CHAPTER 2
CAUSES OF WATER CYCLE VARIATION ON GLOBAL AND REGIONAL SCALES, AND HUMAN INFLUENCES

SYNOPSIS

Societal Need

- Understanding water cycle variability, and how it relates to water resource availability and water-related natural hazards

Scientific Gaps

- Adequate observations (and historic reconstructions) to quantify the variability of relevant water and energy cycle components
- Understanding underlying mechanisms and processes that control variability in the water cycle
- Modeling approaches that can reproduce observed water cycle variability at spatial and temporal scales relevant for water management
- Approaches to partition natural and human-caused variability in the water cycle

Proposed Actions

- An observation program using new and evolving technologies to characterize variability in the water cycle over a range of spatial and temporal scales
- A new commitment to field studies on uncertainties regarding water and energy cycle processes
- Concurrent with field studies, a model development initiative to develop models that can reproduce observed variability and help discriminate natural and anthropogenic sources of variability in the water cycle
- Development of an advanced data assimilation system and products to unify disparate observations, to reduce uncertainty in estimating water cycle variability
- Use of water and energy budget diagnostics to evaluate model performance and to characterize water cycle variability.

Background

Socially important water issues generally involve water cycle variability. This variability is evidenced, for example, in droughts, which can severely strain water and energy supplies, and floods, which are usually accompanied by infrastructure damage and sometimes by loss of life. The demands on finite water resources and potential damage from droughts and floods are increasing steadily with world population. Quantifying and understanding variations in the water cycle—and the extent to which humans can modify them or work around them—is thus becoming increasingly critical.

Any useful analysis of hydrological variability must consider a broad range of spatial scales. At the global scale, water transport is controlled by atmospheric circulation patterns, which are determined in part by ocean temperatures and evaporative fluxes. Land-ocean contrasts in these variables lead to the development of monsoons, which have a tremendous impact on the climates of many regions. At continental scales, precipitation at the land surface is balanced by evapotranspiration, surface and subsurface moisture storage, and streamflow. The quantification of streamflow flux and its dependence on complex continental geomorphology and land cover is critical in managing water resources over large areas. At regional and local scales, convective precipitation is influenced by the structure of the atmosphere near the land surface, the boundary layer, and thus by the nature of the land surface, which is subject to human modification. At these scales, soil, vegetation, geological, and topographic structures lead to unique streamflow and groundwater behavior.

Characterizing hydrological variability also requires considering multiple time scales. Variability at decadal and longer time scales is evidenced, for example, in the Pacific Decadal Oscillation[1] at decadal time scales, and in the paleoclimatic record at even longer (decadal to century) time scales. The El Niño phenomenon, which has significant hydrological impacts throughout the world, has a typical repeat interval of several years. Droughts occur over seasonal to interannual time scales, while individual precipitation events and the physical mechanisms that control them occur over time scales of minutes to hours. Superimposed on these modes of variability are slow "permanent" trends that may be caused in part by increasing concentrations of greenhouse gases and land cover change.

The multitude of relevant space and time scales and the complex ways in which they interact have limited past efforts to quantify the variability of the hydrological cycle. Quantifying variability at decadal and longer time scales is necessarily limited by the length of the instrumental record and the sparseness of useful paleoclimatic proxies. Even variability at shorter time scales is often not well known, owing to incomplete spatial coverage of in situ measurements and complications in interpreting available satellite data (see the section on Program Element 1 below in this chapter). Current measurements of water cycle components thus need to be enhanced spatially and maintained over time. Also, because logistical and economic constraints prevent the comprehensive measurement of water cycle variations, the enhanced measurements must by supplemented by better understanding of the physical mechanisms that control variability. Improved physical models that can better "fill in the gaps" of the measurement record, using techniques such as four-dimensional data assimilation (4DDA) could then be developed. Deficiencies in our current understanding of relevant physical processes is demonstrated by the disparities in model behavior seen in projects that compare different models, such as the Project for the Intercomparison of Landsurface Parameterization Schemes (PILPS) and the Atmospheric Model Intercomparison Project (AMIP) (see, e.g., Henderson-Sellers et al., 1993; Gates, 1992).

[1] Changes in sea surface temperature occurring on a decade time scale have been observed in the Pacific Ocean. These oscillations have been linked to other changes, for example temperatures in Alaska and streamflow in the Pacific Northwest.

Better process understanding and associated improvements in physical models should also lead to improved hydrological prediction, as discussed in Chapter 3, and to improved understanding of the coupling of water, carbon, and nitrogen cycles, as discussed in Chapter 4. In addition, improvements in physical process understanding and modeling are critical to distinguishing natural variability in the water cycle from human-induced variability. Only by understanding and modeling the relevant mechanisms can we establish, for example, whether CO_2-induced warming is likely to intensify the global hydrological cycle, leading to greater global mean precipitation and more frequent hydrological extremes.

A better picture of anthropogenic impacts on the global water cycle will eventually emerge only through a combination of better observations, process understanding, and modeling. Global-scale anthropogenic change may perhaps be best inferred by changes in selected indices, which may be composites of seemingly disparate quantities. For example, observed changes in basin runoff, global precipitation, groundwater levels, or large-scale water vapor transport may not individually be sufficient to imply causation by humans. However, geographical patterns of changes in these quantities, occurring together, may clearly point to human influence. Identification of such broad signatures, if they exist, will require significant interdisciplinary coordination. Once characteristic signatures of human activities on the water cycle are determined, they can be used to guide monitoring strategies and data recovery efforts.

In summary, society's needs for sustainable water supply and management, for control of natural hazards, and for sustainable aquatic environments all demand improved quantification of global water cycle variability and improved understanding and reliable modeling of the mechanisms that control it, including human activities. These research needs are captured in the three goals outlined below.

Goals

Goal 1: Quantify variability in the water cycle.

Why? Water is one of the most basic needs of human civilization. Manifestations of variability in the water cycle at the land surface, like floods and droughts, critically affect the way in which humans interact with their environments, and at the most basic level, the ability of populations to survive (Box 2.1). Nevertheless, many aspects of water cycle variability have never been adequately quantified. We do not yet have the data needed to address many water-related problems (both current and future) of fundamental importance to society.

How? Relevant information can emerge through new observation methods that show great promise for quantifying water cycle variability. Remote sensing will play an increasingly central role, particularly at global scales. Through these new methods and extensions of traditional methods, the monitoring of hydrological variability will be more comprehensive. Data assimilation and budget studies will be used to fill in observational gaps and to help quantify uncertainties.

Goal 2: Understand the mechanisms underlying variability in the water cycle.

Why? Our current understanding of water cycle variability and how it propagates through atmospheric, land, and oceanic domains is only in its infancy. Nevertheless, understanding this variability is critical. Regardless of advances in meeting Goal 1, logistical and economic considerations will limit water cycle measurement. Understanding the processes underlying water cycle variability will help in modeling them better, filling in gaps in the observational record through techniques like 4DDA. Moreover, understanding these underlying mechanisms will ultimately lead to better capacity for prediction (see Chapter 3) and to better understanding human interactions with the global water cycle, the overall goal of this science plan.

How? This goal can be pursued by devising a coherent strategy, built on a foundation of improved observations, that leads to greater understanding of causality. Central to this strategy are carefully designed process studies aimed at quantifying the relevance and rates of poorly understood processes, and a hierarchy of modeling systems (including coupled land-atmosphere-ocean models) that can reproduce the physical processes controlling water fluxes and storage in each domain.

Goal 3: Distinguish human-induced and natural variations in the water cycle.

Why? The global hydrological cycle is naturally highly variable. In addition to the natural patterns, humans may or may not be imparting an additional pattern. Widespread land use change or CO_2-induced warming, for example, may be driving the water cycle to a state it would not naturally attain. Identifying global and/or regional changes in the water cycle related to human activities is essential for guiding further actions.

How? Human influences can be determined by improving, through process studies, field campaigns, and other observational analyses, the ability of models to reproduce observed variability in the water cycle over a range of space and time scales. Through these models and additional observational studies, we must determine the signature of human activities on the water cycle. We must examine the observational record for evidence of this signature and establish new observational and modeling strategies to monitor human impacts into the future.

Program Elements

Five program elements—observations, process studies, modeling, 4DDA, and budget studies—provide the foundation to achieve the three goals outlined above. A sixth program element – knowledge transfer – is aimed at ensuring that the scientific advances are appropriately linked to programs that use the results to address operational issues in water resources. Some of the main connections among these elements, or "tools," and the three goals are indicated in Figure 2.1. Quantifying variability in the water cycle requires direct observations, data assimilation products, and budget studies. Identifying the underlying causes of variability requires detailed process studies and reliable modeling of the relevant physical processes. Physical models are essential for identifying human contributions to variability, where there are such human influences. Observations are critical for process studies; both process studies and observations can contribute to studies addressing human impacts. The scheme shown, while not all inclusive, shows some of the connections between the elements, such as the reliance of reanalysis (and data assimilation) on both modeling and observations. Each of the five program elements is now described in turn.

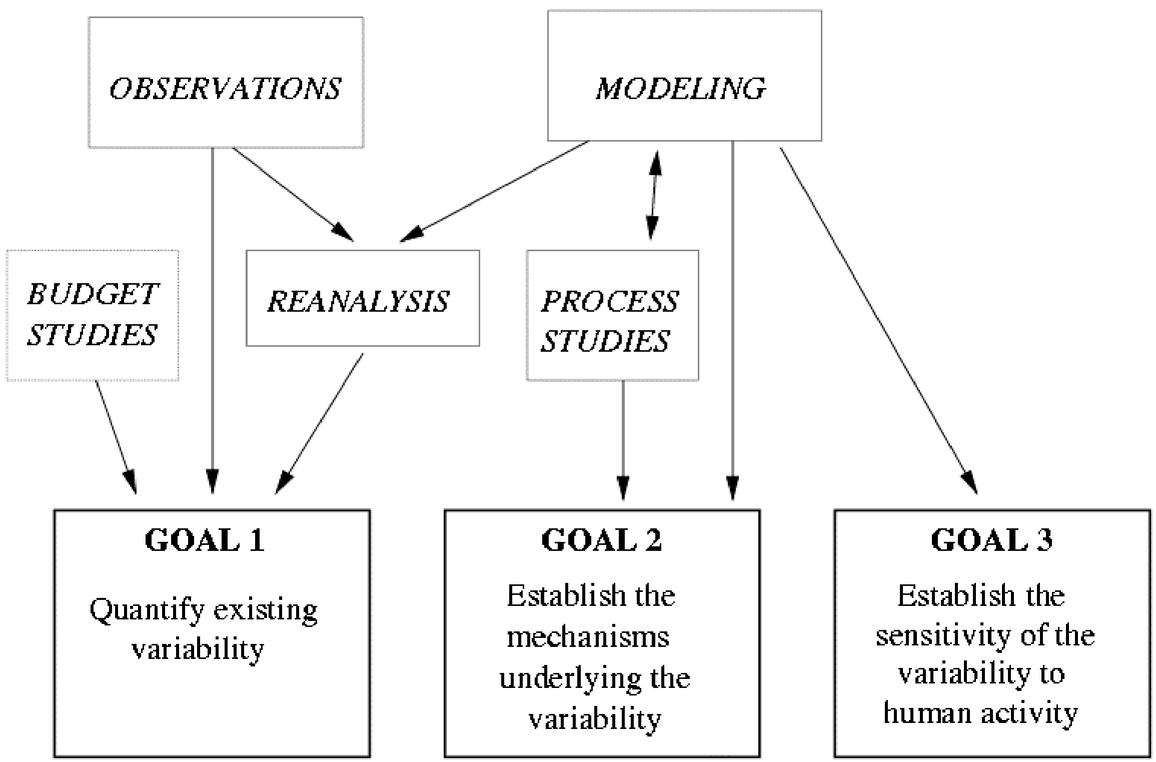


Figure 2.1: Some relationships among the five program elements and the three goals identified in the text (which together represent Science Question 1 identified in Chapter 1).

Program Element 1: Observations and Measurements

Water Vapor. Water vapor has been measured traditionally by balloon-borne radiosondes, which can also be used to measure wind. While these measurements have been the backbone of the atmospheric observation network, there are serious limitations to such water vapor measurements, especially in the upper troposphere. Limitations in the horizontal, vertical, and temporal resolution of the moisture fluxes, as well as in the accuracy of these measurements, are reflected in the difficulty of accurately estimating (1) the vertical distribution of water vapor, (2) the divergence of the wind field and related vertical motions along with the vertical distribution of the horizontal and vertical moisture fluxes, (3) the persistence and strength of transport by "jets" not resolved by the network, and (4) the full diurnal cycle of the moisture fluxes. Estimating water vapor convergence is especially problematic because of the considerable spatial variability of both wind and atmospheric humidity owing to a number of mesoscale phenomena. Most in situ observing systems cannot provide the measurement density to quantify water vapor convergence on anything but large (continental) scales.

[add acronym footnote here] Fortunately, there are a number of new initiatives and instruments being developed to overcome these deficiencies. Remote-sensing methods (e.g., wind profiler and doppler radar velocity data) can be used to characterize low-level jets and other significant features with high time and space resolution. The AIRS/AMSU/HSB sounder system on EOS-Aqua (to be launched in December 2000), will be followed by an operational instrument on the NPP "bridging mission" and NPOESS. Repeated semi-quantitative maps of atmospheric water vapor can be obtained at short time intervals from geostationary platforms such as GOES-8 satellites, and allow inferring both water vapor amount and advection. In addition, water vapor sensors placed on commercial aircraft offer the best prospects for systematically acquiring accurate reference humidity data in the upper troposphere. Finally, estimates of water vapor fluxes can be improved substantially through data assimilation.

Clouds. The distribution and optical properties of clouds determine the fraction of radiant energy flux that is reflected or emitted to space and the fraction that is absorbed in the atmosphere or at the surface. However, the physical processes that control water vapor distribution in the atmosphere are not understood sufficiently to know whether deep convection has a net moistening or drying effect on the upper troposphere and whether this unknown effect will have an important influence upon the radiation field. Observation-based estimates of atmospheric water transport are usually based on the assumption that condensation is negligible. Although this is a useful assumption for the lower tropospheric values and total column average, cloud water may be relatively more important in the upper troposphere. Thus, related knowledge may be critical in answering some of the outstanding global change questions, including whether and the extent to which water vapor provides any important positive feedback in greenhouse warming. Because of the strong dependence of cloudiness on weather systems dynamics and a multiplicity of microscale processes (down to the scale of condensation nuclei and aerosols), the goal of relating global cloud distribution and optical properties to basic physical processes has so far been elusive. Although some of the data needed to address these questions could be collected in intensive field campaigns, much of the relevant data at the global scale are already being collected by geostationary satellites. These data need to be better exploited in the future, in part by developing better databases of cloud properties.

Precipitation. Historically, estimates of precipitation over land have been based on interpolation of point measurements from rain gauges and snow measurements. However, this approach suffers from sampling errors associated with the sparse areal density of stations, particularly for convective rainfall. Additionally, systematic errors are associated with biases in the location of gauges (especially in areas of high topographic relief) and in the undercatch of precipitation by individual gauges, especially for solid or intense precipitation. The new network of WSR-88D radars (Klazura and Imy, 1993; Crum and Alberty, 1993) has the potential to improve precipitation estimates in the United States by vastly increasing the effective sampling density of precipitation. Ultimately, methods will be developed that optimally combine information from gauges and radars. An unanswered question is the value of radar-derived precipitation estimates for quantitative climatological studies. Precipitation estimates based on GOES satellite imagery (Hsu et al., 1996) have shown some promise in regions where radar and gauges are unavailable (e.g., mountainous areas). However, these estimates are usually not accurate enough for surface hydrologic prediction. Outside the United States, particularly in underdeveloped areas of the world, existing surface-based observations networks are grossly inadequate to characterize the spatial distribution of precipitation. Deficiencies of existing networks have become apparent in recent devastating floods in areas like Central America (Hurricane Mitch) and Africa (Mozambique floods).

Estimating precipitation over oceans is even more problematic. In situ measurements at island stations and on buoys are extremely sparse and may be biased (precipitation is usually enhanced by the presence of an island). Thus, considerable effort has been devoted to developing satellite-based remote-sensing methods. Infrared-based algorithms are primarily based on cloud-top temperature and are meaningful only in the case of deep penetrating convection (prevalent in the tropics). Microwave techniques are sensitive to the amount and distribution of precipitating ice particles and water drops present in the atmospheric column. The proposed Global Precipitation Mission (GPM) would provide 3-hourly, 4-km precipitation coverage over the globe between 55 degrees N and S and could be the cornerstone of global observations over both oceans and land.

Evaporation. Water vapor fluxes between Earth's surface and the atmosphere are not amenable to routine measurement on the global scale. Evaporation depends on stability and turbulent characteristics of the planetary boundary layer, and these are imperfectly known, even over the ocean. The most promising way to acquire reliable values of global evaporation over the oceans and continents is a focused research effort to improve formulation of boundary-layer turbulent fluxes in atmospheric circulation models, as applied to operational 4DDA systems, weather forecasts, and eventually climate models. It has been shown (Anthony Hollingsworth, private communication 1990) that even a relatively minor modification in the parameterization of ocean evaporation could materially change global precipitation climatology.

Over land, sparse networks of evaporation pans provide some estimates of potential evaporation, but corresponding estimates of actual evapotranspiration are limited by the complex controls imposed by soil water availability and vegetation (Box 2.2). As a result, current estimates of evapotranspiration are only weakly linked to observations. Some (e.g., Maurer et al. 1999 [OR 2000?]) have suggested that evaporation is better calculated as a residual from observed precipitation and atmospheric moisture convergence or from a high-resolution surface hydrologic model. Specialized equipment and technical expertise can, however, provide accurate evapotranspiration measurements at small spatial scales. Tower observations of surface latent heat flux, typically using eddy correlation or Bowen ratio approaches, and covering footprints of a few km^2 or less, have begun to evolve in the United States through the AmeriFlux network, in Europe through EuroFlux, and globally through Fluxnet. At present, the tower flux data resulting from intensive field campaigns that preceded the evolution of networks mentioned above (e.g., FIFE, the HAPEX campaigns, BOREAS, and others) have been used in various model evaluation and testing efforts. However, Fluxnet and related observations are not currently distributed or archived via global data exchange networks. Additionally, methods have not yet evolved to assimilate or otherwise use the data from flux networks for real-time (or retrospective, in the case of reanalysis) estimates of evapotranspiration fields.

Surface Runoff. Streamflow is an integrator of surface runoff, absent seepage or exfiltration from or to the river channel. Thus, aggregate runoff from a basin of any size can be estimated from stream discharge observations at gauging stations whose location defines an upstream drainage area. The USGS stream-gauging program routinely collects streamflow data for more than 7,000 stations in the country; and daily streamflow records totaling more than 400,000 station-years are held in USGS archives. Disaggregation of observed discharge into spatially distributed runoff within a gauge's drainage area requires additional information or modeling, for which no standard method currently exists. For this reason, water-balance analyses are most readily conducted at or above the length scale of gauged basins. Additionally, not all runoff leaves a river basin through the surface river network. Groundwater flux across the boundaries of small basins can be significant, and this possibility must be considered case by case. Interbasin transport of water via pipelines, irrigation ditches, and water supply channels can also be a significant term in local water budgets.

Outside the United States, particularly in less developed parts of the globe, runoff is more poorly characterized, even for large rivers. For this reason, there is considerable uncertainty in estimates of the total amount of freshwater leaving the continents. For instance, riverine discharge of freshwater to the Arctic is an important driver of the thermohaline circulation of the global oceans, which is believed to exert an important control on climate. Yet estimates of the long-term average discharge to the Arctic vary from 3,300 to 4,300 km^3 per year (Bowling et al., 2000). A proposed satellite altimetry mission (Vorosmarty et al., 1999) provides one option for a coherent global estimate of the discharge of large rivers

Groundwater. Groundwater flow divergence (that is, lateral flow) and changes in groundwater storage are not well observed globally. The location and density of groundwater monitoring wells is largely determined by management concerns. Groundwater fluxes and storage changes are currently considered only cursorily, if at all, by climate monitoring networks. Interpreting monitoring well data is greatly complicated by local effects, such as pumping, which makes determination of regional fluxes, and hence surface water balance, difficult. In some cases, water balances can be estimated over regions (e.g., large river basins) for which geologic considerations dictate that groundwater flow across the boundaries is likely minimal. Even in these cases, however, changes in groundwater storage can complicate interpretation of regional water budgets.

Current groundwater observation networks are unable to provide fundamental information about the amount and interannual variability of three critical fluxes. First, in systems ranging from large rivers to semi-arid riparian areas, groundwater-surface water interchange is not well characterized (and is largely ignored in the current generation of land-atmosphere models). Second, groundwater discharge to estuaries and oceans is largely unmeasured, even though some studies have shown it can account for a substantial fraction of net movement of freshwater from the continents to the oceans (Zekster and Loaiciga, 1993). Third, observation networks cannot discriminate among groundwater recharge mechanisms that may dominate over different time scales. For example, diffuse vadose-zone recharge in undeveloped arid and semi-arid zones may be important over decade-to-century periods, while on shorter time scales water fluxes may involve net upward flow, not recharge, because of vapor transport.

Soil Moisture. In contrast to groundwater, soil moisture lateral movement (hence divergence) can usually be ignored at large scales. However, temporal variations in soil moisture play a critical role in surface water balance. The surface hydrologic response—that is, partitioning of precipitation into direct runoff and infiltration—is largely determined by antecedent soil moisture. Soil moisture is a primary determinant of evaporative resistance as well. Compared to groundwater storage, soil moisture generally varies over much shorter time scales, typically at the scale of individual storms.

Like groundwater, soil moisture is poorly monitored by existing global networks. Direct observations are problematic, because soil moisture is strongly affected by soil characteristics that typically vary over spatial scales of meters. For this reason, in situ observation networks can only capture large-scale features of soil moisture storage (Vinnikov et al., 1999). New observation methods offer promise for better defining spatial variations in near-surface moisture storage. The feasibility of both passive and active (radar) monitoring of near-surface soil moisture has been examined extensively and demonstrated in field experiments like SGP97 and SGP99 (Jackson et al., 1999, 2000).

Snow. Observation networks exist to estimate snow water equivalent in mountainous areas, such as the western United States, where snow water storage is an important source of runoff in spring and summer. These networks are mostly restricted to high-elevation areas where a disproportionate amount of runoff originates. They are also designed more to provide an index of future runoff than aggregate measures of moisture storage. Over large areas, such as the plains of the north-central United States and Canada, snow depth is monitored throughout the winter and spring because of its implications for spring flooding and its effect on soil moisture in agricultural areas. This monitoring network is, however, quite sparse, especially in areas of low population density. Some success has been achieved in estimating snow extent using visible-band remote sensing (e.g., AVHRR and GOES are used by the NOAA Operational Hydrologic Remote Sensing Center in St.

Paul, Minnesota). Passive microwave sensors have been used to estimate water equivalent of snowpack over large areas, although these methods are limited to dry snow conditions and work best in areas, such as the plains, where vegetation cover is sparse. [fix up acronym soup here?] Improvements in the spatial resolution of passive microwave snow water estimates (currently about 25 km for products based on SSM/I) are expected with the AMSR imaging radiometer, to be launched on both the EOS-Aqua and Japanese ADEOS II satellites. However, neither the range of sensor frequencies nor other characteristics are specifically designed for the measurement of snow properties. NASA has included in its post-2002 plans an exploratory cold seasons/regions process observing mission aiming, among possible objectives, to yield higher resolution, global estimates of snow water storage.

Glaciers and Ice Caps. The small bodies of ice that make up the Earth's glaciers and ice caps have been undergoing significant recession, with measurable impacts on sea level, water resources, and ecosystems. Emerging space-based measurements offer the potential to track changes in glacial area. However, complementary ground-based measurement networks are limited, and ground-based measurements are needed to take full advantage of space-based information to estimate mass changes. A second critical need is for coordination of international measurements and data to assure the long-term viability of glacier measurements.

An international program, GLIMS (Global Land Ice Measurements from Space) was recently established to monitor the world's glaciers, primarily using data from Landsat and the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) instrument on EOS Terra. GLIMS aims to track snow areal extent, location of snow line at the end of the melt season, ice velocity field, and location of terminus of glaciers worldwide. Also planned is a network of centers around the world that will monitor the glaciers in their regions, and a database capable of storing and manipulating the data. GLIMS' targets consist of all permanent land ice except the "uniform" interiors of Antarctica and Greenland. The number of glaciers in the world is not well known. Two large digital inventories (World Glacier Monitoring Service (WGMS) and Eurasia at the National Snow and Ice Data Center (NSIDC)) have been combined and represent about 80,000 glaciers. These inventories include latitude, longitude, an estimate of glacier area, and for some glaciers, a large number of scalar parameters describing the size and condition of the glacier. Efforts like GLIMS will be essential to adequately monitor changes in water storage in glaciers and icesheets, which account for a substantial fraction of the world's reserves of freshwater.

Ice Sheets. Most of the Earth's freshwater resides in the two major ice sheets Greenland and Antarctica, and most of their volume lies above sea level. Thus, loss of only a small fraction of this volume could have a significant effect on sea level. Over the past century, sea level has risen 10 to 25 cm (IPCC, 1996), with the contribution from changes in the ice sheets highly uncertain due to very limited measurement networks that operate over the decade-to-century time frame.

The Greenland ice sheet spans an area of 1.75×10^6 km^2, nearly a quarter of the area of the continental United States. With a volume of 2.65 x 10^6 km^3, it contains enough water to raise current sea level by 7 m. In addition, because of its high albedo and large size, it plays an important role in the Arctic climate system, acting as a barrier to large-scale circulation, and also by affecting the system through its moisture, energy, and momentum exchanges with the atmosphere. The Antarctic ice sheet has an area of 12.1×10^6 km^2, a volume that would raise sea level about 70 m if the ice melted. Despite the importance of ice sheets in the climate system, information on the current state of their mass balance, as well as their behavior in a changing climate, is limited.

While space-based observations offer the best prospect for measuring the rate of ice-sheet-wide thickness change—that is, if the relevant programs are sustained for decades—new ground-based efforts are needed both to understand the causes of observed changes and to validate satellite measurements. NASA's Program for Arctic Regional Climate Assessment (PARCA), has focused on the water balance of Greenland since the mid-1990s, closely linked to the expected 2001 launch of an altimetry mission for measuring ice sheet elevations.

There are four main themes in this program: ice accumulation and ablation (loss), drainage glaciers, and ice shelves. First, shallow ice cores distributed over an ice sheet have proven to be absolutely essential and very cost-effective for establishing spatial ice accumulation in Greenland. A comparable program is needed in Antarctica, and periodic resurveys in Greenland are also needed. Aircraft radar surveys of shallow layers are needed to interpolate accumulation estimates between core measurements. Second, an expanded, long-term network of automatic weather stations is needed on both ice sheets to estimate ablation. In Greenland, there are currently only 20 stations in place, with about twice that number in Antarctica. Distributed meteorological data should be accompanied by intensive energy-balance studies and modeling. Third, intensive in situ and aircraft studies are needed of major drainage glaciers and ice streams to estimate losses from the ice sheets. The focus should be on areas that aircraft and satellite studies show to be changing rapidly. Fourth, in situ and modeling studies of ice shelf/ocean interactions are key to understanding ice shelf mass balance. Stability of the Antarctic ice shelves is sensitive to climate change. Measurements of atmosphere-ocean fluxes are needed in the ocean near and beneath the shelves, along with glaciological measurements of ice shelf mass balance.

Program Element 2: Process Studies

Water Vapor. An important source of error in climate predictions is the treatment of upper tropospheric water vapor. Although the amount of moisture in the upper troposphere is much lower than in the lower troposphere, it is known to have a strong influence on longwave radiation and thus on the atmospheric greenhouse effect. Few observations are available to constrain models, which as a result usually inadequately represent cumulus clouds, detrained cirrus, and appropriate upper tropospheric humidity fields. This deficiency results primarily from insufficient knowledge of clouds' effects on the environment, mainly because of our inability to resolve the microphysics of cloud systems in global climate models. This limitation will likely be alleviated by advances toward mesoscale-resolving global atmospheric models, advances made possible by rapid progress in supercomputer performance together with global climate models that have traditionally developed crude parameterizations based mainly on lower tropospheric observations. The latter limitation can only be overcome by a focused research effort based on a variety of tools. These include in situ field studies, global sampling projects based on active and passive observation from space (e.g., Cloudsat, PICASSO/CENA, and EOS-Aqua satellite observing program), and numerical experimentation with a hierarchy of cloud-resolving models (CRMs) as well as global climate models.

Understanding the couplings between large-scale atmospheric condensation, cloud formation and dissipation, and precipitation is critical. Some models have postulated clouds where there is precipitation, while others have attempted to parameterize clouds by surrounding relative humidity. Both these approaches fail to represent coupled cloud, water vapor, and precipitation processes. Field studies like FIRE, CAEMEX, and others have enabled progress in this area. But specially designed in situ field measurements are still needed to obtain the information required for better representing cloud processes in models.

Precipitation and Cloud Microphysics. One of the main sources of error in predicting precipitation owes to the inability of current atmospheric general circulation models to correctly reproduce the strength, development, and track of weather disturbances globally. This problem results in part from insufficient spatial resolution, which severely limits the resolution of topographic features and of the mesoscale structure of organized weather systems. Inadequate representation of microphysical and turbulent properties of cloud systems is another important source of precipitation prediction errors. The spatial resolution limitation should be alleviated by the ongoing trend toward mesoscale-resolving global atmospheric models, a trend made possible by rapid progress in supercomputer performance. The limitation caused by inadequate knowledge of cloud processescan only be overcome by a focused research effort based on a variety of tools, including in situ field studies, global sampling projects based on active and passive observation from space (e.g. Cloudsat, PICASSO/CENA, and EOS-Aqua satellite observing program) and numerical experimentation with a hierarchy of cloud-resolving models (CRMs).

Currently, models can at best predict aggregated properties of convective precipitation over the spatial scale of many storm cells. The inability of models to place precipitation at the correct location at the correct time (even while aggregated properties may be reasonably well predicted) has led to the use of observed precipitation rather than model-computed precipitation in land data assimilation systems (see the section below on Program Element 4). Analogous problems exist for mesoscale orographic (mountain-related) precipitation (Colle et al., 1999). These questions have important implications for understanding extreme precipitation events as well.

With respect to convective precipitation, there are two major gaps in understanding. The first is the role of surface fluxes in setting up convective instabilities. The second concerns the interactions that determine precipitation intensity once the instability is achieved. Regarding orographic precipitation, current understanding of cloud microphysics, as represented in orographic parameterizations, tends to overpredict the upslope precipitation maximum, particularly when the models are run at increasingly high resolution (e.g., down to a few kilometers). Furthermore, current models often do not predict the spatial extent of tropical systems well. Studies are needed that focus on cloud microphysics during intense convective and orographic events. Field studies like FIRE and CAEMEX have enabled progress in this area, but better in situ field measurements are needed, designed specifically to obtain the data required for better representing precipitation processes in models.

Land-Atmosphere Coupling. Over the last decade, a series of land-atmosphere intensive field experiments have been conducted, including FIFE, HAPEX-MOBILHY, BOREAS, HAPEX-Sahel, and the Large Scale Biosphere-Atmosphere Experiment (LBA) in the Amazon. These experiments typically consist of a series of intensive observation periods, embedded (at least in more recent experiments, like BOREAS and LBA) within an ongoing observation period of one or more years. They allow important improvements in parameterization of land surface and boundary layer processes in numerical weather prediction and climate models. Many key questions remain unanswered, however, and model evaluation projects like PILPS and GSWP have shown that observation programs must recognize the role of moisture storage in the land system (primarily as snow and soil moisture). This finding indicates that observation periods must include a strategy that extends over multiple annual cycles, while still observing surface and energy fluxes directly to the greatest extent possible.

These conditions pose important instrumentation, manpower, and financial challenges. Nonetheless, we believe that the time has come to initiate a new paradigm for land-atmosphere field campaigns. One such paradigm might be a set of global land-atmosphere validation sites, perhaps consisting of nested catchments up to a maximum scale at which atmospheric water budgets could reasonably be considered closed. (Some aspects of the CASES design might be considered in this respect). These field sites would contain certain semi-permanent instruments, including flux observations similar to those being carried out in the BERMS BOREAS follow-on. But particular attention would be given to the ability to close the surface and atmospheric energy balances over multiyear periods. Superimposed on the long-term observations might be a series of more intensive observing periods, like those in FIFE and BOREAS. A second important feature of these sites would be to provide validation data for EOS-era and beyond remote-sensing platforms. Clearly, such an activity could leverage other ongoing and planned surface flux observations (e.g., those of AmeriFlux, EuroFlux, and Fluxnet), and perhaps some of the observations being made at existing small research catchments. However, activities like PILPS have made clear that existing data sets and field programs are not sufficient to support better characterization of land surface and boundary layer processes.

Cold Season Processes. Cold land areas represent a major component of the Earth's hydrologic system. Over 60 percent of Northern Hemisphere land area (and 30 percent of total global land area) is snow-covered in mid-winter; and about 10 percent of the globe is permanently covered by snow and ice. Seasonal snow cover and glaciers store large amounts of freshwater and are therefore critical components of the land surface hydrologic cycle. Seasonal and permanent frost in soils reduce both infiltration into and migration of water through soils, and severely reduce the amount of water that can be stored in soils. By reducing infiltration, frozen soils can dramatically increase the runoff generated from melting snow. The importance of seasonally and permanently frozen land surfaces extends far beyond surface hydrologic processes, however. These areas also interact significantly with the global weather and climate system, the geosphere, and the biosphere. Whether surface water is liquid or frozen has important consequences for surface albedo and net radiation, as well as for latent energy exchanges. Betts et al. (1998), for example, found that because numerical weather prediction models do not correctly account for frozen surfaces, they tend to overestimate springtime latent energy fluxes, leading to forecast errors of up to 5° C in lower tropospheric temperatures. In seasonally frozen environments, vegetation growth seasons are determined primarily by the thawed period. In turn, the timing of spring thaw and the duration of the growing season are strongly linked to the carbon balance of seasonally frozen landscapes. Permanently frozen areas are also important components of global biogeochemical budgets.

Much remains unknown about the effects of cold season processes on land-atmosphere interactions. There is only cursory understanding of how the extent of snow and frozen ground affect weather and climate. Improved understanding of these linkages will require a combination of field campaigns to better understand related physical processes, and in turn to improve their representation in coupled land-atmosphere models, along with corresponding model advances.

Ocean-Land-Atmosphere Interactions. The most economically and socially significant droughts and (to a less extent) floods are those persisting for long periods over large areas. Such widespread and persistent events are associated with large-scale and persistent anomalies in the atmosphere's general circulation, which features dominant subcomponents such as the tropical Hadley and Walker circulations (including monsoons) and the subtropical, mid-latitude, and Arctic jet streams. These major circulation components and their seasonal cycles are a complex thermodynamic response to the seasonal march of the solar-driven distribution of surface heating across Earth's ocean and land surfaces. The resulting surface heating pattern represents a complex interaction among dynamic ocean currents, major land continents (size, shape, position), continental orography (mountains, plateaus), sea ice, and dynamically changing coverage of vegetation, soil moisture, and snowpack over land. This surface complexity gives rise to major, seasonally migrating, regional maxima and minima in sea surface temperature (SST), land surface temperature (LST), and sea surface and land surface evaporation. These in turn can lead to anomalies in major clusters of deep tropical convection, in such regions as Southeast Asia, central and northern South America, and central Africa. Departures in the seasonal progression, position, and intensity of these major centers of tropical deep convection are known to spawn persistent anomalies in the atmospheric general circulation that can lead to persistent droughts and large area flooding.

The onset and position of major clusters of deep tropical and subtropical convection are also influenced by other land surface phenomena, such as soil moisture, surface albedo, the extent and depth of snowpack in nearby regions of elevated terrain, and land use change (e.g., deforestation). Process studies are needed to document spatial and temporal correlations between land surface anomalies and convective rainfall, and to propose physical mechanisms for these correlations as suggested by observations and as confirmed in follow-on modeling studies.

The likelihood of human-induced global warming has highlighted the interactions among ocean, land, and atmosphere, especially concerning the different heat capacities of oceans (high) and land (low), and the atmospheric response to both. During the known warming trend of the 1980s and 1990s, the near-surface temperature change over land was amplified, especially in the Northern Hemisphere, while that over oceans was moderated. This cold-ocean/warm-land pattern of Northern Hemisphere winter temperature changes (the so-called COWL pattern) affects large-scale atmospheric circulation and the way in which the planetary waves therein set up relative to land-sea boundaries. The recent COWL pattern may be substantially attributed to the natural climate variability associated with the superposition of the North Atlantic Oscillation (NAO), the Pacific-North American (PNA) teleconnection pattern, and the El Niño Southern Oscillation (ENSO) (Hurrell, 1996).

Measurements of stable water isotope concentrations in precipitation can potentially provide unique information on the evaporative sources of water (e.g., ocean vs land), its prior phase transformations, and the nature of its transport through the atmosphere. Research is needed to improve the interpretation of water isotopes deposited in present-day and paleo precipitation in terms of climatic parameters.

The Land Surface as an Interface between Fast and Slow Climate Processes. The coupling of land, biosphere, atmosphere, and oceans has a wide range of characteristic time and space scales. For example, there are “slow” (e.g., deep groundwater and ocean) and “fast” (e.g., atmospheric water vapor and surface moisture) components in this system. Variability and memory in the global water cycle is due to both the cycling of water among reservoirs with various storage capacities and the development of feedback dynamics resulting from linkages among the reservoirs. Land memory, in particular, can significantly affect atmospheric variability and predictability, especially over the interior of the continents. Because the atmosphere is forcing the land surface, land memory feedback on this forcing can lead to greater persistence of anomalies. When appropriately and accurately represented in atmospheric forecast models, proper inclusion of land-surface processes in models may also lead to enhanced atmospheric predictability. Better understanding of the role of “fast” and “slow” processes is needed in several areas:

1. Relative contributions of local and remote forcing mechanisms to total variability of the coupled system(s) as related to storage in the component subsystems. The time-scales associated with reservoir size (surface and subsurface storage of moisture) depend in complex ways on both climate and geology. These connections need to be clarified if we are to develop a better understanding of connections among the landscape, hydrologic response, and the persistence of climate anomalies. Studies of surface and subsurface water budgets are needed to better describe the surface water-groundwater interactions that operate over these longer time scales.

2. The scaling properties of hydrologic variability as monitored or modeled at different spatial and temporal resolutions. Hydrologic states such as soil moisture and snow cover influence the surface flux of moisture and energy only under a limited set of conditions that depend on surface properties and atmospheric forcing. In some time scales (i.e., storm, inter-storm, and seasonal) and geographic regions, fluxes of moisture and energy are essentially independent of land surface moisture. There is a need to identify and investigate climatic regimes that prevent (or enhance) surface conditions from influencing fluxes into the lower boundary of the atmosphere. The seasonal cycle and interannual variability of each of these regimes need to be understood to predict variability in regional climates.

3. Local and regional feedback mechanisms. If positive feedback mechanisms are present in the coupled land-atmosphere system, an initial anomaly can persist through reinforcement.

Program Element 3: Modeling

As Figure 2.1 indicates, physically based global numerical models can contribute significantly to estimation of water cycle components and their variations (e.g., through four-dimensional assimilation of observational data). These models are also critical for assessing water cycle responses to human interventions. Improving the performance of these models is equivalent to decreasing the errors they generate in simulating observed hydrological fluxes, cloud distributions, water vapor transport, and other phenomena. Currently, these errors tend to be large, as shown by the PILPS and AMIP projects noted above.

Errors, of course, can migrate between different components of the modeled climate system. Consider as an example the coupling between land surface and the atmosphere. In nature, the variability of land surface hydrologic processes (e.g., stream discharge, groundwater recharge, or latent heat flux) is highly sensitive to the amount, intensity, form, and spatial distribution of precipitation. A coupled modeling system is subject to the same sensitivity. Thus, errors in simulated precipitation can lead to significant errors in simulated runoff, recharge, and evaporation.

Computational limits to model resolution clearly induce model error. When variability that lies at the heart of a process (e.g., variations in equivalent temperature that control convection) cannot be resolved explicitly, the effects of that variability on the process must be parameterized; and parameterizations of nonlinear processes are inherently imperfect. By running the models under increased spatial and temporal resolution, reliance on parameterizations should decrease, and errors should be reduced. Increased resolution requires increased computational power and the further development of numerical methods such as distributed computing, massively parallel computing, and semi-Lagrangian techniques.

Regardless of advances in computational technology, however, the resolution achievable in these models will never be high enough to capture all of the relevant hydrological variability. Thus, some reliance on parameterization is unavoidable. Improved parameterizations require an improved understanding of the physical mechanisms that underlie the processes modeled. In short, they require (1) detailed analyses of data generated in process studies and field experiments, and (2) bright, creative minds that can translate the results of these analyses into parametric representations that can efficiently and reliably reproduce the behavior of the more complicated system. The first requirement is addressed in the previous section. The second requirement implies a need for a well-supported program that encourages a variety of scientists to direct their attention toward the parameterization problem.

Further, success in modeling requires the adequate measurement of the physical properties or parameters used by the model to describe the system. In addition to addressing the hydrological fluxes and reservoirs as discussed under Program Element 1 above, then, detailed measurements of auxiliary data are also needed. Such data include, for example, soil texture and vegetation properties.

The evaluation of hydrological models against observations is of course critical, but it has been somewhat haphazard in the past. The machinery of the PILPS and AMIP validation components has been experiment-specific, so that participating modelers must often reformulate the packaging of their products several times. Support for the standardization of inputs and outputs in validation studies could simplify validation tests. A model test facility at a major existing center could further facilitate model development and validation, as could the development of enhanced physics evaluation strategies, such as single column models. Additional validation data sets are always needed.

All of these issues must be addressed to improve model performance. Note, however, that even a perfect model is useless unless it is applied effectively. Applying models to problems of societal relevance, such as identification of human signatures in the climate record, requires both careful design of relevant numerical experiments and proper interpretation of the experimental output—and neither is necessarily straightforward. Furthermore, disagreements in the findings of different modeling groups are highly likely. These disagreements must be quantified and fully understood for a consensus scientific opinion to emerge.

Program Element 4: Data Assimilation

The combination of short-term model predictions with observations, known as four-dimensional data assimilation (4DDA), is a critical element of our modern weather and climate prediction systems. No observational network could ever provide by itself the comprehensive gridded network of information needed to initialize a numerical weather prediction model or to develop a comprehensive geographic climate database. Analytic accuracy is continuing to improve as an increasing diversity of high-resolution observations from new in situ and remote-observing systems are incorporated. Accuracy also progresses as initialization techniques and the underlying models used for the analyses continue to improve. The first analyses were global. But regional data assimilation systems are now providing the improved analyses of atmospheric water and energy transports that are needed to better understand regional water cycling. These data products will facilitate analysis of water cycling at smaller spatial and temporal scales than has ever been achieved. Understanding the three-dimensional and diurnal structure of energy and water fluxes is critical for the continued development of atmospheric models at these and larger scales.

Assimilation of Atmospheric Water Vapor. Water vapor is now routinely assimilated from radiosonde observations. The primary source of assimilated data in practice is radiosonde profiles, although satellite-based humidity estimates are promising. With the advent of new water vapor sensors on many satellites, and many new ground-based systems, it is imperative that all relevant water vapor products be assimilated to develop high temporal and spatial resolution over all geographic regions. This will be especially important in areas where the radiosonde network is sparse, such as over oceans, much of Asia, and Southern Hemisphere continents.

By accommodating measurements of wind, data assimilation has the potential to develop high-resolution water vapor convergence values. In this case, the numerical model essentially acts as an interpolator, consistent with the constraints of model dynamics/thermodynamics. Cullather and Bromwich (2000) have shown that use of model analysis fields of net convergence for the Arctic basin provides much better estimates of atmospheric moisture balance than direct use of radiosonde profiles.

Land Data Assimilation. A Land Data Assimilation System (LDAS) is the land-surface/hydrological component of a coupled land-atmosphere model, structured so that it can be forced by either observed or model fields. The motivation for LDAS is to provide initial fields of land surface state variables (especially soil moisture) at the beginning of a coupled model forecast cycle. Gridded precipitation fields derived from observations are run on a parallel track with the coupled model, providing initial values for the forecast that are not corrupted by errors in the model’s precipitation analysis fields. As currently implemented at The National Centers for Environmental Prediction (NCEP), the gridded precipitation fields are provided by the so-called Stage IV product from WSR-88D radar; and solar radiation is derived from half-degree surface radiation fluxes inferred by the

National Environmental Satellite, Data, and Information Service (NESDIS) from operational GOES-8 satellite observations. Near-surface winds, humidity, and temperature data are currently taken from coupled model analysis, but they are candidates for replacement by observations in the future. The development and testing of LDAS is still a subject of ongoing research, but in the near future the LDAS state variables (soil moisture, skin temperature, snow water storage) and surface fluxes (evapotranspiration, surface sensible heat flux, and runoff) should prove to be more reliable than those generated by the existing assimilation schemes for the same surface variables. LDAS outputs can also be used to explore land surface climate scenarios available from GCMs. Eventually, LDAS schemes may also form a bridge from the land surface parameterization schemes used in numerical weather prediction models to operational hydrologic prediction schemes.

The evolving focus on assimilation of land surface variables into coupled land-atmosphere predictions should result in significant improvements in forecast accuracy and range. Snow water equivalent, for instance, is beginning to be assimilated, though soil moisture remains a problem. At present there is no observational database for soil moisture on a continental scale. Also unknown is how to assimilate subsurface temperature. Streamflow and precipitation measurements could provide additional information about how to update snow and soil moisture values as well as the atmospheric dynamical fields that implicitly depend on their values.

Precipitation. The GEWEX global precipitation climatology project (GPCP) has been providing global precipitation data for a number of years over both land and ocean (Xie and Arkin, 1996). An effective precipitation analysis that combines in situ observations with satellite estimates has been developed for large-scale climate models. High resolution can now be obtained over selected land regions like the United States. For example, national hourly precipitation analyses are now being developed. These analyses are based on the new WSR-88D radar-based precipitation estimates and hourly rain gauge observations, combined by a multisensor precipitation analysis algorithm. This algorithm was developed initially by the regional River Forecast Centers of the National Weather Service Office of Hydrology. Through the efforts of NCEP and the Office of Hydrology to develop centralized access to this information nationwide, the Hourly National Precipitation Analysis became available in real time on an experimental basis starting May 1996. This precipitation product is also being tested as a possible input to the Eta[2] model assimilation and is one of the bases for the new NCEP regional reanalysis.

Program Element 5: Water and Energy Budget Studies

To determine the net effect of water on climate, then the full cycle of evaporation, water vapor transport, cloud formation, precipitation, and runoff must be considered as an integral system. For example, on average, the amount of atmospheric water converged

[2] The Eta model is so named on the basis of the co-ordinate system it uses.

into a particular land region must be equal to the amount of water that streams send to the oceans. Budget studies emphasize this integral system approach by asking how accurately we can measure and simulate all components.

Early atmospheric moisture budget studies indicated that the amount of moisture convergence into particular regions did not equal the amount of streamflow out of the regions (Roads et al., 1994). Discrepancies were thought to be due to inadequate sampling by twice-daily radiosonde observations. Later budget studies emphasized analysis products, which showed that significant residual corrections were still needed to get the budgets to balance. These residual corrections were related to the tendency of analysis models to systematically move toward their own climatology. Since this systematic residual is not negligible, it provides a useful measure for evaluating the accuracy of an analysis.

Budget studies also provide a means to determine quantities that are not directly measured. For example, evaporation calculated from observed precipitation and the analysis of large-scale moisture convergence may be superior to evaporation calculated directly in models. Soil moisture variations, calculated from the differences between precipitation, evaporation, and runoff, may be superior to any in situ or remote-sensing measurement. Current budget studies are addressing even more subtle questions, such as how the budgets are changing over time on diurnal, seasonal, and interannual time scales, as well as how the corresponding energy budgets are affected by latent heat of evaporation and condensation.

Understanding how all of these water and energy components interact (i.e., getting the budgets right) on global, regional, and local scales is critical for improving climate predictions. Intensive studies within certain regions must be compared to budget studies in climatically different regions to obtain the needed understanding. Also, vertical distributions of water (in the atmosphere, surface, and subsurface) need to be better understood—budgets can be performed over vertical layers as well as over areas.

Finally, only a few studies so far have attempted to understand the role that water and its phase changes play in atmospheric energetics. However, there have been a substantial number of studies showing the importance of surface evaporation in determining surface temperature. Separating the effects of surface evaporation and surface net radiation is required to get a better handle on near-surface temperature prediction. Preliminary forecast methods have begun to take advantage of the influence of evaporation on surface radiation to develop monthly surface temperature forecasts.

Program Element 6: Knowledge Transfer

Developing and managing water resources depends critically on the understanding of the natural variability of water supply sources. For surface water supply management, the primary source to consider is usually streamflow, although for large lakes (e.g., the Great

Lakes and the Great Salt Lake), precipitation minus evaporation over the lake surface can be a major driver as well. For groundwater supply management, the needed understanding concerns the variability of recharge, which is related to infiltration less evapotranspiration extractions from the vadose zone. Notwithstanding the close relationships between water cycle variability and the design and management of water resource systems, the link between these applications and scientific advances has been tenuous at best. Most water resource systems are designed and managed using characterizations of water source variability based entirely on historical observations. For instance, almost all water managers characterize the natural variability of reservoir inflows by treating historic inflow sequences as equally likely to occur in the future. Sizing of many, if not most, reservoir systems is based on simulation of system performance with assumed future demands applied to a prescribed system format (e.g., number, size, and location of reservoirs) that itself is simulated with historic observations of streamflows. The implications of climate and land cover change, which would suggest nonstationarity in the inflow sequences (changes in time of the statistics of streamflow), is rarely considered. Likewise, and arguably more important over reservoir planning horizons, the effects of decadal-scale variations in climate, owing to phenomena like the Pacific Decadal Oscillation, are not considered. In the realm of prediction (considered in Chapter 3), streamflow forecasting methods that account for seasonal to interannual climatic variability (e.g., ENSO) are in their infancy.

While fault can easily be found with methods used in practice to characterize natural variability of land surface hydrologic processes, a gap has opened between science and applications. For instance, coupled land-atmosphere-ocean models represent the variability of precipitation and evapotranspiration, which are the key drivers of surface hydrologic processes. In principle, long simulations, or ensembles of simulations, with such models could be used to design and manage water resource systems. However, such models at present are nowhere near accurate enough for these purposes. Figure 2.2, for instance, shows the mean simulated seasonal hydrograph for the Columbia River at the Dalles based on hydrologic simulations forced with (precipitation and temperature) output from a regional climate model, compared with the output of the same hydrologic model forced by observed precipitation and temperature. The seasonal high flows (in June) based on climate model forcings are about double observed values, largely as a result of bias in the model-predicted precipitation. Nonetheless, approaches are evolving to deal with such bias issues, both for the short term, through statistical post-processors, and for the longer term, through improvements in model representation of moisture transport and precipitation algorithms.

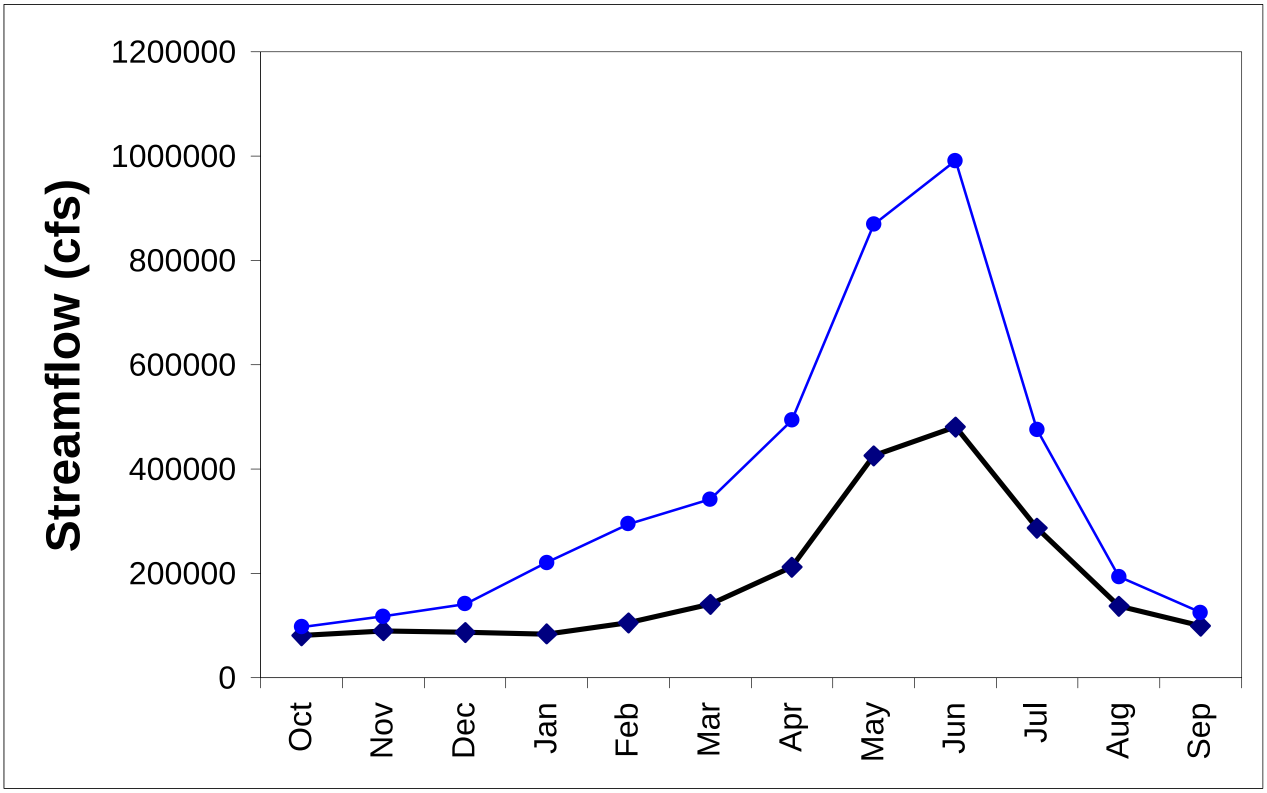


Figure 2.2. Simulated streamflow for Columbia River at the Dalles based on a hydrologic model forced with precipitation and temperature values predicted by a regional climate model output (blue line) and actual observations (black line). (Results provided courtesy of Alan Hamlet, Dept of Civil and Environmental Engineering, University of Washington. See Leung et al (1999) for study details.)

Water resource management is an obvious example of the value of connection between science and applications; many others could be cited. In general, the development of closer ties between water cycle science and applications would have potential advantages for both. Some of the benefits for applications have been mentioned above. Specifically, using methods tied more closely to scientific understanding of land-ocean-atmosphere interactions would reduce the necessity for assumptions, implicit or explicit, about statistical stationarity of historical observations. Moreover, uncertainties inherent in the length of historical records would be avoided, and a better means would exist to address situations for which observation records are short or nonexistent (the latter is often the case in developing parts of the world). From the standpoint of the science, a stronger tie to applications would create a higher standard for evaluation of model performance, which should accelerate model development and help to identify weak links in the science (as well as lead to better applications).

Initiatives

Observations

Water Vapor. Innovative measurements of water vapor, developed through field and remote-sensing experiments such as GVaP and ARM, should eventually be incorporated into standard measurement systems. Along with water vapor observations, improved estimates of wind are being developed (using wind profilers), so that water vapor fluxes and moisture convergence can be better estimated from observations and analyses. Water vapor fluxes will become better resolved and analyzed in intense low-level jets, near the diurnally varying boundary layer and in the upper troposphere. Increased observations over wider climatic ranges and wider elevations are needed to progress in characterizing time and space scales of water vapor. Estimates of water vapor fluxes can also be improved substantially through data assimilation (see the earlier section in this chapter on Program Element 4), especially in conjunction with new wind measurement systems and new regional analysis systems.

Clouds. NASA has already made a major investment in cloud and radiation process research with the preparation of a three-satellite constellation for active and passive remote sensing of cloud/aerosol distribution and optical properties (Cloudsat, PICASSO/CENA, and EOS-Aqua). Considerable improvements in physical understanding and model representation (parameterization) are expected from this effort by 2005. In addition, the ongoing Tropical Rainfall Measurement Mission (TRMM) precipitation radar is already providing accurate and very detailed three-dimensional data on convective cloud systems, data that can eventually lead to much improved representation of rain-producing processes in atmospheric circulation models. Unique new observations provided globally by experimental satellite missions such as TRMM, as well as Cloudsat and PICASSO/CENA, would provide new insight in cloud microphysics and three-dimensional structure.

A coordinated system should be developed to process existing archived cloud data (cloud top temperature, optical thickness, area coverage, etc.) derived from geostationary satellites at a spatial resolution of 5 to10 km and a temporal resolution of half an hour. The primary use would be analysis of cloud system dynamics. In particular, understanding the moistening effect of clouds, as well as cloud ensemble subsidence drying, would begin in earnest once adequate data sets were available to understand cloud ensemble properties and upper tropospheric moisture distributions.

Precipitation. Within the United States, the WSR-88D radar system is superior to rain gauge networks for monitoring the space-time structure of heavy rainfall, even though many problems need to be resolved in estimating rain rate from these radars (NRC GEWEX Panel, 1999). However, the accuracy of NEXRAD and satellite estimates is ultimately limited by the gauge observations used in their calibration, and the radar data record is short. Therefore the gauge network remains the backbone of the precipitation observation system, especially for climatological applications. The instrumentation technology, especially on-site data-recording and transmission facilities (if any) are badly antiquated in NOAA's Cooperative Observer Network, which is the primary climate observation system for precipitation and temperature. Additionally, electronic compilation of relevant meta-data (histories of gauge type, exposure, site climate), which is needed for gauge bias adjustments, is incomplete. Current precipitation data sets need to be extended in space and time to maximize the value of existing historical observation records. Because precipitation variations are intimately linked to soil moisture and runoff variations, new high-resolution gridded precipitation analyses will be critical for developing better large-scale understanding of the global hydrologic cycle.

On a global scale, the proposed international Global Precipitation Mission (GPM) would provide about 3-hour revisit intervals between +/- 55 degrees latitude, and would represent a huge advance in spatial and temporal resolution and extent over existing station-based global archives. Recognizing that precipitation is the most important variable for characterizing the global water cycle and that it is the least well predicted variable at all scales, the climate and hydrologic research communities are strongly supportive of this mission. Remote sensing of frozen precipitation by satellite sensors is still problematic; but the two-frequency microwave precipitation radar that would be built by Japan for GPM may provide a new source of information on surface snow cover.

Evaporation and Energy Fluxes. Existing surface flux networks, like AmeriFlux, should be expanded to include more sites, and to provide a complete suite of surface heat and radiative fluxes and hydrologic state variables (including soil moisture) sufficient to close the local energy balance. Consideration should be given to establishing a rotating sub-network to expand the range of land cover types and hydroclimatic conditions represented. SURFRAD-like capability should be provided at or near all permanent surface flux sites. The number of permanently located sites within the continental United States might be about 100, with a similar number of rotating sites. Evaporation over the ocean also needs to be monitored on a regular basis, instead of in limited field experiments.

Unlike water vapor, precipitation, and clouds, evaporation and other surface energy fluxes are too expensive to measure everywhere. A concerted effort to simulate evaporation correctly at specific sites over land and oceans needs to be undertaken. Intercomparison of models, with the limited numbers of sites available, needs special attention because models will ultimately provide the best global-scale evaporation estimates.

Surface Runoff. A global capability needs to be developed to estimate, in near–real time, the discharge of major rivers at their mouths and at key points within the continents. This could be achieved by the Hydrologic Altimetry Satellite (HYDRA-SAT), for which planning is currently underway. Within the United States, a program for stream gauge support specifically directed toward hydrologic research activities, like development and testing of HYDRA-SAT, should be implemented. This activity should leverage existing USGS stream gauging and related research programs, which need to be strengthened to have a stronger link to water-related climate research.

Groundwater. A regional-scale network of sites should be developed to simultaneously monitor surface meteorology, soil moisture, and groundwater levels. Remote-sensing data to support identification of recharge and discharge areas, as well as geologic conditions, should also be obtained. The sites would support development and validation of numerical models of groundwater flow and transport.

Soil Moisture. New observation methods offer promise for better defining variations in subsurface moisture storage. Soil moisture near the surface strongly affects the dielectric properties of soil, and hence the emission and backscatter of microwave radiation. The feasibility of both passive and active (radar) monitoring of soil moisture has been examined extensively. For both cases, observation is limited by the depth of penetration of microwave radiation, usually on the order of the wavelength used. There is therefore a challenging tradeoff among antenna size, horizontal resolution, and the ability to penetrate vegetation and the top-most soil layer. The consensus is now that the L band (about 20 cm wavelength) represents the best tradeoff for passive measurements and probably would be best for active systems as well. At L-band, a vegetation threshold of about 5 kg biomass/m^2 can be penetrated, which corresponds to grasslands, most croplands, and shrublands, but would exclude most forested areas. As part of its post-2002 planning process, NASA has identified a potential experimental demonstration mission for soil moisture measurement, aiming to provide about 10-km spatial resolution and 2- to 3-day repeat cycle. The antenna technology to support such a mission is not yet in hand, but a 10-year development horizon appears plausible. The European Space Agency has approved in principle an experimental Soil Moisture and Ocean Salinity measuring mission (SMOS) that would provide about 50-km spatial resolution with a 3-day repeat cycle, on a shorter development schedule than the proposed NASA mission.

Snow and Cold Processes. Improved spatial resolution of passive microwave snow water estimates (currently about 25 km for products based on SSM/I) is expected with the AMSR imaging radiometer, to be launched on both the EOS-Aqua and Japanese ADEOS II satellites. However, neither the range of sensor frequencies nor other characteristics are specifically designed to measure snow properties. NASA has included in its post-2002 plans an exploratory cold seasons/regions process observing mission. One objective, among possible objectives, is to yield higher resolution, global estimates of snow water storage. Improved seasonally and regionally specific algorithms could be developed for extracting snow water equivalent (SWE) from microwave brightness temperatures. In support of these remote-sensing efforts, an initiative should be undertaken to develop a research-quality data set of the climatology of snow properties over North America. This effort should integrate in situ, microwave, and visible snow measurements. Weekly in situ measurements of SWE should be obtained at selected manual weather observing stations in the United States during periods of snow cover.

In areas such as the western United States, where most of the snow occurs in mountain areas, approaches combining the higher resolution of visible/infrared remote sensing, together with an adequate ground-based network, are needed. The existing network of

SNOTEL and snow-course measurements needs to be augmented with a network specifically designed to obtain spatially representative point measurements of SWE.

A cooperative effort addressing glacier monitoring has already been established (see “Glaciers and Ice Caps” under the section for Program Element 1). The primary need is to bring sufficient resources to this program to achieve its measurement and other science goals.

With regard to ice sheets, four main areas require attention. First, a new program is needed for shallow ice coring for ice-sheet accumulation estimates, accompanied by an aircraft program for aircraft radar sounding and modeling. The second need is for an expanded network of automatic weather stations in the Arctic and Antarctic. The third is for studies on drainage glaciers and ice streams. Finally, the fourth is for studies of ice-shelf/ocean interactions.

Process Studies

Water Vapor. Initiatives such as the GEWEX and ARM water vapor experiments should include field campaigns over relevant global regions to characterize water vapor and cloud distribution, especially in the upper troposphere. In addition to using state-of-the-art water vapor measurements, these experiments should be carried out in conjunction with mesoscale models and especially global to regional climate models. Climate models do not currently have useful observations for modeling upper tropospheric cloud and water vapor. These variables are thought to be important in determining climate model sensitivity to increased greenhouse gasses.

Precipitation and Cloud Microphysics. The primary thrust of an initiative on precipitation and cloud microphysics should be to improve the predictability of precipitation in three important situations: (1) convective precipitation over land, (2) orographic precipitation, and (3) monsoonal systems.

The main elements would include—

- An intensive field campaign (probably over the central United States in summer) designed to characterize deep convective precipitation over land.
- An initiative to improve prediction of orographic precipitation. This activity that would include both a continuing observation network and one or more intensive field campaigns. These would be supported by ground-based observations designed to define spatial distribution of precipitation in mountainous areas within at least two climatological regions, probably including continental and coastal maritime regions.
- An intensive field campaign designed to characterize precipitation associated with monsoonal systems. The design would be somewhat similar to that of the first field campaign described above, but would be implemented over a considerably larger area and over a time frame of about 2 months.

Although the field components of the initiative in precipitation predictability will vary, they will in general consist of a combination of boundary layer observations, aircraft observations during precipitating events, upward-looking surface measurements, and synoptic scale information (which could come largely from existing sources)—all coordinated with satellite observations (e.g., CloudSat and PICASSO). The field experiments should be accompanied by advanced numerical experiments to untangle some of the uncertainties in current modeling schemes. In a sense, this effort could be posed as a "computational design problem" for cloud-resolving models. These experiments would have additional benefits in providing better parameterizations for larger scale (e.g., global) models.

Land-Atmosphere Field Experiments. A set of global land hydrology validation sites (probably at least 10) should be implemented, at which continuing observations of surface moisture and energy fluxes would be collected. Also, subsurface moisture data (for saturated and unsaturated zones) should be collected over closed catchments large enough to allow closure of the surface water budget. These continuing observations could be supplemented by periodic rotating field campaigns, which would integrate surface, aircraft, and satellite observations.

Cold Season Field Experiments. The proposed cold season initiative includes retrospective data analysis over a range of spatial scales (subcontinental, continental, global), and model experiments to help isolate the linkages among components of the water cycle. The initiative would also include field experiments, with a focus on spatial scales that influence the role of cold season process on moisture storage at the land surface and on larger scale land-atmosphere interactions. These interactions concern the effects, for instance, of snow presence/absence on albedo, of frozen surface processes on land-atmosphere turbulent energy transfer, and of riverine runoff on the circulation of large water bodies like the Arctic Ocean.

A combination of intense field campaigns and continuing observations should be implemented to define the spatial variability of snow properties. The master design would integrate continuing data collection with periodic intensive field campaigns, oriented to key snow characteristics, such as new snow, rain on snow, and refreeze. These field campaigns would include a combination of in situ, aircraft, and satellite remote-sensing observations.

Ocean-Land-Atmosphere Interactions. A primary effort in the area of ocean-land-atmosphere interactions must be to achieve better understanding of the phenomena that give rise to major departures in the behavior of centers of deep tropical convection. These phenomena therefore lead to persistent anomalies in global circulation, moisture transport, and hence large area droughts and floods. The World Climate Research Program (WCRP) and its subprograms, CLIVAR, GEWEX, and ACSYS have promoted a comprehensive climate system research strategy aimed at better understanding the interactive role of the land, atmosphere, and ocean in the movement of water globally. Several supporting efforts, like the Global Ocean Observing System (GOOS), and the Global Ocean Data

Assimilation Experiment (GODAE), are making important contributions, but the U.S. contributions have generally been uncoordinated. There is a need for enhanced global ocean observations, combining satellite remote sensing and long-term deployment of arrays of ocean buoys or subsurface floats, which would enable documenting, modeling, and, eventually, predicting the life cycle of global climate variability modes. Such efforts, while not the province of the Global Water Cycle Initiative alone, must be closely coordinated; they have strong implications for improved understanding of the global water cycle. It is especially important that the studies of these dynamic processes address changes in heat and water fluxes between the surface and the global atmosphere.

We therefore propose a set of field experiments and modeling programs that would identify and quantify connections among oceanic, land, and atmospheric processes. These field experiments would be integrated with planned regional studies like VAMOS that address, among other things, (1) the connection between the low-level jet (LLJ) in South America and tropical Atlantic SSTs, (2) the hydroclimatology of the Rio de la Plata Basin and its connections with the LLJ and the South Atlantic Convergence Zone, and (3) the impact of land processes on the formation of marine stratocumulus clouds. This initiative would go beyond these regional studies, however, to devise a set of coordinated field, remote-sensing, and modeling experiments designed to better understand the role of regional anomalies in global water transport, particularly persistent deviations in global moisture transport that lead to extreme droughts and large area flooding.

Land Surface as Interface between Fast and Slow Processes. Much of the work needed to understand the effects of land in modulating land-ocean-atmosphere interactions involves modeling studies, which is the primary thrust of this initiative. However, supporting field activities are needed in several areas, mostly to provide observations at multiple temporal scales to isolate the effects of fast and slow processes. This work will require that enhanced field campaigns like those outlined above (see the previous page on "Land-Atmosphere Field Experiments") include a multiyear component, in which large-scale surface conditions, surface fluxes, and atmospheric variables would be observed as in past campaigns like FIFE and BOREAS; but they would be supplemented with simultaneous observations of the slower components of the land system, like groundwater levels and other subsurface moisture stores.

Models

Fellowship and Exchange Programs. Fellowship and exchange programs should be developed to foster the involvement of scientists at all levels (including students) in developing and improving coupled land-atmosphere models.

Model Testing Facilities. Model testing facilities should be established at existing weather and climate prediction centers (like NCEP), which would be charged with facilitating model evaluation and transfer of methods from the research to the operational modeling community. These facilities would promote standardized flux couplers and interfaces, standardized archiving, and other technical innovations (like visualization and parallel software structures) that would enhance the ability to use center models and data streams for model development.

Improvements in Land Surface and Atmospheric Models. A next generation of land-atmosphere models would better represent precipitation processes, as well as land surface characteristics (groundwater, snowpack, ice sheets, lakes, dynamic vegetation, and convection). Emphasis should be placed on innovative development and evaluation strategies, like the use of single-column models, cloud-resolving models, and direct eddy simulation.

Model Evaluation Programs. Model evaluation programs like AMIP, GLASS, PILPS, GSWP, and their extensions should be supported.

Enhanced Numerical Methods. A major initiative should be undertaken to increase the computational efficiency, and thereby the model resolution, of coupled land-atmosphere models.

Coordinated Modeling Studies. The improved models stemming from the above initiatives should be evaluated through a set of coordinated modeling studies, to be undertaken in parallel by multiple groups. These studies would be designed to—

- Further our understanding of complex coupled hydrological systems (e.g., through analysis of process study data)
- Establish the sensitivity of the hydrological cycle to the full range of human activity, so that current signatures of human activity in the observational record can be identified, and society has the information needed to avert potential hydrological disasters associated with new activities.

The modeling groups would share data and analysis responsibilities to increase the potential for scientific consensus.

Four-Dimensional Data Assimilation (4DDA)

Atmospheric Data Assimilation. Historically, data assimilation has focused on the atmospheric states of temperature, mass or pressure, and winds. Typically, the "water" components of humidity, clouds, and precipitation were given relatively little attention, because observations of these components were sparser. However, new satellite sensors (e.g., SSM/I, AMSU, and TRMM) have changed this situation. GEWEX and USWRP research programs have highlighted the four-dimensional assimilation of water vapor, cloud water, and precipitation as central thrusts of their atmospheric 4DDA activities. A water-focused 4DDA initiative should be undertaken through collaborative partnerships between these programs and their supporting agencies (NASA, NOAA, NSF, DOE), in their water-focused field experiments and intensive observing programs, and in their model-based 4DDA computational centers and infrastructure. A critical obstacle to improving model predictions of the global water cycle is a deficiency in the current ability to represent the atmospheric energy balance. Model predictions can be improved through assimilation of satellite radiance observations of upwelling earth-surface emissivity in various spectral bands. Over oceans, the primary requirement is sea surface temperature (SST). Over land (and sea ice), the surface emissivity problem is more difficult and challenging, because the forward models for land surface emissivity require knowing many land-surface states simultaneously, including surface skin temperature, soil moisture, vegetation density and greenness, soil type, dew, and snowpack characteristics. Nonetheless, observations of some of these variables are available, and should be incorporated into the proposed next-generation data assimilation initiative.

Land Data Assimilation. Progress in land data assimilation (soil moisture and temperature, snowpack, vegetation density and greenness) is lagging behind its atmosphere and ocean counterparts and must be accelerated. A new component of GEWEX known as GLASS (Global Land Atmosphere System) has been launched with major thrusts in land data assimilation. The Water Cycle Study should promote GLASS. One existing vehicle for this thrust is a new U.S. multiagency initiative known as the Land Data Assimilation System or LDAS. LDAS is a NOAA and NASA funded partnership among NCEP, NASA/GSFC, NWS/OH, NESDIS and university partners to demonstrate, first, a national land data assimilation prototype, and then, a global land data assimilation system. The Water Cycle Initiative should encourage other agencies and universities to participate in LDAS. Snowpack and high-latitude glaciers are acknowledged critical reservoirs of freshwater; and their evolution and variability play crucial roles in the variability of the global water and energy cycle. LDAS and similar activities should be expanded to include a focus on data representing these land cover conditions, especially through remote sensing.

Ocean Data Assimilation. Quantifying the magnitude, distribution, and variability of ocean surface fluxes of water, heat, and momentum over the globe is a fundamental component of the Water Cycle Study. Thus, ocean data assimilation initiatives are important counterparts of atmospheric and land data assimilation. Support of and participation in the emerging international Global Ocean Data Assimilation Experiment (GODAE) should be promoted. Satellite remote sensing is clearly a central component of ocean data assimilation. Additionally, initiatives to expand existing arrays of fixed and drifting ocean buoys, including some fixed buoys with a lower atmosphere profiling capability, should be supported. The latter are needed to increase our understanding of the atmospheric boundary layer over the ocean surface.

Sea Ice Assimilation. Satellite remote sensing of sea ice cover with both passive microwave and active radar sensors is revolutionizing the data assimilation of sea ice. NOAA, NASA, and DOD have extensive sea ice analysis initiatives. To complement the advances in sea ice cover remote sensing, initiatives are needed to improve the three-dimensional (depth) representation of sea ice through data assimilation that advances physical thermodynamic and hydrodynamic sea ice models.

Global and Regional Reanalysis. A powerful and relatively new tool for examining, quantifying, and understanding the global water cycle is long-term retrospective global and regional 4DDA. Retrospective 4DDA is referred to as "reanalysis," denoting the reexecution of a fixed configuration of a state-of-the-art global or regional 4DDA system from the beginning of viable geophysical observational databases (e.g., around 1950). Reanalysis is an important component of the Water Cycle Study strategy (Figure 2.1). To date, global 4DDA spanning one to five decades has been carried out by NCEP (with NCAR), NASA/DAO, and ECMWF. Next-generation reanalyses should focus on increased spatial resolution; incorporation of more comprehensive data sets on atmospheric water vapor, especially in the satellite era; incorporation of land surface observations where available, such as snow cover extent; and better representation of land surface processes using state-or-the-art land surface schemes.

Budget Studies

Evaluation of Observed Budgets. A continuing effort to use observations to close water budgets is critical. These studies form the background and observations needed for model budgets. New data sets geared specifically for budget studies need to be developed. These include gridded (or equivalent) observations of streamflow, naturalized streamflow and observed streamflow over continental domains, gridded high-resolution precipitation data, and so on. Development of continental- to global-scale hydrometeorological data sets should be strongly encouraged.

Evaluation of Analysis Budgets. Because analysis budgets provide the main link between models and observations, they should be rigorously tested against all observations, especially hydrometeorological observations developed to cover wide space and time scales. As this comparison takes place, improved reanalysis models will need to be developed. Besides evaluating reanalysis models against available observations, by evaluating budget terms, the model's drift can be diagnosed. This drift is nonnegligible, since all models have different budget balances than those in nature when started with observed values. Only after long integrations will the model adjust to negligible drift, at the expense of then having errors in all hydrologic terms. Reducing the importance of the tendency term in analysis models will provide increased confidence in our ability to model and eventually predict features that have poor observations (e.g., continental evaporation), though all hydrometeorological terms suffer from poor observations owing to the wide variety of space and time scales that need to be resolved.

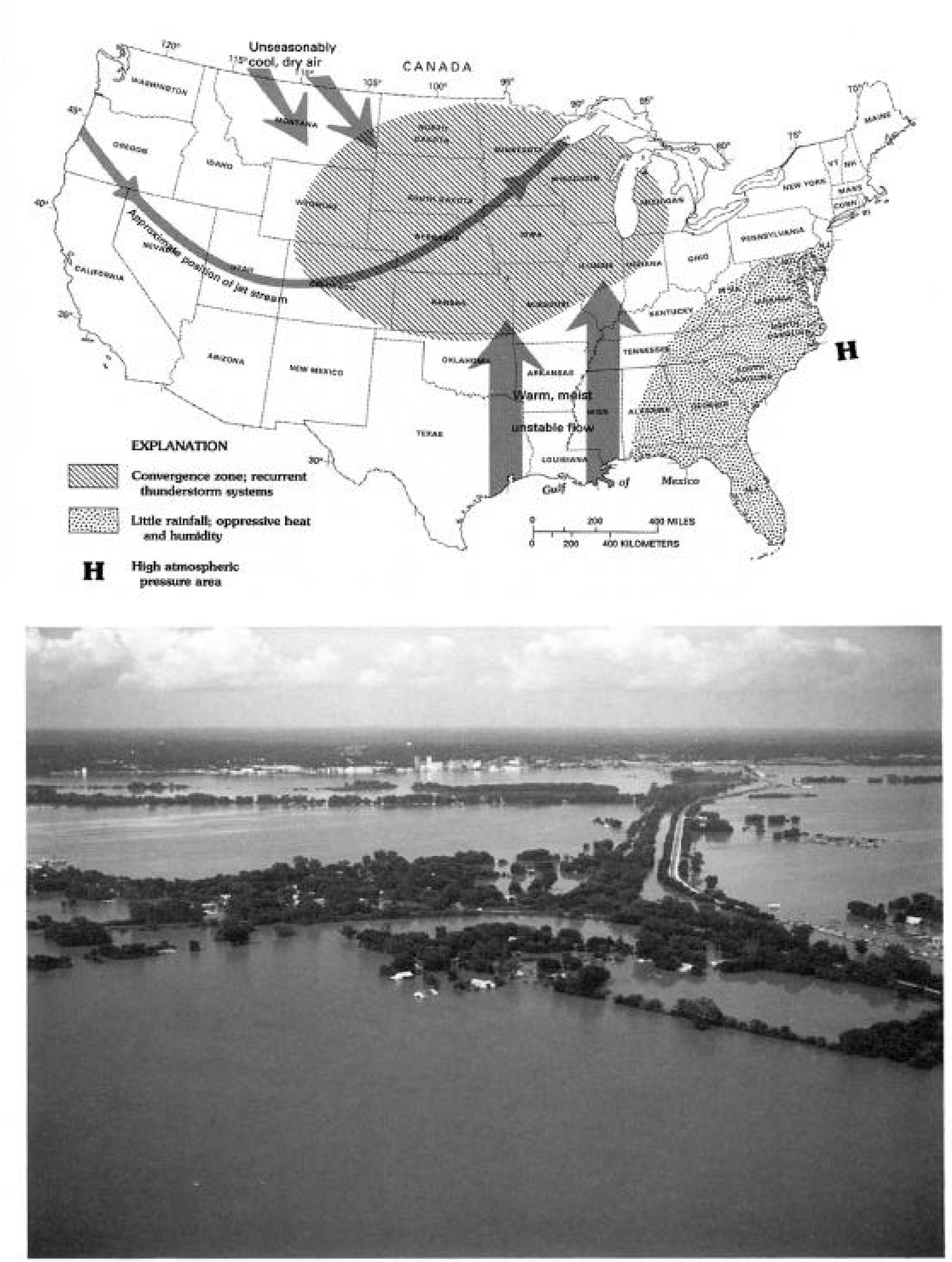
Evaluation of Global and Regional Model Budget Structures. Most budget studies to date have emphasized vertically integrated water budgets. Efforts to understand how water is partitioned between the lower and upper atmosphere, and upper and lower soil moisture levels and snow, are all needed to eventually develop accurate predictive capability. New budget studies covering snow accumulation, melt, runoff, and evaporation of snow from continental regions are needed to understand how snow contributes to the water cycle. New budget studies showing how release of latent heat by condensation and cooling by evaporation affect the energy cycle are needed to better understand the role of water in driving the general circulation.

Knowledge Transfer. The knowledge transfer initiative should be designed to develop estimates of the natural variability of surface hydrological processes that can be incorporated into water resource systems design and management, with reduced dependence on historical observations. This achievement might be reached through a cooperative applications program, which would be a joint activity of the lead science agencies involved in the process studies and modeling initiatives discussed in the last few pages, along with universities, and federal (e.g., U.S. Army Corps of Engineers and U.S. Bureau of Reclamation) and local agencies with planning and management responsibilities. The applications initiative would be funded and managed by one or more of the science agencies, with funding directed toward demonstration applications of new methods to estimate natural variability and their incorporation in operational water resources planning and management. Past experience has indicated that successful demonstration programs require that funding be provided for dedicated personnel to work in an operational setting, with dedicated support separate from operational responsibilities. This arrangement might be possible through a fellowship system that assigned personnel on a part-time rotating basis to a government research laboratory or university, and part-time to a government agency or university. The lead agency or agencies would solicit proposals requiring evidence of participation from both a credible science-based organization and an operational agency.

Efforts should go beyond the water resources community, and include regional decision makers and resource managers for whom climate and hydrological information can make an impact. Research is also needed on the demand for, use, value, and means of presenting and delivering new climate and hydrologic information. This research must be done regionally, to achieve a clear understanding of what information is needed for regional decision making.

Box 2.1. 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



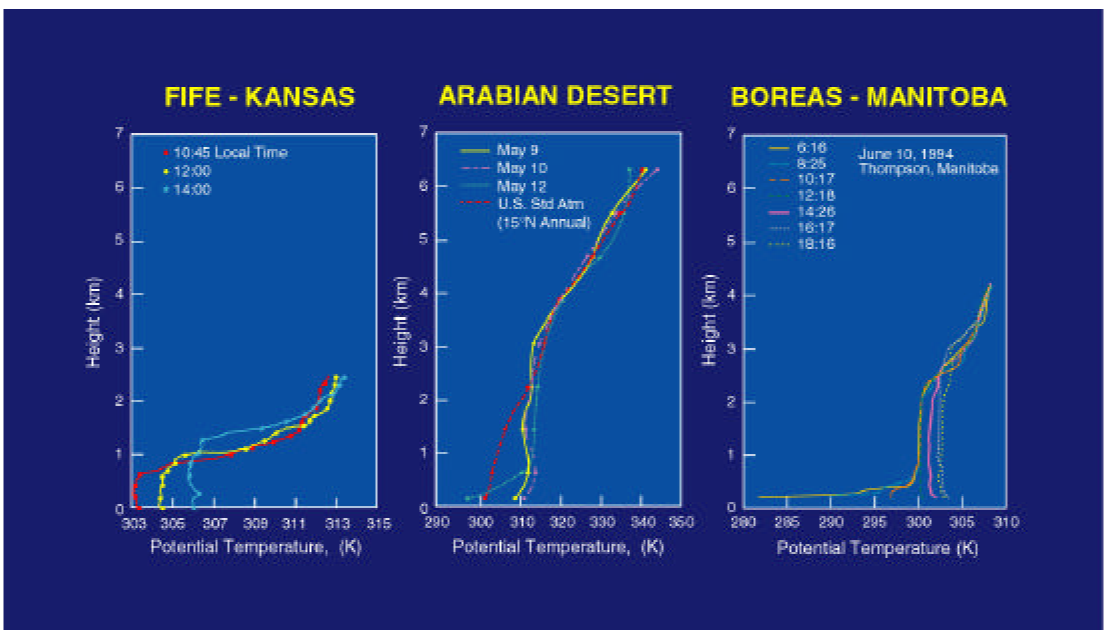
Dominant weather patterns over the United States for June-July 1993 (top panel) and flooding near West Alton, Illinois, during July 1993 (bottom panel) (USGS, 1993).

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.

Box 2.2. The "green desert"

The Boreal Ecoystem-Atmosphere Study (BOREAS) was a large-scale interdisciplinary field experiment conducted in Canada's northern boreal forests between 1994 and 1996, under the sponsorship of Canadian (primarily the Canadian Space Agency and Atmospheric Environment Service) and U.S (primarily NASA) agencies. It consisted of intensive observation periods of several weeks' duration, as well as longer term observations over spatial scales ranging from about 1 km to about 1,000 km. Surface, aircraft, and remote-sensing observations were all used to assess interactions of the boreal forests with the atmosphere. One of BOREAS's key findings was that even in the middle of the growing season evapotranspiration rates are quite low. As shown by the figure, one effect is that atmospheric boundary layers are surprisingly deep and turbulent during the growing season, a condition that is more typical of a lower latitude arid zone than would be expected in an area of plentiful water. The observed low evapotranspiration is explained in part by the nutrient-poor environment, to which the boreal forest has adapted through low photosynthetic rates. Another factor, most important in the spring, is that high sensible heat fluxes are caused by late thawing of the soil, which suppresses transpiration. Further, in wetland areas, the canopy intercepts almost all of the available energy, so that wet soil and moss-covered surfaces play only a minor role in the surface energy balance, even though they have plentiful moisture. The observed deep boundary layers under conditions of ample surface moisture are not properly represented in most numerical weather prediction models, and was identified by the European Centre for Medium-Range Weather Forecasts as one reason for their model's overestimation of precipitation and cloudiness over the boreal region during the growing season. These modeling biases have now largely been corrected through model improvements stemming from BOREAS.



Potential temperature profiles for May and June 1994: Kansas grasslands (FIFE site; left panel), Arabian Desert (center), and BOREAS site, Manitoba (right panel). The BOREAS profile much more closely resembles that of the Arabian Desert than that of the FIFE site [Figure courtesy of Forrest Hall, NASA/GSFC].