, carbon, and nitrogen fluxes coupled to ecosystem responses.
Goal 3: Distinguish human-induced and natural variations in the coupling of water, carbon, and nitrogen cycles.

The crosscutting pillar initiatives are the following:

Pillar Initiative 1: Determine whether the global water cycle is intensifying and, if so, to what degree human activities are responsible.

Pillar Initiative 2: Determine the deeper scientific understanding needed to substantially reduce the losses and costs associated with water-cycle calamities such as droughts, floods, and coastal eutrophication, and incorporate it into prediction systems.

Pillar Initiative 3: Develop the scientifically based capacity to predict the effects of changes in land use, land cover, and cryospheric processes on the cycling of water and associated geochemical constituents.

Table 2.1, reproduced from the water cycle science plan, identifies the needs and proposed actions under each of the three science questions.

The water cycle science plan is developed around five main chapters: (1) rationale for the science plan, (2) causes of water cycle variation on regional and global scales, and human influences, (3) predictability of variations in regional and global water cycles, (4) determining links between water, carbon, nitrogen, and other nutrient cycles in terrestrial and freshwater ecosystems, and (5) an integrated water cycle science plan. In comparing the science questions posed in Table 2.1 to the water cycle science plan's chapters, we note that there is a direct correspondence between the central three chapters (Chapters 2–4) and the three questions; in fact, the chapters provide the background and rationale for the science questions.

TABLE 2.1. Identified Needs and Proposed Actions for Each of the Main Science Questions in the Water Cycle Science Plan

Science Question 1	Science Question 2	Science Question 3
What are the causes of water cycle variations on both regional and global scales, and to what extent is this variation induced by human activity?	To what extent are variations in the regional and global water cycle predictable?	How are water and nutrient cycles linked in terrestrial and freshwater ecosystems?
Scientific Gaps • Observations to quantify the variability of relevant water and energy cycle components • Understanding of processes that control water cycle variability • Modeling approaches that can reproduce observed water cycle variability at scales relevant to water resource management • Approaches to partitioning natural and human-caused variations in the water cycle	Scientific Gaps • A description of the spatial and temporal regimes within which hydrologic variables can be accurately predicted to forecast floods and droughts • Understanding of fluxes among key hydrologic reservoirs to enhance prediction accuracy and reliability • Methods to transfer knowledge effectively from physical climate and hydrologic models to strategies for water resource management	Scientific Gaps • Observations of C and N reservoirs and fluxes • Observations of water use and of institutional controls on water use • Understanding of the linkages between changes in land use and changes in water and nutrient cycling • Models of transport of C and N to coastal oceans; fully coupled biosphere-climate models; and coupled models of water demand, agricultural practices, land use, and water quantity and quality
Proposed Actions • An observation program using new and evolving technologies to characterize water cycle variability • A new commitment to field studies to resolve uncertainties about water and energy cycles • A model development initiative to reproduce observed water cycle variability and to help discriminate natural and anthropogenic sources of variability • An advanced data assimilation system and products to unify disparate observations, and to reduce uncertainty in estimates of water cycle variability • Use of water and energy budget diagnostics to evaluate model performance and to characterize water cycle variability	Proposed Actions • Identification of predictable water cycle components at all pertinent temporal and spatial scales • Quantifying prediction uncertainty through a program of monitoring, process studies, and model development • Developing and implementing instruments, methods, networks, and assimilation techniques to estimate the two presently unobserved fluxes, recharge/discharge and evaporation • An interdisciplinary initiative that uses a systems modeling framework to integrate users' requirements into the design and implementation of observing systems, model-based prediction, and forecast verification	Proposed Actions • Integrated remote and ground-based observation programs, with observations conducted at a hierarchy of spatial and temporal scales and recorded in a sustainable data archive and retrieval system • Field studies to establish quantitative descriptions of processes relevant to coupled C-N-water cycling • Conjoining observations and models to understand and quantify slower feedback mechanisms of vegetation structural dynamics on coupled C-N-water cycling • Knowledge transfer program for collaboration and communication among researchers, decision makers, and stakeholders

SOURCE: USGCRP (2001).

3
Responsiveness of the Water Cycle Science Plan to the USGCRP Charge

We summarize here our findings with regard to the water cycle science plan's responsiveness to the study group's charge (see Chapter 1). Overall, we found that the water cycle science plan is a well-written document that is largely successful in making the case for an emphasis on an expanded USGCRP research agenda focused on the water cycle. The comments and criticisms that follow should be viewed in this light. Though there are important issues that must be addressed if the water cycle initiative is to meet its promise, we find the water cycle science plan to be a useful first step in planning the scientific pursuit of the vital questions associated with the water cycle.

As acknowledged in its preface, the plan is ambitious and "will require diligence and hard work by program managers." The challenges, both financial and programmatic, are clearly stated. We note that for over 25 years, there has been concern related to a lack of understanding regarding the water cycle and how it may be affected by climate change and the subsequent impacts on water resources (NRC, 1974; Waggoner, 1990). Indeed, these and other concerns about climatic change led to the U.S. Global Change Research Act of 1990 (PL 101-606), with Congress establishing the U.S. Global Change Research Program (USGCRP) and instructing federal research agencies to cooperate in developing and coordinating a "comprehensive and integrated United States research program." This historical perspective is a useful backdrop to place the water cycle science plan in perspective. The references above (NRC, 1974, and Waggoner, 1990), which span over two decades, demonstrate long-standing needs for research on the water cycle.

The utility of the water cycle science plan to the cooperating agencies depends on both the focus of the plan established by the specific charges given to the WCSG and the extent to which the resulting science plan provides a basis for effective agency implementation plans. In general, we find that the water cycle science plan is faithful to the charge provided to the WCSG by the USGCRP. This context frames our comments on the utility of the water cycle science plan to the USGCRP agencies. In this chapter comments are provided on the water plan as a whole, followed by comments directed at the six specific charges to the WCSG.

Overall Utility of the Water Cycle Science Plan

In developing a global water cycle science plan, the WCSG is faced with the existence of a plethora of water research programs and activities that address various aspects of the global water cycle on various time and space scales. As the report notes on page 5 of its summary, "All agencies of the U.S. Global Climate Research Program (USGCRP) have programs related to the water cycle"—as do agencies outside USGCRP. Additionally, USGCRP agencies have water cycle programs that are not considered part of their USGCRP activities. Our committee recognizes that the WCSG developed its plan within this research environment.

The WCSG report makes the case that coordination of water cycle research is necessary for making progress in this area of global change science, and the new research resulting from the coordinated program would be greatly beneficial to the nation. The WCSG recommended a coordinated program built around the three science questions, each with three goals (see Chapter 2). These three questions can be summarized as follows:

1. What causes water cycle variability?
2. How predictable is the water cycle?
3. How is the water cycle linked to the nutrient cycle?

In addition, three crosscutting, "first-priority" pillar initiatives are provided as guidelines "to know where to begin."

Our committee believes that this is a successful framework for structuring a coordinated water cycle science plan. We grappled with the very broad charge to the WCSG in regard to "a research strategy and science plan" that covered virtually all aspects and components of the water cycle, research related to the application of water cycle science in water management, and the role of water in the nutrient cycle. The WCSG report is credible in that it (1) provides a research framework structured around three science questions that our committee also believes capture the important unresolved scientific issues, (2) identifies scientific gaps and proposed actions related to these questions, (3) gives a comprehensive description of the current water cycle research activities, and (4) contains many valuable research activities to address the science questions, including the pillar initiatives as areas of initial agency focus. The committee finds much in the report around which agencies could develop implementation plans.

The broad research program, which the water cycle science plan outlines in general terms, spans and links to a broad spectrum of climate science issues, and it overlaps and interfaces with many USGCRP elements. The broad nature of the subject will result in important items being omitted, and our committee identifies a number of these. There are areas where the report is unclear and provides insufficient detail, and we comment on these. Finally, the report tends not to prioritize activities or strongly recommend a strategy to address scientific goals and initiatives, and we suggest priorities as an input to the overall USGCRP implementation process as we were requested to do in our charge.

As examples, the water cycle science plan is heavily focused on the terrestrial components of the water cycle and on related biogeochemical aspects. An important aspect of the global water cycle is to understand the air-sea water and energy exchange, and how these interactions govern water and energy cycles on intraseasonal to centennial time scales and on regional and global scales. These aspects are not discussed in the water cycle science plan.

From a programmatic perspective, the water cycle science plan does not articulate, even in general terms, how the global water cycle initiative should be integrated into the larger climate research agenda. It is necessary that the agency implementation plans take each of the broadly stated action items (see Table 2.1) and follow with a further breakdown into specific activities that link or interface them to other USGCRP program elements (or USGCRP agency programs.)

Much more work needs to be done by the agencies with respect to prioritization and timing of the proposed activities. Still needed is a clear statement of those elements that can be addressed effectively during the next few years, those that will require a decade or so to develop, and those very long-term goals where readiness is not apparent and which will take more that a decade to develop fully.

In this light, we have concerns with the first pillar initiative, acceleration of the water cycle, which with the other pillar initiatives is ranked as a high-priority, near-term research activity. It is recognized that determining any changes to the intensity of the globally averaged hydrologic cycle would serve as an excellent metric for the globally averaged hydrologic response to global warming. At global scales, determining this intensity reduces to evaluating either globally averaged precipitation or evaporation. In practical terms this is infeasible due to a lack of adequate observations. Determining the intensity it requires consideration of the terrestrial, oceanic, and atmospheric branches of the global hydrologic cycle.

Before addressing the challenge of determining whether the hydrologic cycle is accelerating, we believe that a necessary first step must be to close the water budget both regionally at the scale of large river basins and globally through a combination of space-based and ground-based observations. If hydrologic science is currently unable to measure fluxes sufficiently accurately to close the water budget at virtually any scale, then it is not clear what measurement strategy could be used to measure "acceleration." To do this from data alone (or data combined with model results) will require a decade or more of significantly improved observations. Thus, it could be argued that this must be realistically viewed as a long-term objective. But closing the water budget entails a challenging research strategy in itself, including development of the observational strategy, measurement capability, and modeling assimilation support for such closure.

Similarly, for Pillar Initiative 2 (relating to understanding water-cycle calamities), basic work is needed to validate the representation of the water cycle in climate models and to describe and, in some cases, first identify the processes linking climate variability to calamitous events. For example, climate variability is implicated as a factor in coastal eutrophication, but capability to predict the occurrence and intensity of episodic eutrophication and related anoxia events has yet to be developed (NRC, 2000a). It appears that the water cycle science plan takes for granted that this basic, foundational work either has been done or results will be available where needed to support the science plan. The success of this pillar initiative is predicated on a coordinated interagency program that makes end-users important drivers of developments in the research and operational communities. Otherwise, the value of predictions for hazards mitigation may be limited.

The success of the third pillar initiative, which is directed toward developing the scientific capacity to predict the effects of changes in land use, land cover, and cryospheric processes on the cycling of water and associated geochemical constituents, and which cuts across the science questions, is dependent on developing quantitative benchmarks for models that are used in such assessments. More programmatic guidance on how agencies would develop and use these benchmarks is important; otherwise, the current rate of progress is probably inadequate to realize this initiative.

Overall, implementation of the water cycle science plan by cooperating agencies should give priority to basic work in the following three areas:

1. assembling and defining the observational requirements for regional and global and regional water budget variables,
2. establishing quantitative benchmarks for improvements in the characterization of the water cycle components of climate models, and
3. determining the scientific needs of water resource managers, and making these needs the drivers of basic and applied water cycle research.

Comments on the Specific Charges Given to the WCSG

From these overarching comments, the committee has further comments on the six specific charges that were provided to the WCSG, and we have advice to give to the USGCRP as it develops a water cycle implementation plan.

Charge 1. Quantitative understanding of atmospheric, terrestrial, and oceanic interactions that govern water and energy cycles on intraseasonal to centennial time scales and on regional and global scales; this including, inter alia, the roles of water vapor, clouds, and precipitation processes; biogeochemical processes; terrestrial and aquatic ecosystem influences; and the roles of surface and subsurface waters within the overall hydrologic cycle.

The water cycle science plan addresses this through Science Question 1, which is focused on understanding water cycle variability; Science Question 2, which focuses on how the water cycle is linked to the carbon and nitrogen cycles; and Pillar Initiative 1, which is to determine whether the water cycle is intensifying. The understanding of linkages between the water cycle processes and biogeochemical processes is the focus of Science Question 3 and Pillar Initiative 3.

We have the following comments regarding this broad charge:

• Addressing this charge requires spanning a large and disparate community of professionals engaged in water science and management. This is an important goal for water cycle research, but given the existing disciplinary divisions, it is unclear whether the agencies will obtain the guidance from the plan on how to bring together the communities required for this element—or even how to parse the scientific problem into feasible components.

In addressing this broad charge, it is easy to overlook important elements. This may have happened with regard to the sea-air interactions, which are not discussed in the water cycle science plan. If sea-air interactions are not adequately addressed, planetary-scale processes, which fundamentally force atmospheric circulation and therefore play a central role in land surface hydrology, will also be difficult to address.

• The present ability of agencies to address the causes of water cycle variability, predict this variability, and measure any intensification of the water cycle may be lower than for other elements of the water cycle science plan. We are concerned that the goal of measuring the intensification or acceleration of the water cycle, depends on the sufficiency of the observations that results in first closing water budgets, both regionally and globally. Since both precipitation and evaporation have large uncertainties, determining changes in the residence time of water seems highly challenging. Moreover, identifying the natural versus human-induced variability is a problem of attribution that also seems overly ambitious at this juncture. Background presented in the water cycle science plan (mostly in Chapters 2 and 3) could be clearer in advancing a conceptual model for variability (local versus remote, one-way versus two-way interaction, feedbacks, etc.) needed to provide a "blueprint" for addressing this charge. From such a model, the report could more clearly identify the building blocks for answering the most fundamental question: what are the human-induced versus natural causes of variations and change? Thus, the agencies in coordinating their implementation plans must be assured that this important science question is adequately addressed.

• One of the proposed actions in the water cycle science plan is the interdisciplinary initiative to design and implement observing and estimation strategies for quantifying evaporation and recharge. This high-priority issue can only be solved with interagency coordination. The three storages in the water cycle (i.e., atmosphere, surface, and subsurface) are linked by the evaporation and recharge fluxes. Nevertheless, there are currently neither observing networks nor proxy measurements that can provide reliable estimates of these important fluxes. Evaporation and recharge are now mostly estimated as residual of mass balance and therefore also include all measurement errors in the other terms. More direct measurement and estimation techniques need to be devised for these fluxes. Evaporation and recharge are especially challenging fluxes to quantify because the relations and measurements used for their estimation are scale dependent. Furthermore, their spatial and temporal patterns are strongly influenced by biota. Finally, these fluxes mark the place at which the water cycle and the biogeochemical cycle link together. Their estimation at relevant scales where couplings take place is thus especially important.

• Regarding understanding the linkages between water cycle and biogeochemical processes, we agree that the carbon cycle should be synergistically studied with the water cycle, and strong links between the U.S. Carbon Cycle Plan (see http://www.carboncyclescience.gov) and the terrestrial water cycle are needed. But other biogeochemical components are equally important to understanding human-induced effects on the nutrient cycle (Science Question 3/Goal 3; and Pillar Initiative 3). Specifically, the water cycle science plan might have called for a stronger effort in addressing the transport, storage, and transformations of sediment and chemical nutrients. For much of the United States, these constituents are the major causes of aquatic system degradation—relevant to Goal 2 under Science Question 3. Furthermore, one of the critical issues in carbon cycling is storage of chemical nutrients in sediments.

• Lack of an atmospheric chemistry element. The water cycle science plan states that water is the universal solvent. It is also the main source of hydroxyl, the atmosphere's detergent. We note that the plan leaves aside the whole issue of atmospheric chemistry, although other aspects of geochemistry are included. The discussion in the plan regarding water quality (see page 7 of the plan) is interesting in this regard, but we did not see any attempt to draw a connection with U.S. effort to understand atmospheric deposition to water surfaces. (e.g., National Acid Precipitation Assessment Program). In addition, considering upper-tropospheric water vapor (see page 29 of the plan) opens the doors to consideration of atmospheric chemistry, both in the stratosphere and troposphere. This may be beyond the scope of the water cycle initiative, but better observations are certainly needed in the upper troposphere for improved understanding of the water cycle variability.

Charge 2. An improved representation of these processes in climate and other models, across the relevant space and time scales, that will allow simulation of the hydrologic cycle and its interactions with the rest of the earth system.

The water cycle science plan discusses many of the elements needed to address this charge. In general, Chapter 2 of the plan provides the necessary material related to improving the parameterization of the processes in climate models—namely the five program elements, which are observations, process studies, modeling, data assimilation, and budget studies. We are concerned that these elements *describe* ongoing and recent activities (observations, process studies, modeling, etc.), but they do not *evaluate* the appropriateness or sufficiency of these activities for addressing the science questions, nor do they *recommend* implementation activities needed to move the science forward. The water cycle science plan does not provide a research strategy or sufficient scientific direction to USGCRP agencies to prioritize their implementation activities and carry out the research needed to address the science questions and pillar initiatives central to the water cycle initiative.

Charge 3. An understanding of the response of the water cycle to environmental change and accompanying impact on water resources.

The water cycle science plan responds well to this element by recommending the development of an integrated approach ("systems modeling framework") for water resources management to utilize the improved prediction of water cycle variability under Science Question 2. In addition, improved understanding of the water and biogeochemical processes by water and ecosystem management is part of the pillar initiatives. This linkage is consistent with the U.S. Global Change Research Act and the USGCRP assessments (e.g., National Assessment Synthesis Team, 2000; Gleick and Adams, 2000), and thus these elements clearly belong in the water cycle initiative.

Under Pillar Initiative 3, a significant part of the scientific effort is directed at the decision processes associated with improved prediction capabilities. Although the water cycle science plan recognizes the importance of these decision processes, more follow-on coordination is needed for the science initiative to help water management agencies develop effective implementation activities. For example, there is a plan to "assist water resources managers in using ensemble forecasts in their operation of water resource systems." But this presumes that all that is required is straightforward technology transfer. Without specific research, it is unclear whether increased predictive capability will result in sufficiently increased benefits to motivate water managers to adopt new tools and practices. It is important that agency and interagency implementation plans in this area establish the users and operational communities as stakeholders in the research and technology transfer activities.

A focus on eventual utility of the science to water managers does serve to provide structure to water cycle studies described in the water cycle science plan, but this research may not serve the most pressing needs of water managers (see, for example, NRC, 2001a). The potential benefits from the efforts described in the water cycle science plan will require more than a transfer of data, forecasts, and techniques described in Chapter 4 of the plan. In fact, there is the possibility that even given the knowledge argued for in the water cycle science plan, benefits to water resource management may be elusive because of an inability to incorporate that knowledge into management procedures. Thus, there is a need to identify an implementation activity that evaluates how new knowledge on the water cycle scientific goals (e.g., predicting climate variability) could be used by water managers. We recommend that the USGCRP include, or at a minimum more actively engage, water management agencies (e.g., Bureau of Reclamation and the U.S. Army Corps of Engineers). Linkages to irrigation districts and local public and private water utilities, which play a critical role in management of water systems, would also be useful.

Charge 4. A capability to model and, where appropriate, predict variations in global and regional hydrologic processes and water resources on seasonal to interannual time scales and longer time scales.

Science Question 2 and its supporting Chapter 3 address this charge directly. Chapter 3 of the plan has specific goals and program elements, thereby providing a framework to consider Science Question 2. In general, we feel that Chapter 3 of the plan provides an excellent initial foundation from which a research program on predicting water cycle variations can be developed.

The concerns listed above under Charge 3, regarding the ability of the water management community to benefit only through technology transfer, are also relevant here, since goal 2 (in Chapter 3) suggests that improved predictions of water resources can occur through improved quantification of fluxes between hydrologic reservoirs (soil water and atmospheric water) without research into water resources decision making. "Improved quantification of fluxes between hydrologic reservoirs" is necessary but not sufficient for improved water management.

Charge 5. The requirements for comprehensive, systematic space-based, ground-based, and in situ observations in support of

the water cycle science objectives, with consideration of the compatibility of measurements across scales and processes.

The WCSG addressed this charge by providing throughout the water cycle science plan descriptions of current observations and potential observations. However, the discussion regarding observations is limited and does not define which observations are critical to the water cycle initiative, which are currently adequate, and which are lacking. Because observations are at the heart of the initiative and are one of the major manifestations of its implementation, special attention needs to be paid to this issue. *Based on the science questions and proposed actions in the water cycle science plan, a set of measurement requirements need to be defined for monitoring the water cycle variables. The needed measurement requirements include measurement accuracy, sampling density, and measurement support scale as well as readiness.*

After the measurement requirements have been defined, the agency and interagency implementation plans can identify the required infrastructure, and its phasing, in proposals. This information would assist the USGCRP and cooperating agencies in defining the necessary observation requirements and in identifying those aspects of their science questions that can and cannot be answered with current and planned observational systems. In addition, the water cycle science plan must reinforce the need for in situ observational networks, which have degraded significantly over the last 20 years. The need for climate quality observational networks has been recognized (NRC, 2001d). The water cycle science plan assumes that new satellite observations (e.g., observations from NASA/EOS and post-EOS-era NPOESS systems) will flow easily into the plan's research elements and that sufficient ground validation measurements are available to make the new satellite observations useful. Concern has been expressed regarding the sufficiency of climate quality data and whether National Polar-orbiting Operational Environmental Satellite System (NPOESS) will satisfy these needs (NRC, 2000a, b). But we believe that specific agency efforts for both in situ and satellite observations are required to assure adequate observations for the science goals and pillar initiatives presented in the water cycle science plan.

Charge 6. Guidance on the linkages, areas of cooperation, and potential integration with other relevant national and international programs to make the initiative a success.

The charge to the WCSG included providing guidance to the USGCRP agencies regarding linkages and cooperation with national and international programs. USGCRP requested WCSG's assistance in four areas related to these linkages: (1) identifying which USGCRP agencies may be best positioned to tackle particular portions of the water cycle plan, (2) identifying non-USGCRP agencies and groups carrying out related water cycle research in the United States with whom the USGCRP agencies should coordinate their research, (3) identifying USGCRP research activities that interface with water cycle science, and (4) identifying international programs with which the USGCRP agencies should coordinate their water cycle science research. We believe that the water cycle science plan has mixed success in providing this advice.

In providing advice as to which USGCRP agencies are poised to tackle various elements, the document does provide a comprehensive compilation of activities that need to be undertaken, and the programs in various U.S. agencies (Appendix C of water cycle science plan). However, as part of its guidance to USGCRP, the plan could have provided WCSG's perspective on how its recommended science plan would be coordinated across USGCRP agencies by matching agency programs with elements of this science initiative. This lack of coordination across USGCRP agencies has been a concern expressed in other NRC reports (see NRC, 2001c). It was not clear to the committee how this vital coordination of work will take place. As part of this coordination activity, we believe that fostering cooperation with non-USGCRP agencies, particularly water management agencies, is critical to fulfilling the potential for improved water resource management called for in the water cycle science plan.

The water cycle science plan, through its recognition of linkages between water and carbon, has made a very effective case that USGCRP water cycle initiatives should interface with those stemming from the Carbon Cycle Science Plan. The Science Question 3 in the plan—"How are water and nutrient cycles linked in terrestrial and freshwater ecosystems?"—provides the opportunity to link to other programs. Many of these are listed in Appendix C of the plan (e.g., NSF's Long-term Ecological Research (LTER) sites, the multiagency National Acid Precipitation Assessment Program, and the USGS Water, Energy, Biogeochemical Budget (WEBB) program, among others). Providing guidance on how the proposed water cycle science initiative and its implementation can interface with these programs is now critically important.

With respect to cooperation with international programs, the water cycle science plan lists the activities of many programs (Appendix C of the plan), and U.S. agencies (notably NASA and NOAA) and U.S. scientists contribute significantly to these international climate activities. Still to be designed is a framework on how the new USGCRP water cycle science will contribute to the international climate programs. The need for stronger international connections has been noted previously (see NRC, 2001c) and needs to be considered in agency implementation plans.

In particular, we believe that there is potential for a stronger international focus with respect to the water resources activities called for in the plan. Understanding and assisting in water resources issues around the world are important to U.S. foreign policy and national security, which implies that these issues should be a high priority for the U.S. hydrologic research and applications communities. In so doing, science can achieve practical advances as well as foster international understanding. Contributing to the understanding of water resources and of their links to climate variability seems a nearly ideal way for the United States to step forward to make a scientific contribution that is global not only in its domain of study but also in its domain of application.

4
Findings and Recommendations

Our review produced the following findings and recommendations.

FINDINGS

1. The water cycle science plan successfully makes the case that coordination of water cycle research is necessary for making progress in this area of global change science, and the new research resulting from the coordinated program would be greatly beneficial to the nation. The plan recommends developing a coordinated plan around three science questions that we agree are of the utmost importance to USGCRP water cycle research. Thus, the plan offers a useful and challenging science plan to the USGCRP agencies, and we support the new initiative contained in the plan.

2. The USGCRP agencies need to develop as soon as possible implementation plans to address the research proposed in the water cycle science plan. As stated in our review, we are concerned about the prioritization and implementation of the research identified in the plan. One effective approach to enhancing coordination would be for the USGCRP agencies, through their Interagency Working Group on the Global Water Cycle, to organize a "commitments" meeting. The purpose of such a meeting would be for the agencies to discuss overall research priorities and identify the elements of the water cycle science plan for which they will take the lead roles. These commitments for research should take into consideration the recommendations of the water cycle science plan and the comments found in this review.

3. The USGCRP, through its Interagency Working Group on the Global Water Cycle, should develop a mechanism to coordinate the various agency implementation plans and to bring the disparate science and

management communities together. Otherwise, insufficient attention may be given to interagency activities, identification of integration topics across agencies, and general coordination. The water cycle is so pervasive in climate issues that many of the proposed activities are components of research carried out by a number of USGCRP agencies and World Climate Research Program (WCRP) activities. How should the water cycle be integrated into this larger climate science agenda? Historically, USGCRP agencies have pursued their research activities in a rather independent manner. Coordination of the efforts of separate agencies that are largely either underway or planned under other climate research umbrellas presents a significant challenge to the water cycle initiative.

4. The water cycle science initiative approach to prioritizing the science questions is to identify pillar initiatives. We recognize that the USGCRP agencies must consider which elements they will focus on early in their implementation planning. Establishing priorities and setting near-term goals must be a component of the interagency coordination activity recommended above. Nonetheless, we recognize that there are elements that can be effectively addressed during the next few years and those that will require a longer period of a decade or more. The agency implementation plans must be sufficiently coordinated to provide this prioritization and the required resources.

RECOMMENDATIONS

The science questions, goals, and pillar initiatives found in the water cycle science plan presuppose a sound foundation of observations, a thorough understanding of hydrologic processes active on the scale of large river basins and globally, and accurate representation of the water cycle within climate models. The first priority of the USCGRP must be to assure that this foundation is in place. Therefore, we urge the USGCRP agencies in developing their implementation plans to assure that these needs are met first and foremost. Therefore, we believe strongly that implementation of the water cycle initiative by cooperating agencies must give priority to basic work in the following three areas:

1. Clearly define quantitative observational data requirements for regional and global water cycle elements. Pillar Initiative 1 and the first two science questions require as a first step that the climate community be able to assemble observational data that allow the detection of climate signals and close the water balance for large areas and river basins by the use of observations, including the determination of precipitation and evaporation over the oceans. Reports identifying the need for a climate observing system are available to guide implementation in this area (NRC 1999a, b). Such reports should be the starting point to define the quantitative characteristics of the observing requirements for water cycle variables. Such a set of requirements does not currently exist, and their creation is critical to transition the water cycle science plan into effective agency and interagency implementation plans. The requirements should also include the synergistic use of research-based observations with operational-based observations.

2. Validate the water cycle components of climate models. The science questions contained in the water cycle science plan that are related to understanding and predicting variability require an improved understanding of hydrologic processes and their representation in climate models. Therefore, it seems that advances in this area are also fundamental to the water cycle science plan, and the research community is poised to make these advances. Advanced climate change impact assessments are dependent on progress in this area. The path forward in this area requires the identification of the weakest elements in the characterization of the water cycle, and it requires the identification of quantitative improvement goals.

3. Improve the understanding of hydrologic processes that link climate variability to outcomes relevant to the management of water and related natural resources, and hazards. The science requirements of application users need to be brought to the forefront and made important drivers of research related to the water cycle. The agency implementation plans must ensure that research and development thrusts are traceable to requirements of the science and applications users.

Work in these three areas will help assure that the science questions and pillar initiatives proposed under the water cycle initiative can be successfully addressed and answered.

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Appendix A

Letter from USGCRP Requesting Review of Water Cycle Initiative Science Plan

August 27, 2001

Stephen D. Parker, Director
Water Science and Technology Board
National Research Council
2101 Constitution Ave., NW
HA 462
Washington, DC 20418

Dear Dr. Parker:

We are writing to you on behalf of the USGCRP Interagency Working Group on the Global Water Cycle (GWC) to request your assistance in the review of the recently published report, "A Plan for a New Science Initiative on the Global Water Cycle." At the request of the Subcommittee on Global Change Research and with the support of the USGCRP agencies, Prof. George Hornberger established a Study Group in 1999 to consider water cycle issues. During the spring of 2001 his group completed their work and the final report was published this summer.

The Water Cycle Study Group was charged with the responsibility of formulating a research strategy and scientific plan for investigating the global water cycle, its interactions with climate, and an enhanced understanding of the fundamental processes that govern the availability and the biogeochemistry of water resources. In short, they were requested to develop the strategy and science plan for a national program. This "Science Plan"is intended to produce:

1. A quantitative understanding of atmospheric, terrestrial, and air-sea interactions that govern water and energy cycles on intraseasonal to centennial time scales and on global and regional scales: this includes, inter alia, the roles of water vapor, clouds, and precipitation processes; biogeochemical processes, terrestrial and aquatic ecosystems influences; and the role of surface and subsurface waters within the overall hydrologic cycle;
2. An improved representation of these processes in climate and other models, across the relevant spatial and time scales, that will allow simulation of the hydrologic cycle and its interactions with the rest of the earth system;

3. An understanding of the response of the water cycle to environmental change and the accompanying impact on water resources;
4. A capability to model and, where appropriate, predict variations in global and regional hydrologic processes and water resources on seasonal to interannual time scales and longer time scales; and
5. The requirements for comprehensive, systematic spaced-based, ground-based and in situ observations in support of the water cycle science objectives, with consideration of the compatibility of measurements across scales and processes.

The final water cycle report documents the research needs for understanding the Global Water Cycle and recommends three principal initiatives that should be undertaken by USGCRP agencies to address priority science questions. Within the USGCRP we are currently in the preliminary stages of determining how we will approach these scientific problems on an interagency basis. This includes developing implementation strategies and plans and seeking funding for new water cycle initiatives. It would be greatly appreciated if you could coordinate a review of the report that has input from the Committee on Hydrologic Sciences (COHS), the Climate Research Committee (CRC) and any other committees that you may find helpful in providing credible guidance to the USGCRP agencies. The review will be used by the Interagency Global Water Cycle Working Group in developing a consolidated USGCRP implementation plan for the Global Water Cycle.

Thank you for your attention to this matter. If we can be of further help in this process we would be happy to provide additional background information.

Sincerely,

Robert A. Schiffer	Richard G. Lawford
Co-Chair	Co-Chair

USGCRP Interagency Working Group on the Global Water Cycle

cc: Dara Entekhabi
Joe Friday
Margaret Leinen
Richard Moss

Appendix B
Biographical Sketches of Committee Members

Eric F. Wood (chair) is a professor in the Department of Civil Engineering and Operations Research at Princeton University. His areas of interest include hydroclimatology with an emphasis on land-atmosphere interaction, hydrologic impact of climate change, stochastic hydrology, hydrologic forecasting, and rainfall-runoff modeling. Dr. Wood is an associate editor for *Reviews in Geophysics, Applied Mathematics and Computation: Modeling the Environment, and Journal of Forecasting*. He is a member of the Board on Atmospheric Sciences and Climate, the Climate Research Committee, and the Committee on Hydrologic Science. He is a former member of the Water Science and Technology Board and BASC's GEWEX panel. Dr. Wood received an Sc.D. in civil engineering from Massachusetts Institute of Technology in 1974.

Mary P. Anderson is a professor in the Department of Geology and Geophysics at the University of Wisconsin, Madison. Her current research interests include the effects of potential global climate change on groundwater-lake systems and quantifying groundwater recharge. She is editor of *Ground Water* and has received both the 1998 O. E. Meinzer Award (Geological Society of America) and M. K. Hubbert Award (National Ground Water Association). She is a member of the Committee on Hydrologic Science and a former member of the Water Science and Technology Board. She is a fellow of the Geological Society of America and the American Geophysical Union. Dr. Anderson received a Ph.D. in hydrology from Stanford University.

Antonio J. Busalacchi, Jr., is director of the Earth System Science Interdisciplinary Center (ESSIC) and professor of meteorology at the Uni versity of Maryland, College Park. His research interests include the development and application of numerical models combined with in situ and space-based ocean observations to study the tropical ocean response to surface fluxes of momentum and heat and tropical ocean circulation and its role in the coupled climate system. Dr. Busalacchi has extensive NRC experience as a member of the Panel on the Tropical Ocean/Global Atmosphere (TOGA) Program and the Panel on Ocean Atmosphere Observations Supporting Short-Term Climate Predictions. He is presently a member of the Climate Research Committee. He holds a Ph.D. in oceanography from Florida State University.

Dara Entekhabi is a professor of civil and environmental engineering and atmospheric and planetary sciences at the Massachusetts Institute of Technology. His research interests are in improving the basic understanding of land-atmosphere processes that may form the basis for enhanced hazards predictability. Specifically, he conducts research in land-atmosphere interactions, remote sensing, physical hydrology, operational hydrology, hydrometeorology, groundwater-surface water interaction, and hillslope hydrology. He received his B.A. in geography and two M.A. degrees from Clark University. Dr. Entekhabi received his Ph.D. in civil engineering from the Massachusetts Institute of Technology. He is chair of the NRC's Committee on Hydrologic Science.

William K. Nuttle is an independent consultant in Ottawa, Ontario, Canada. Until recently, he was director of Everglades Department, South Florida Water Management District, and was executive officer for the Florida Bay Science Program immediately prior to that. An expert in the ecohydrology of wetlands and environmental science, he has coordinated extensive estuarine and wetlands research programs in south Florida. Currently he is visiting scholar at the Southeast Environmental Research Center, Florida International University. Previously, he held positions with Memorial University of Newfoundland and the University of Virginia. Dr. Nuttle has also consulted widely on topics generally related to coastal, wetland hydrology and the interface between research and environmental management. He is a member of the Committee on Hydrologic Science. Dr. Nuttle received his M.S. and Ph.D. (1986) degrees in civil engineering from the Massachusetts Institute of Technology and his BSCE from the University of Maryland.

Marc B. Parlange is a professor of hydrology and chair of the Department of Geography and Environmental Engineering at the Johns Hopkins University. His primary research interest is in hydrology and fluid mechanics in the environment, especially questions of land-atmosphere interaction; turbulence and the atmospheric boundary layer; watershed-scale hydrology; and vadose zone transport processes. He is a member of the Committee on Hydrologic Science. Dr. Parlange received his B.S. (1984) in applied mathematics from Griffith University in (Brisbane, Australia), and his M.S. (1987) in agricultural engineering, and his Ph.D. (1990) in civil and environmental engineering from Cornell University.

Kenneth W. Potter is a professor of civil and environmental engineering at the University of Wisconsin, Madison. His teaching and research interests are in hydrology and water resources, including hydrologic modeling, estimation of hydrologic risk, estimation of hydrologic budgets, watershed monitoring and assessment, and hydrologic restoration. A past member of the Water Science and Technology Board, Dr. Potter served as chair of NRC's Committee on American River Flood Frequencies and served as vice-chair of the Committee on Flood Control Alternatives in the American River Basin. He is a member of the Committee on Hydrologic Science and the Committee on Restoration of the Greater Everglades Ecosystem. He received his B.S. in geology from Louisiana State University and his Ph.D. in geography and environmental engineering from Johns Hopkins University.

Eugene M. Rasmusson is a senior research scientist at the Cooperative Institute of Climate Studies (CICS) at the University of Maryland. He received his Ph.D. in meteorology from Massachusetts Institute of Technology. In 1999, Dr. Rasmusson was elected to the National Academy of Engineering. His research expertise lies in general climatology with an emphasis on seasonal to interannual climate predictability. Dr. Rasmusson is presently chair of the NRC's Climate Research Committee. Other NRC contributions are wide-ranging, including membership on the Board on Atmospheric Sciences and Climate (1992–1996), the Global Ocean-Atmosphere-Land System Panel (1994–1996), the Panel on Model-Assimilated Data Sets for Atmospheric and Oceanic Research (1989–1991), the Committee on USGS Water Resources Research (1988–1993), and the Advisory Panel for the Tropical Ocean/Global Atmosphere (TOGA) Program (1984—1985).

Dian J. Seidel leads the climate variability and trends group at the NOAA Air Resources Laboratory in Silver Spring, Maryland. She received her B.A. from the University of California, Berkeley, her M.S. from San Jose State University, diploma from the Von Karman Institute for Fluid Dynamics, and her Ph.D. from the University of Maryland. Her recent research focuses on observational studies of atmospheric temperature and water vapor changes, climate extremes, and meteorological data quality. She is a recipient of both the Prof. Dr. Vilho Vaisala Award from the World Meteorological Organization and the NOAA Administrator's Award. She is a member of the NRC's Climate Research Committee.

John L. Wilson is professor of hydrology and chairman of the Department of Earth and Environmental Science at New Mexico Tech, Socorro. He studies fluid flow and transport in permeable media, using field and laboratory experiments and mathematical models. In the past this has included studies of the movement of water, nonaqueous phase liquids, dissolved chemicals, colloids, and bacteria through porous, fractured, and faulted media. He was the 1992 Darcy Lecturer for the Association of Groundwater Scientists and Engineers. He was elected Fellow of the American Geophysical Union in 1994. He received the O. E. Meinzer Award from the Geological Society of America in 1996 and was elected Fellow of the Society in the same year. He is a member of the Committee on Hydrologic Science. He received his B.S. from Georgia Institute of Technology and his M.S., C.E., and Ph.D. from the Massachusetts Institute of Technology.