The Global Water Cycle: An Integrated Research Plan

by

The Water Cycle Study Group*

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CHAPTER 1 -- RATIONALE

A global cycle with regional and local impacts

Water, and its cycling in the Earth system, is critical for both human populations and ecosystems. Projections of human demand and availability of fresh water suggest that we are approaching severe limits in the next 50 years. Water resources are utilized and managed primarily at the local scale, yet the water cycle processes responsible for sustaining and renewing them operate over scales as large as the globe. Fluctuations in these water cycle processes can induce severe weather and hydrologic extremes such as droughts and floods. These extremes have significant impacts on the economic infrastructure, human health and ecosystem integrity that are realized and responded to regionally and locally but are driven by global scale processes.

To date, our ability to assess variability in water resource availability and to predict and mitigate impacts of hydrologic extremes has been hampered by large uncertainties that result from our limited understanding of the global scale water cycle. For example, uncertainties in estimates of the water storage in, and fluxes among, the various reservoirs of the water cycle are associated with significant closure errors in the global water balance (Chahine, 1992). Closure errors in the estimated water balance are likely to increase in light of increases in water demand with increasing human populations and fluctuations in storage associated with future climate variability. Some researchers have suggested that global climate change may be accompanied by increasing frequency and intensity of hydrologic extremes (IPCC, 1996). Unfortunately, the general circulation models (GCMs) that are currently available to simulate coupled ocean-atmosphere effects on climate poorly simulate precipitation even when they accurately reproduce observed changes in atmospheric temperature, as has been demonstrated for simulations of recent El Nino and La Nina oscillations (Soden, 1999, 2000).

An integrated program of research devoted to improving scientific understanding of the water cycle at a broad spectrum of scales, including global, regional and local is essential. Particularly, our understanding must be sufficiently complete to permit a clear description of feedbacks among processes at a given scale, be it local, regional, or global, with other processes at different scales. Finally, our understanding of the water cycle must include explicit linkages to cycles of energy, carbon, and nutrients in the Earth system, to reduce uncertainties in estimates of water availability, water movement, and impacts on ecosystems. Improved understanding is also key to enhancing our ability to predict hydrologic extremes under both current conditions and those that might occur within the coming decades. The time is ripe to initiate such a program for the three reasons discussed below.

Recent human activities and climate variability have the potential to significantly perturb patterns and fluxes of the global water cycle.

Variability in hydrological processes occurs over a range of time and space scales. On the decadal time scale, the droughts of the 1930's (e.g. Earle, 1993) and 1950's in the western US are typical of several dry periods in the record of the past several centuries, with the late 1500's 20-year drought being the most severe of the past several centuries. On a seasonal time scale, runoff timing from snowmelt can be strongly affected by decadal changes in atmospheric circulation patterns (e.g. Dettinger and Cayan, 1995). There is evidence that precipitation is being delivered in more high-precipitation storms in recent years relative to earlier decades of the 20th century (e.g. Karl and Knight, 1998). Variability on even longer times scales also has been documented. Paleolimnological records indicate prolonged drought conditions in the tropics lasting 100 years or more as well as equally prolonged periods of very wet conditions (e.g. Street-Perrott, 1995).

Changes in land cover and land use have been enormous in the US and in the world. The world population has more than doubled since 1950 and is likely to increase by an additional 3 billion by 2050. These changes have local, regional, and even global effects on the hydrological cycle (e.g. Pielke et al., 1999). Changes in climate likewise influence the water cycle, with strong implications for water resources use (e.g. Lettenmaier and Sheer, 1991). Changes in the water cycle are also linked to changes in biogeochemical cycles (e.g. Aber, 1999) given that water is either the main transporting medium for such chemicals and/or directly impacts the processes producing and dissipating these chemicals.

We have limited capabilities to predict perturbations in the water cycle and to mitigate the resulting stresses on water resources, agriculture, and natural ecosystems.

Water management in the United States and other nations has traditionally focused on manipulating and safeguarding the supplies of freshwater to meet the needs of users. The effects of this "supply management" approach have been felt broadly across many sectors of the economy, from municipal water supply to irrigation. Increasing development costs, capital shortages, government fiscal restraint, less favorable storage reservoir sites, and increasing concern for the environment have forced water managers in the United States and elsewhere to begin to rethink traditional approaches to water management and to experiment with new ones. [USGS, http://water.usgs.gov/watuse/wutrends.html] The need for better water management strategies is particularly critical in developing countries where it has been estimated that existing systems may lose 40 to 60 percent of available water and where the poor are often left with costly water of very dubious quality (Crossette, 1999). It has been reported that global water use efficiency will have to double over the next 25 years if the world's food supply is to keep pace with population (ES&T 1999). As water resources are utilized more fully throughout the world, precise and reliable management tools become increasingly necessary.

The development and exploitation of new scientific methods and results have the potential to improve the efficiency of our management approaches, particularly if the scientific advancements are tuned to meet the needs of water, land-use, and natural resource management. The lead times for some alternatives for managing water resources (e.g. construction of irrigation facilities or desalinization plants) are long and the associated investments are large. Lead times for other alternatives, such as improved operating rules for reservoirs or regional conjunctive management of groundwater and surface water supplies, may be shorter, but also involve significant economic risk. Furthermore, there are numerous political and regulatory issues involved in implementing water management strategies. As water resource management addresses wetland, fishery, invasive species and other aquatic biota issues, improved integration of flow regime and biotic responses at a range of time scales will be required. In addition to improvements in assessing the quantity of the resource, techniques for assessing water quality, particularly widespread salinity problems, are a critical need. The potentially large impacts on both the environment and society must be assessed beforehand in the best possible ways. Uncertainties in the water cycle limit our capabilities to assess these impacts.

Recent land use changes are associated with rapidly changing human and ecosystem vulnerabilities to hydrological extremes. For example, more people now live in floodplains and in the paths of hurricanes and cyclones than at any time in history. The Mississippi floods of 1993, which resulted in tremendous economic losses throughout urban and agricultural areas of the Midwest, and the devastation to coastal areas caused by hurricanes Andrew and Floyd are but a few of the recent examples of this vulnerability. Planning for and mitigating effects of these hydrologic extremes requires significant improvements in predictive capabilities at annual, seasonal and shorter time scales. Our limited understanding of the linkages between the water cycle and other components of the global climate system is a major impediment to refining predictions on these time scales.

New and developing technologies for measuring, modeling and organizing data related to the Earth's water cycle, provide opportunities to gain a fuller understanding of water cycle processes to support improved management decisions

"Remotely sensed observations of land surface conditions from satellites and suborbital platforms (e.g., aircraft and balloons) provide synoptic high-resolution coverage that is unprecedented in the hydrological sciences. The new information available from remote sensing technology may initiate important shifts in the conceptual basis for hydrology." [Entekhabi et al. 1999] Examples of the burgeoning use of remotely sensed data abound. Improved rainfall estimates are being derived from ground-based radar and from satellite. The availability of remotely sensed data has been responsible for many of the advances in snow hydrology that allow prediction of basin response to the inputs of water, energy, and chemicals (e.g. Bales and Harrington, 1995). The use of surface and borehole geophysical methods has led to great improvements in our ability to characterize subsurface flow regimes. New developments in ground based instruments allow automated measurements in remote locations that could result in continuous records of hydrological parameters at a variety of locations and can be used to 'ground truth' remote sensing observations. Biotic parameters, including extent of riparian wetlands and in-stream algal and plant growth, may also be detected through remote sensing.

The continued development of data assimilation methods for use in hydrology (e.g. McLaughlin, 1995) will make hydrological data for variables and for locations available where they have not been heretofore.

Improvements in modeling have been addressed directly to problems of water management (e.g. Wagner, 1995). Significant progress has been made through well-managed programs to compare various models and to note how improvements might be made, for example, by calibration (Wood et al., 1998). The recent demonstration of predictability of seasonal anomalies superimposed on the noisy background of weather fluctuations (Shukla, 1998) and the recent success of forecasts related to the 1997-98 El Nino (Barnston et al., 1999; Mason et al., 1999) indicate that improved tools are becoming available that should allow scientific advances to be brought to bear on important societal problems.

Benefits and critical elements of an integrated water cycle science program

The emerging monitoring and modeling efforts, as well as new developments in these areas, should allow for rapid improvements in capabilities to predict water cycle variability and extremes over a variety of time and space scales. Better water-cycle measurement and prediction methods can lead to very large benefits for resource management and regional economies if variability and associated uncertainties can be understood, quantified and communicated effectively to decision-makers and the public. Advances in water-cycle predictive capabilities can be used to inform decisions related to land management and associated management of chemicals such as fertilizers and irrigation practices.

Understanding the global water cycle is also central to understanding the potential human, economic and ecological consequences of global environmental change. "Water is at the heart of both the causes and the effects of climate change. It is essential to establish rates of and possible changes in precipitation, evapotranspiration, and cloud water content… Better time series measurements are needed for water runoff, river flow and the quantities of water involved in various human uses" (NRC, 1998). Ascertaining the rate of cycling of water in the Earth system, and detecting possible changes, is a first-order problem as regards the issues of renewal of water resources and hydrologic hazards.

What is needed in a water cycle science program, however, goes beyond simply accelerating research that is currently underway. We need new ways of developing scientific understanding of water and its movement in the earth system, that are not constrained by the traditional disciplines – atmospheric, ocean, and hydrological sciences - that have structured our study of water problems to date. The future opportunities and challenges exist across the disciplines, and it is at the boundaries of the traditional disciplines where the new frontiers lie. For instance, hydrologists have extensively studied the mechanisms by which precipitation leads to the generation of runoff – but the integrated effects that lead to the dynamics of freshwater delivery to the oceans, and its space-time variability, are largely ignored, except in the crudest sense, by the oceanographic community. Likewise, hydrologists have interacted only to a limited extent with the atmospheric sciences community, which has as a central interest precipitation formation but generally is much less interested in the space-time variability that controls surface hydrological processes. Critical observational issues remain to be addressed. The "atmospheric rivers" by which water vapor is transported, and their sources and sinks, are quantified much more poorly than the terrestrial rivers studied by hydrologists. Storage and fluxes through subsurface groundwater reservoirs are even more difficult to quantify by direct measurements. A more balanced understanding of the fluxes, storage, and dynamics controlling movement of water in the land, atmosphere, and oceans will be the central challenge to the hydrological sciences in the 21st century.