GCIP

Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project

A REVIEW OF PROGRESS AND OPPORTUNITIES

Global Energy and Water Cycle Experiment (GEWEX) Panel
Climate Research Committee
Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources
National Research Council

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Cover: Saarinen's Gateway Arch (1965) on the banks of the Mississippi River at the Jefferson National Expansion Memorial Park in St. Louis, Missouri, commemorates the westward expansion of the United States after Thomas Jefferson's purchase of the Louisiana Territory (1803) from Napoleon. St. Louis, a crossroads for the early French, British, and Spanish empires in North America, was a focal point for Mississippi River trade and a principal marshaling ground for the pioneer wagon trains setting out to the West on the Santa Fe and Oregon trails. The artist, Grace Roads (b. 1921), met her husband, Paul, in St. Louis (1944). They now reside in Lafayette, Colorado, part of the original Louisiana country comprising all the lands draining into the Mississippi—claimed in 1682 by René-Robert Cavelier, Sieur de La Salle, in the name of King Louis XIV. Mrs. Roads is the mother of John Roads, a member of the GEWEX panel.

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Foreword

The very nature of weather and climate demands an international perspective and a comprehensive research approach. For more than a decade, the World Climate Research Program (WCRP) has provided the context and vision for international collaboration directed toward the study of the key areas of uncertainty in our understanding of the climate system. Our efforts to understand climate variability and to predict future climate change have highlighted many aspects of the hydrologic cycle and the exchange of energy and water at the atmosphere–surface interface as areas of critically needed study. In response to this need, the international partners of the WCRP developed GEWEX (Global Energy and Water Experiment) as a major focus of international study.

The objectives of GEWEX are challenging, particularly since the nature of water and energy exchange at the atmosphere–land surface is so dependent on a wide variety of geographic factors.

No single comprehensive regional experiment can yield sufficient information to describe and characterize water and energy budgets. For this reason, the GEWEX effort to join atmospheric and hydrologic sciences is based on a research strategy that includes a number of regional studies across the world. The Continental-Scale International Project (GCIP), which has as its objective the characterization of water and energy cycling in the Mississippi Basin, is one of the major GEWEX regional study areas. GCIP focuses on understanding annual, interannual, and spatial variability, the development and evaluation of regional coupled hydrologic/atmospheric models, the development of data assimilation schemes, and the development of accessible, comprehensive data bases. Improved water resource management on seasonal to interannual time scales is a key GCIP goal.

The United States provides scientific expertise, leadership, and resources to ensure that WCRP research programs continue to be some of the most successful research programs in the earth sciences. In the case of GCIP, a major international study within the boundaries of North America, U.S. vision and commitment are essential. In achieving GCIP objectives, we improve our ability to predict future climate change and variability globally, while substantially improving our ability to assess the nature of climate and hydrologic variability within the U.S. Thus, our contributions have international significance while being of immense practical importance to our nation. We can expect GCIP to yield a number of clear, practical accomplishments in addition to improved capability to manage water and water resources. GCIP objectives specifically address the requirements needed to improve regional predictions. Regional predictions are of critical importance in assessing the impacts of climate variability and climate change. This report of the Global Energy and Water Cycle Experiment (GEWEX) Panel provides both leadership and vision by clearly reviewing our progress to date and by describing the opportunities for future progress.

Eric J. Barron
Co-chair Board on Atmospheric Sciences and Climate

Preface

A review of the Global Energy and Water Cycle Experiment (GEWEX) Continental Scale International Project (GCIP) is provided in this report. The concept of GCIP was conceived in 1990 as the United States' contribution to the overall scientific strategy of the World Climate Research Programme (WCRP) and GEWEX. As the first of the five Continental Scale Experiments (CSE), GCIP was established to quantitatively determine the hydrologic cycle and energy fluxes of the Mississippi River basin. The other continental-scale experiments will have similar objectives but for different geographic regions. The development and evaluation of coupled hydrologic-atmospheric models at resolutions appropriate to large-scale continental basins are critical to the successful achievement of the GCIP goal. The resulting coupled models will assist scientists and engineers in testing scenarios and making predictions which are more relevant at scales useful for water resources management, including drought and flood risk assessments.

Our review of the GCIP program shows that, while a great deal of progress has been made, the linking of hydrologic processes at different temporal and spatial scales remains a complex problem. It is encouraging to observe that both the atmospheric and hydrologic communities further recognize that an interdisciplinary approach and joint cooperation are required to ensure progress in developing advanced schemes which represent the hydrologic cycle in coupled models. Additional progress will also require improvement in the use of available measurement technologies for precipitation, surface radiation fluxes, wind and humidity, and soil moisture. A number of remote-sensing observation programs being planned by the international community and scheduled for launch in the first decade of the new millennium [i.e., NASA's Earth Observing Satellites

(EOS)] will greatly enhance the opportunity for progress in this area. However, realization of the full potential of these new measurements will require planning and cooperation among scientists and agencies. Participation by NASA, NOAA, NSF, and USGS is particularly important.

It is imperative that GCIP's scientific contributions not be viewed in a purely disciplinary context, because GCIP was intended primarily to be an interdisciplinary program. The GEWEX Panel realizes that there are many other critical and high-priority, single-discipline hydrologic and atmospheric problems which are not addressed under the GCIP research program. For example, improvements in cloud-resolving models and modeling of rainfall-runoff processes are but two of such critical problems. Further progress in rainfall-runoff models, for instance, is critical for accurate catchment-scale flood prediction and water resources management purposes. GCIP researchers must be ready to apply these advances when they become available. In addition, initial reports from a series of climate assessment workshops being held throughout the United States indicate that interdisciplinary studies directed at water resources are one of the primary needs in most regions of the country. Therefore, improvements of operational hydrologic and water resources management tools are critical in helping to bring global and GCIP/GEWEX-scale climate predictions down to a scale important for addressing local and regional water resources issues. The directions outlined in this report will assist agencies in implementing efforts toward meeting these critical needs.

Finally, on behalf of all panel members I wish to acknowledge the contributions of many colleagues during the course of this review: S. Benjamin, E. Berbery, R. Carbone, H. Gupta, B. Imam, Z. Janjic, R. Lawford, J. Leese, D. Lettenmaier, K. Mitchell, M. Moncrieff, E. Rasmusson, H. Ritchie, J. Schaake, D.-J. Seo, J. Shuttleworth, E. Wood, and Q. Zhao. I would also like to offer special acknowledgment on behalf of the GEWEX panel to the following staff of the National Research Council: William Sprigg, Frank Eden, Peter Schultz, and Kelly Norsingle.

Soroosh Sorooshian
Chair, GEWEX Panel

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Wilfried Brutsaert, Cornell University, Ithaca, New York
Thomas Dunne, University of California, Santa Barbara
William L. Fisher, University of Texas, Austin
Efi Foufoula-Georgiou, University of Minnesota, Minneapolis
James Hurrell, National Center for Atmospheric Research, Boulder, Colorado
Jan Paegle, University of Utah, Salt Lake City

The report was also reviewed by one reviewer who preferred to remain anonymous. While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

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The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

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Executive Summary

The Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP), formulated in 1990 by the World Climate Research Programme, is a joint effort of atmospheric scientists and hydrologists to develop data sets, models, and a research framework to understand land-atmosphere interactions on climatic time scales (i.e., seasonal, annual) in the Mississippi River basin. The overall goal of the GCIP is to demonstrate skill in predicting changes in water resources on time scales up to seasonal and annual, as an integral part of the climate system.

The National Research Council's (NRC's) GEWEX Panel was asked to evaluate the proposed research strategy for GCIP and to suggest revisions to the overall program, particularly the U.S.-based effort. The panel began this study by assessing the objectives of GCIP in the context of its overall goal. Based on this review, the panel recommends the following objectives for GCIP:

1. Determine and explain the annual, interannual, and spatial variability of the water and energy cycles within the Mississippi River basin.
2. Develop and evaluate coupled hydrologic-atmospheric models at resolutions appropriate to large-scale continental basins.
3. Develop and evaluate atmospheric, land, and coupled data assimilation schemes that incorporate both remote and in situ observations.
4. Provide access to comprehensive in situ, remote sensing, and model output data sets for use in GCIP research and as a benchmark for future studies.
5. Improve the utility of hydrologic predictions for water resources management up to seasonal and interannual time scales.

These five objectives are modified slightly from GCIP's previous objectives (GCIP, 1993). The panel based this review on the modified objectives.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

Substantial progress has been made toward GCIP's objective of characterizing the variability of water and energy cycling in the Mississippi basin. Further progress will require increased care in the estimation of such critical variables as precipitation and surface radiative fluxes. Improvements in the use of available measurements could markedly enhance the value of GCIP. Rigorous investigations of local and remote forcing of hydroclimatic anomalies are needed to satisfy the objective of explaining the observed variations of the water and energy cycles in the Mississippi River basin.

Some of the most advanced regional-scale models in the world are being developed by GCIP. Parameterizations in these models, including clouds, precipitation, and radiation require special attention, however. Large-scale hydrologic modules also have to be included in these models. Systematic comparisons, such as those being carried out by the Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS) over parts of the Mississippi basin are important for understanding model biases. High-resolution modeling studies—for example, of how the land surface affects the Great Plains low-level jet—are also important because many important features of low-level jets are not easily observed with the current sparse observational network.

GCIP is developing a comprehensive set of regional analysis archives from three regional data assimilation systems (Eta, Mesoscale Analysis and Prediction System, Regional Finite Element). These regional archives are likely to be highly model dependent, however, and must be compared with each other as well as with global analyses and field observations. Surface products will be one of the most innovative and potentially most problematic regional analysis outputs. These surface products have to be compared to outputs from hydrologic models, especially Land Data Assimilation Systems (LDASs), which are just beginning and require special attention. Finally, given all the scientific developments that will occur in the development of analysis methods for these surface variables as well as atmospheric variables, including longwave radiation and precipitation observations, it is important that GCIP begin to plan for an eventual reanalysis of GCIP projects.

GCIP's data collection and management effort has done a commendable job of beginning the initial data acquisition and archiving. It now has to add a scientific users group to identify data sets of highest priority to GCIP researchers. The scientific users group should recommend methods for the efficient archiving and reprocessing of high-volume Next-Generation Weather Radar (NEXRAD) data for climatological precipitation estimates. Methods to archive and access research data, especially remote sensing data sets created by individual GCIP scientists, also have to be developed.

GCIP's research focus on hydrology is primarily geared toward addressing atmosphere-land-surface interactions. The panel recognizes, however, that there are many other important hydrologic issues not covered under the purview of GCIP's research—such as surface and subsurface interactions—that are critical for an "end-to-end" approach to the hydrology of the Mississippi River basin. Furthermore, although GCIP's primary goal has been identified as demonstrating skill in predicting changes in water resources on various time scales, GCIP is not directly involved in the development of any new water resources management models. It is anticipated that GCIP's observational and modeling efforts will enhance the "front-end" modeling tools used for water resources management purposes. At the present time, the panel believes that the increased involvement of some additional key agencies is needed. These agencies could address some of the hydrologic and water resources issues that are not the main focus of GCIP but are critical nonetheless to GCIP's overall goals. Fostering an interactive dialogue between GCIP and the water resources management community to formulate research priorities currently not addressed by GCIP is critical to the program's success. The panel recognizes that many of the crucial hydrologic research questions have been identified in the NRC report *Opportunities in the Hydrologic Sciences* (NRC, 1991) and that much of this research would be of great benefit to GCIP and any future large-scale hydrologic studies.

MAJOR RECOMMENDATIONS

GCIP is the first international project to bring together the hydrologic and meteorological science communities for a common research goal. This cooperation has already been beneficial to both communities and is the basis for the initial success of GCIP. Thus, the panel's primary recommendation is that GCIP should **stay the course** and continue with the implementation of its scientific research plans. In addition, the panel recommends that GCIP focus its efforts in the following areas:

- Develop accurate quantitative precipitation estimates based on high-resolution weather radar observations.
- Develop improved large-scale estimates of soil moisture consistent with large-scale estimates of precipitation, evaporation, and runoff.
- Further improve the coupling between atmospheric and land surface hydrologic models.
- Develop and apply coupled land data assimilation systems.
- Prepare data archives to facilitate future reanalyses.
- Foster active dialogue between GCIP and the water management community.

From a wider national perspective, GCIP does not address hydroclimatic phenomena that are characteristic of the semiarid U.S. Southwest, a region where the availability of water is a critical resource issue as well as a challenging scientific problem. Applying the methodologies and technical facilities developed for GCIP to a study of the Colorado River basin and surrounding mountain regions is a challenge for the future.

GCIP accomplishments include the following: (1) the most comprehensive accounting to date of atmospheric and surface water and energy budgets on a continental scale; (2) the advancement of land surface parameterizations and atmospheric models incorporating hydrologic principles; (3) the development of new regional land surface data assimilation methods using new high-resolution precipitation observations; (4) the development of a comprehensive GCIP data set that will be a basic support for twenty-first century developments in remote sensing and data assimilation; and (5) a new paradigm for water resources management utilizing new operational weather prediction analyses and forecasts. When fully implemented, GCIP can be expected to strengthen our nation's capability for climate prediction and water resource management. It will provide a sound basis for hydroclimatological research at the beginning of the twenty-first century.

Introduction

Demonstrate skill in predicting changes in water resources on time scales up to seasonal and annual as an integral part of the climate system.

During the past century, many anomalous climatic events have disrupted American lives. Persistent Great Plains droughts, such as those of the 1930s and the recent one in 1988, ruined Midwest crops and farmland. The Mississippi floods of 1927 and 1993 and the Northwest floods of 1996-1997 were equally devastating. Even larger regional climatic variations may occur in the future, especially if the global climate is seriously influenced by the rise in greenhouse gases, as models and some observations indicate (IPCC, 1996b). To what extent are such events predictable? Do we have the capability to predict future water resources under present or modified climate conditions? The benefits of accurately predicting regional climatic variations over seasons and longer time periods are so great (NRC, 1995) that the scientific community is now strongly motivated to meet the challenge of developing a real-time prediction capability on climatic time and space scales. However, both the application and the eventual utility of seasonal to interannual climate predictions also depend upon the ability to translate general circulation forecasts into significant hydrological information relevant to water resources management, agriculture, and forestry for specific regions.

A number of scientific questions must be resolved to develop such a prediction capability. Do we adequately understand the mechanisms that underpin natural hydrologic variations in our climate system? Is it possible to predict these variations accurately at seasonal and longer time scales? How do hydrologic and energy cycles vary over the United States, and how will they change in the near and long-term future? Water and energy budgets are understood qualitatively but are not known quantitatively on regional or even continental scales, partly because of deficiencies in available observations and partly because of a lack of accurate models.

However, more than qualitative information is needed for application to the management of water and other natural resources. Precipitation events occur over a range of spatial scales, from small afternoon showers to synoptic-scale storms that develop within the planetary circulation. The heterogeneous land surface integrates these transient precipitation events over longer periods, so that streamflows tend to vary on daily to weekly time scales, depending on the size of the drainage basin. Except for short-term recharge events, the characteristic time scale of soil moisture fluctuations is weeks to months. The feedback between the components of the hydrological system and the recycling of water in the atmosphere generates variability on similar time scales. Observing, understanding, and modeling these processes through the full range of spatial and temporal scales are essential for developing long-range predictive capability for the water and energy cycles.

Scientists recognize that such regional variations are part of the natural variability and/or change of the global climate system. GEWEX, an international research program to study fast climate processes in the atmosphere and at the Earth's surface, approaches the problem of climate variability from a global perspective. The GEWEX research strategy aims to study and parameterize generic processes representative of global climate. The GEWEX Continental-Scale International Project and comparable studies in other regions of the world (see Appendix A) constitute an apparent departure from this global outlook, motivated by the need to find a common ground between atmospheric and hydrological sciences. The spatial scales covered by GCIP are those at which both atmospheric circulation dynamics and hydrological process models can be formulated meaningfully. Nevertheless, the objective of relevance to global climate is not lost, ensuring that the transportability of GCIP results to comparable climatic regions is an explicit concern of the project.

NOAA has taken the lead in organizing a GEWEX continental-scale research project (WCRP, 1992) that aims to determine quantitatively the energy and water budgets of the Mississippi River basin (Figure I.1). "Mississippi" is a native American Indian word meaning "Great River," and the Mississippi is sometimes referred to as "Old Man River." Spanning about 2350 miles from its headwaters in Lake Itasca, Minnesota, to its mouth in the Gulf of Mexico, south of New Orleans, Louisiana, the Mississippi is one of the largest river systems in the world. Major rivers, including the Illinois, Missouri, Ohio, Arkansas, and Tennessee, among others, contribute to the Mississippi flow. At the mouth, the flow of the Mississippi constitutes the major freshwater discharge from North America.

The Mississippi River basin, bounded by the Rocky Mountains in the West and the Appalachian Mountains in the East, covers most of the continental United States (area: 3.2×10^6 km^2). This huge continental basin contains several distinct

FIGURE I.1 The Mississippi River basin is bounded by the Rocky Mountains in the West and the Appalachians in the East. Understanding the water and energy cycles of this basin, including the heavily regulated Mississippi and other rivers, is a major objective of GCIP. (Courtesy of National Geographic.)

regional climate regimes that have become separate foci for GCIP. These include (1) the Arkansas-Red River basin, a focus for arid summertime hydrologic processes; (2) the headwaters of the Mississippi River in Minnesota and Illinois, a focus for wintertime hydrologic processes; (3) the upper Ohio and Tennessee-Cumberland Rivers, a focus for semihumid processes and water resources management associated with the Tennessee Valley Authority; and (4) the upper Missouri and Yellowstone Rivers, a focus for orographic processes.

A multiplicity of GCIP data acquisition and assimilation activities are funded both in government laboratories and in universities. The operational phase, aiming to provide the best information available in near real time, is part of a NOAA core project, whereas the research phase, which aims to develop even better products from more comprehensive models and reanalyzed data, will constitute the basic research component of GCIP. Because of GCIP, our nation's regional assimilation capabilities have been upgraded to synthesize a wider diversity of inputs and to produce consistent gridded fields of aerological and hydrological variables over the region on a systematic daily schedule. For the first time, these regional operational products will be archived and distributed as a basic resource for investigations of coupled atmospheric and hydrologic climate processes on spatial scales from local to continental and on time scales from hourly to interannual.

Extensive regional observations are also being gathered, including many upper-air radiosondes, surface weather stations, rain gauges, and stream gauges, in addition to a dense meteorological radar network and satellite observing system [e.g., Geostationary Operational Environmental Satellite (GOES)] in the Mississippi that may be unique in the world. In concert with National Weather Service modernization, GCIP is developing new information from the NEXRAD WSR-88D (Weather Surveillance Radar 1988-Doppler) radars, wind profilers, and automatic weather stations. Because of GCIP, new measurements of snow and soil moisture may become part of the nation's climatic information system.

GCIP also sponsors basic research to (1) characterize the time and space variability of the energy and water budgets from catchment to continental scales and predict how future climate variability will affect these budgets across the spectrum of scales relevant to atmospheric and hydrological processes; (2) develop global and limited-area atmospheric models and hydrologic models ranging from the highest feasible resolution to regional or "macroscale" models and apply these models to the estimation of energy and water budgets; (3) develop information retrieval schemes to integrate existing and future satellite observations and ground-based measurements, including procedures for generating an operational "national precipitation climatology" over the continental United States; (4) develop and disseminate a comprehensive GCIP data base including in situ, model, and remote sensing information; and (5) apply predictive hydrological models utilizing GCIP data sets and models.

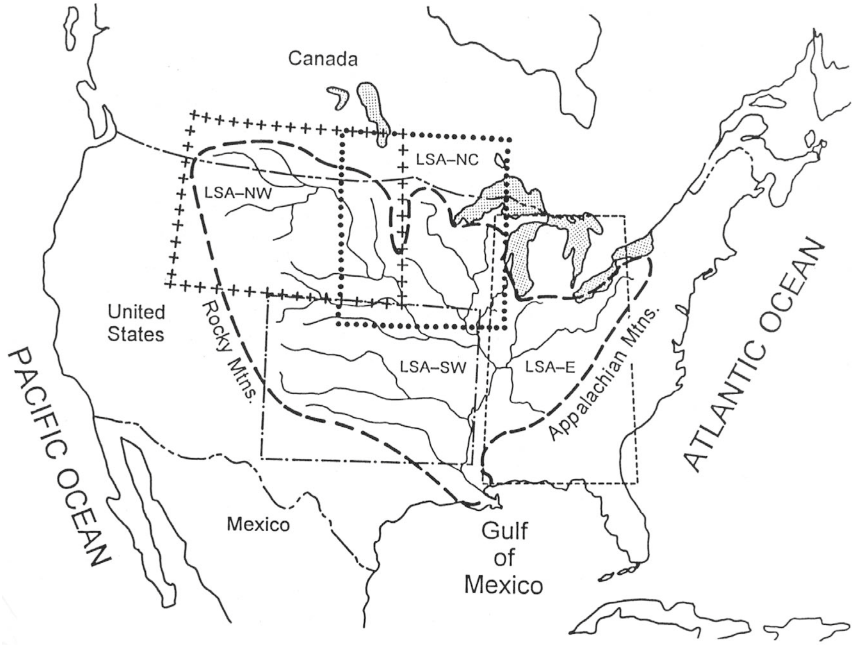

FIGURE I.2 The large-scale areas (LSAs) of GCIP provide a focus for two-year intensive observation activities that will allow GCIP to ultimately scale up to full continental scope.

GCIP received initial funding in 1994 to prepare a program of core and research activities. The various components of the program are described in a succession of planning documents (IGPO, 1993, 1994a,b). Current progress is described in a series of Major Activities Plans for 1995, 1996, and 1997, also produced by the International GEWEX Project Office (IGPO). The GCIP Implementation System Test (GIST) was carried out in 1995, and the data were disseminated widely. The earliest activities were discussed in a series of papers published as a special issue of the *Journal of Geophysics Research* (see Coughlan and Avissar, 1996).

GCIP is now entering its second and most resource-intensive phase, a five-year (1996-2000) Enhanced Observing Period (EOP) and associated Enhanced Seasonal Observing Periods (ESOPs) during which a wide range of special data sets will be assembled for further analyses and model validation. A five-year period was chosen for EOP because it is highly probable that this will include at least one wet year and one dry year as well as several relatively “normal” years. In addition, the complexity of scale interactions that permeate all aspects of the hydrologic cycle has led GCIP initially to adopt a multiscale approach spanning:

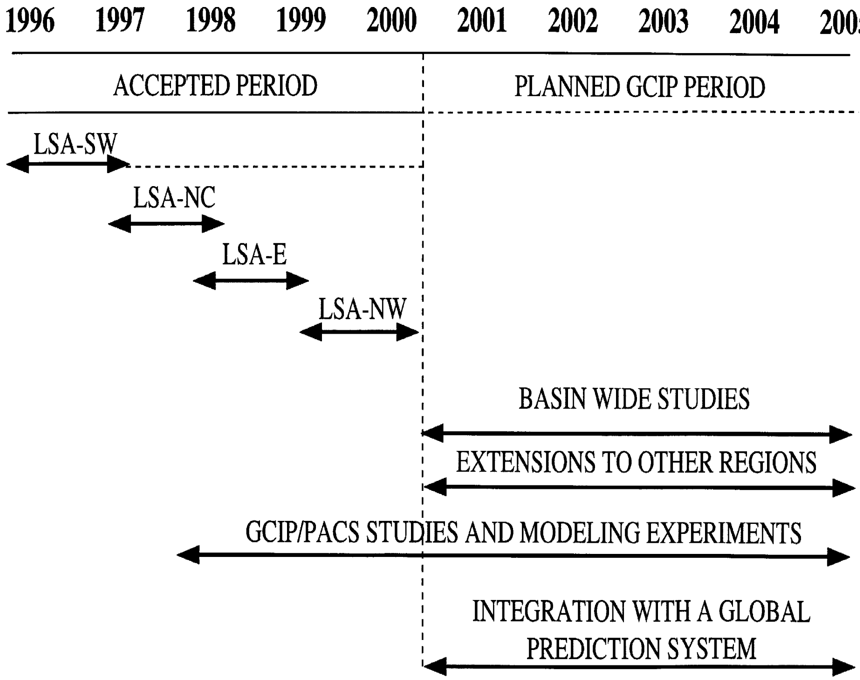

FIGURE I.3 GCIP timeline of activities. GCIP's implementation strategy will start off with the study of summertime hydrometeorological processes in the LSA-Southwest and will next study wintertime activities in the LSA-North Central. GCIP will then move to the humid Appalachians LSA-East and finally go west to the more mountainous LSA-Northwest.

- continental-scale area (CSA) activities, which will continue at a more or less steady level over the whole Mississippi basin for the duration of the EOP. The continental-scale area is well resolved by GCIP's regional analysis as well as global analysis systems. The large area provides another way to link small-scale hydrologic processes to global climate models.
- large-scale area (LSA) activities, which are being implemented successively, following a phased time table of (about) two-year observing periods for each region. LSAs are adequately represented by GCIP's regional models. Four LSAs have been identified, the aggregate of which covers the GCIP domain. These are the southwestern, north central, eastern, and northwestern LSAs (Figure I.2). The areal coverage of the LSAs is on the order of 10^6 km^2. The southwestern area is being emphasized first, followed by the north central, eastern, and northwestern areas (Figure I.3).
- intermediate-scale area (ISA) activities, which include typical river catchments (10^4 km^2 or less) such as represented by operational hydrological models. The hydrologic processes explicitly represented in these models could

potentially be parameterized in regional to global atmospheric models. ISA studies will be phased in accordance with the availability of basic data from LSA and continental-scale activities.

- small-scale area (SSA) activities, which include intensive field observation projects over densely instrumented sites, such as the little Washita experimental river catchment. GCIP provides a unique framework for these small-scale experiments.

By focusing on the study of hydrometeorological processes occurring in various seasons and different parts of the basin, GCIP aims to develop continental-scale hydrologic models and coupled atmospheric-hydrologic models applicable to seasonal and interannual prediction over a wide range of latitudes all over the globe. In particular, it is planned first to develop various parameterized representations of land surface exchanges of energy and water in mesoscale-resolving models and then to test these schemes in a hierarchy of weather prediction models used operationally by the NOAA National Centers for Environmental Prediction (NCEP) and the National Weather Service River Forecast System run by NOAA's Office of Hydrology, as well as a number of other models.

Developing the ability to predict the hydrologic cycle and its components on seasonal to interannual time scales requires the integration of measurements, physical understanding, and models covering many space and time scales. GCIP aims to bridge this spectrum between microscale processes and the synoptic-scale circulation regime by delivering continental-scale field and data sets with the spatial and temporal resolution needed to characterize the continental atmospheric-hydrological water and energy budgets. In order to understand the role of remote forcings on seasonal to interannual variability, GCIP will cooperate with Global Ocean-Atmosphere-Land System (GOALS) and other national programs that bring in remote features of the global climate system affecting the Mississippi River basin. GCIP also aims to foster the closest possible cooperation of research and operational teams and institutions, in order to bridge the gap between understanding the phenomena and applying this knowledge to practical climate forecasting and water resources management on the regional or statewide scales that matter most to end users.

The purpose of this report is to review how GCIP is accomplishing its objectives and to recommend additional actions to accelerate progress. Chapter 1 is a review of the general geoscience issues being faced by GCIP in attempting to understand the continental water and energy cycles. Chapter 2 describes model development activities addressed by GCIP. Chapter 3 discusses the problem of the data assimilation using inescapably sparse observations and predictive models. Chapter 4 covers GCIP data collection and management activities. Chapter 5 discusses application of the results expected from the experiment to hydrologic prediction. Each chapter includes a review of existing and future GCIP activities, as well as an assessment of achievements and recommendations.

To summarize, GCIP is the first international project to bring together the hydrologic and meteorological science communities on a common research goal. This cooperation has already been beneficial to both communities and is the basis for the initial success of GCIP. Thus, the panel's primary recommendation is that GCIP should stay the course and continue with the implementation of its scientific research plans, with modifications as recommended in this report. When fully implemented, GCIP can be expected to strengthen our nation's capability for climate prediction and water resources management. It will provide a sound basis for hydroclimatological research at the beginning of the twenty-first century. Still, the project does not address hydroclimatic phenomena that are characteristic of the semiarid U.S. Southwest, a region where the availability of water is a critical resource issue as well as a challenging scientific problem. Applying the methodologies and technical facilities developed for GCIP to a study of the Colorado River basin and surrounding mountain regions is a challenge for the future.

1

Water and Energy Cycles

Determine and explain the annual, interannual, and spatial variations of the water and energy cycles within the Mississippi River basin.

BACKGROUND

General Characteristics

The large-scale water and energy balances of the Mississippi River basin during the period 1995-2000 will be determined and characterized in the Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP) with high spatial resolution. The normal annual, diurnal, geographic, and vertical variations of surface and atmospheric balances will be defined, as will the major modes of large-scale seasonal to interannual anomalies. The accuracy of these balances will be assessed at various spatial and temporal scales.

GCIP's conceptual framework for analysis of water and energy cycling is that of a coupled land-atmosphere system. Thus, the Mississippi River basin includes not only the land surface and the earth beneath it but also the atmosphere above it. At the largest time and space scales, the cycling of water through the Mississippi basin (at a rate of about 500 km^3 liquid water equivalent per year) can be viewed in three steps: (1) net inflow of water vapor through the lateral atmospheric boundaries of the basin, (2) net transfer of water from the atmosphere to the surface by excess of precipitation over evapotranspiration, and (3) river discharge from the basin to the ocean. In contrast to the water cycle, where exchange between the basin and its environment is exclusively through the lateral boundaries of the basin, the energy cycle is characterized by major radiative exchanges with the extraterrestrial environment. In addition, atmospheric heat flow convergence acts to warm the basin during the winter, and a net divergence cools the basin in summer (Roads et al., 1997). Latent heating and radiative effects of the water substance provide strong coupling between the water and energy cycles.

The picture of net atmospheric water vapor convergence, net transfer to the surface, and runoff to the ocean obscures several important features of water and related energy cycles in the Mississippi basin. The net convergence of water over the basin is actually the difference between very large influxes over the Rocky Mountains and the Gulf of Mexico and effluxes over the Appalachian Mountains (Rasmusson, 1967). Similarly, the net transfer from the atmosphere to the surface is much smaller than either precipitation (about 3000 km^3 per year) or evapotranspiration (about 2500 km^3 per year) taken separately. To understand the balances, therefore, it is necessary to understand how atmospheric moisture, provided by vapor inflow and evapotranspiration, is partitioned into precipitation and vapor outflow, and how precipitation is subsequently partitioned into evapotranspiration and runoff. An analogous issue for the energy balance is the question of how the heat generated by precipitation is partitioned into radiative cooling and atmospheric heat flux divergence.

Additionally, fluxes and stored amounts of water and energy vary in space and time. Parts of these variations are regular, following the annual cycle of solar forcing in time and the physical controls of geography in space. Superimposed on these regular variations are irregular fluctuations or changes caused by the chaotic dynamics of the atmosphere-land-ocean system (e.g., the interannual variability of Mississippi River flow shown in Figure 1.1). Such chaotic behavior is generated both internally in the basin and externally (e.g., by the general circulation of the atmosphere). Storage processes within the basin modulate both the regular and the irregular variations in water and energy fluxes. Much of the internal modulation of the system response is associated with the storage of water on and beneath the land surface (Delworth and Manabe, 1989; Milly and Dunne, 1994; Koster and Suarez, 1995). In a region corresponding roughly to the Mississippi basin, the seasonal change in total water storage has been estimated to be on the order of a 10-cm depth of water (Rasmusson, 1968; Mintz and Serafini, 1981; Roads et al., 1994). GCIP will seek to describe and predict both the regular and the chaotic components of water and energy flux variations.

Geographic and seasonal variability of water and energy cycling are considerable in the Mississippi basin. Annual precipitation is greatest (about 1600 mm) in the southeast of the basin and decreases markedly toward the west, generally following the decreasing trend in vertically integrated atmospheric water content and transport. Under orographic influences, precipitation increases in the Rocky Mountains. The seasonality of precipitation varies from a weak winter maximum in the southeastern part of the basin to a strong summer maximum in the west, and these seasonal patterns follow the respective southern and western vapor inflows.

The geographic distribution of runoff is qualitatively similar to that of precipitation, which partially explains the disproportionate contribution of eastern

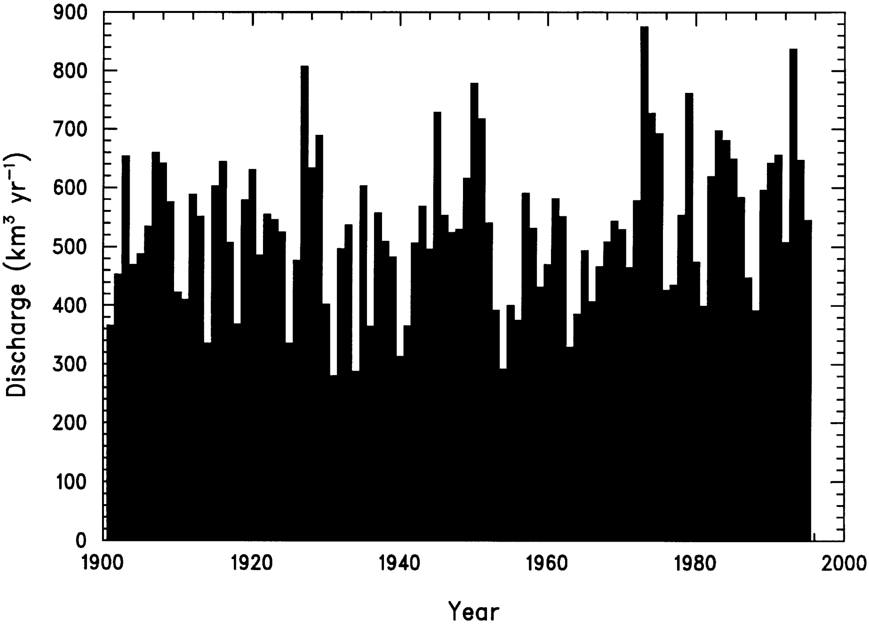

Figure 1.1 Annual discharge of the Mississippi River at Vicksburg. Coefficient of variation = 0.22.

tributaries to the total flow of the Mississippi (Figure 1.2). In addition, the runoff ratio (ratio of mean runoff to mean precipitation) decreases from about 0.5 in the southeast to less than 0.01 in the southwest. The analogous evapotranspiration ratio ranges from about 0.5 in the southeast to more than 0.99 in the southwest. This pattern of partitioning between runoff and evapotranspiration is controlled mainly by annual totals and seasonal changes of precipitation and "potential" (i.e., non-water-stressed) evapotranspiration (Langbein et al., 1949; Milly, 1994), the latter being determined by the surface energy balance. Over much of the basin, the seasonal distribution of runoff is consistent with the interplay between precipitation and evaporation within finite-capacity soil water reservoirs. On the other hand, in the northwest and in the western mountains, runoff peaks strongly in spring when snow melts.

Controls of temporal hydroclimatic variability in the Mississippi basin have been the subject of much speculation and research over the years. Climate model studies have suggested that midlatitude anomalies in soil water could persist for periods of months (Rind, 1982; Yeh et al., 1984). Such model studies also suggested that North American soil water anomalies of sufficient magnitude and geographical extent could induce large systematic responses in computed water and energy balances. Similarly, analyses of observational data (Huang and van den Dool, 1993; Zhao and Khalil, 1993; Huang et al., 1996; Roads et al., 1997)

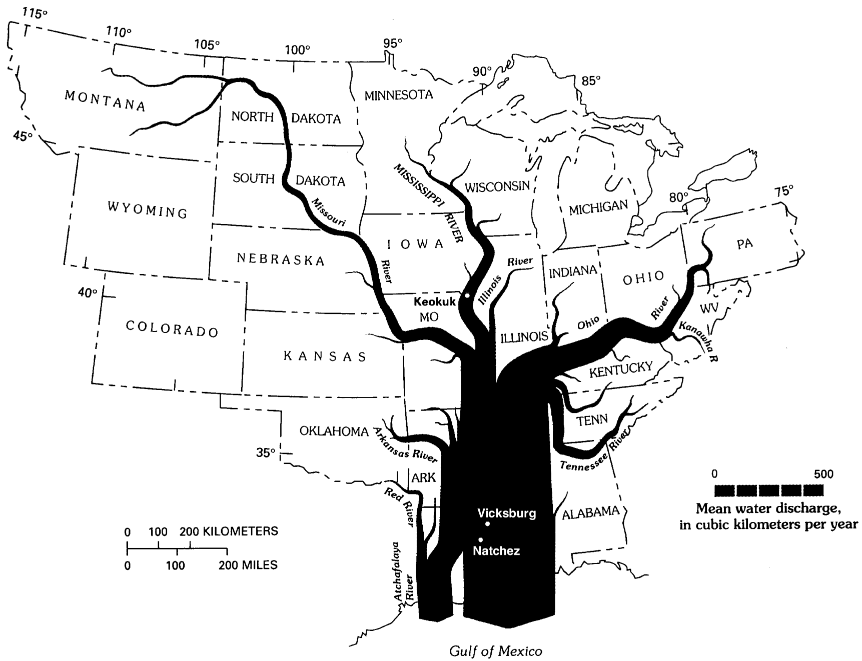

FIGURE 1.2 Mean annual discharge along major rivers in the Mississippi basin. The Ohio River, with one-sixth of the total area, contributes almost half the total flow. Relatively little discharge is produced in the west, where precipitation is lower and evapotranspiration consumes a larger fraction of the precipitation. Source: Meade (1996).

suggest that precipitation-induced soil water anomalies can cause anomalies of evapotranspiration and that the resultant variations of surface evaporative cooling directly affect surface and near-surface air temperatures.

Although the basic mechanisms of direct responses to soil water anomalies are understood, the resultant atmospheric feedbacks are more complex and the subject of great current interest in climate research. Early empirical studies identified a tendency toward persistence of summer droughts that could be ascribed to soil moisture anomalies (Namias, 1958). Recent extreme hydroclimatic events in the Mississippi basin have provided a focal point for studies of land-atmosphere interactions in the GCIP region, illustrating the complexity of the atmospheric response to surface anomalies. The heavy precipitation that caused record-breaking flooding within the Mississippi basin in 1993 has been associated alternatively with high and low soil water anomalies in different areas (Beljaars et al., 1996; Paegle et al., 1996). Physical processes invoked in the alternative explanations include surface-heating effects on the boundary layer capping inversion and associated suppression of deep convection (Lanicci et al., 1987), or influences of surface conditions on the low-level jet in the southern Great Plains. At the other hydroclimatic extreme, initially dry soil conditions in the Mississippi basin have been put forward as a possible cause of the 1988 drought (Oglesby and Erickson, 1989; Atlas et al., 1993).

On the basis of what is known about land-atmosphere interactions, it appears that atmospheric predictability associated with land surface anomalies can be significant during the warm season. Remote influences, such as tropical ocean temperature anomalies [e.g., El Niño-Southern Oscillation (ENSO)], are significant in winter over the United States and may also induce springtime anomalies of soil water that set the stage for later summer anomalies. The potential predictability of Mississippi basin hydroclimatology associated with oceanic influences will be addressed jointly with the Pan American Climate Study (PACS), which is a component of the Global Ocean-Atmosphere-Land System (GOALS) program.

Balance Equations

The conservation of water mass for the Mississippi basin (atmosphere and land combined), or for any subbasin thereof, may be expressed by

$$d(q_a + q_l)/dt = C_q - N, \tag{1.1}$$

in which q_a and q_l are the total atmospheric and land water masses per unit horizontal area, Cq is net inflow (convergence) of atmospheric water to the basin, and N is net land runoff (combined surface and subsurface outflow from the area of interest). Atmospheric water includes vapor, liquid, and solid phases. Land water includes surface water (rivers, lakes, reservoirs, etc.), snowpack, and subsurface storage. The subsurface storage layer consists of a saturated zone below

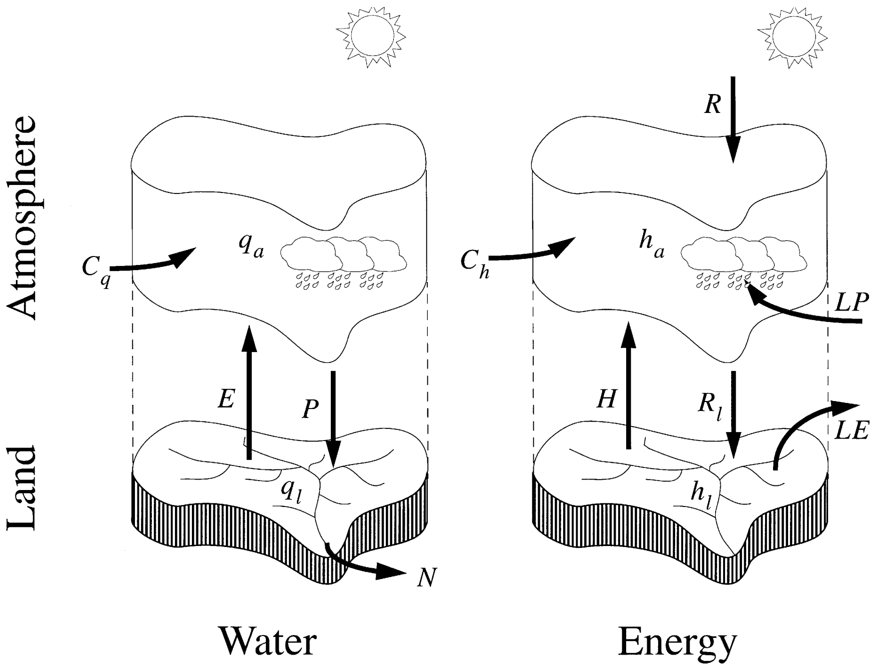

FIGURE 1.3 Major components of the land and atmosphere water and energy budgets (notation defined in text).

the water table and an unsaturated zone above. The most dynamic component of unsaturated-zone storage is water close to the surface (soil water or soil moisture), which interacts closely with atmospheric processes. For the atmosphere and land separately (Figure 1.3, left panel),

$$dq_a/dt = C_q - (P - E) \tag{1.2}$$

and

$$dq_l/dt = (P - E) - N, \tag{1.3}$$

in which P and E are precipitation and evapotranspiration fluxes at ground level. An approximate thermodynamic energy balance equation may be written as

$$d(h_a + h_l)/dt = C_h + R + L\,(P - E), \tag{1.4}$$

in which h_a and h_l are the vertically integrated enthalpy of atmosphere and land, respectively; C_h is a term including net atmospheric convergence of enthalpy and its production by vertical motions; R is the net absorption (absorption minus emission) of radiant energy by the land-atmosphere system; and L is the latent heat of evaporation of water. In general, h_l includes the "cold content" of land $L_f q_{lf}$, where L_f is the latent heat of fusion of water and q_{lf} is the part of q_l that is frozen. For atmosphere and land separately (Figure 1.3, right panel),

$$dh_a/dt = C_h + R_a + LP + H + L_f P_f \quad (1.5)$$

$$dh_l/dt = R_l - LE - H - L_f P_f, \quad (1.6)$$

where R_a and R_l are the parts of net absorption R by atmosphere and land, respectively; H is the upward flux of sensible heat into the atmosphere at ground level; and P_f is the rate of frozen precipitation (part of P) at ground level.

These balance equations indicate the variables of most immediate concern in GCIP. However, the estimation and prediction of these terms often cannot be accomplished without more detailed information on the vertical distribution of atmospheric water content or energy fluxes, individual components of land water storage, or their spatial distributions. Consequently, GCIP cannot be limited to consideration of the lumped, large-scale quantities introduced above but must also analyze many processes at finer scales.

Diagnostic Methods

Observational estimates of atmospheric transport of water (C_q) are based on the assumption that amounts of condensed water are negligible. This is a useful assumption for the total column average, although cloud water may be relatively more important for water budgets in the upper troposphere. The vapor component of C_q has been estimated directly from measurements of the vertical profiles of relative humidity, temperature, and winds from radiosonde data (Starr and Peixoto, 1958; Rasmusson, 1967, 1971; Savijarvi, 1988). However, the radiosonde network has serious limitations in its horizontal, vertical, and temporal resolution, as well as the accuracy of its measurements. These limitations are seen in the difficulty of accurately estimating the divergence of the wind field and related vertical motions, the persistence and strength of transport by "jets" that are not resolved by the network, and the failure to sample adequately the diurnal cycle. In order to avoid some of these limitations, use has been made of analyzed fields (Chapter 3), usually by-products of the weather forecast process, which effectively combine and interpolate all atmospheric observations to yield a complete and dynamically consistent estimate of the state of the atmosphere at the time of the analysis (Sargent, 1989; Roads et al., 1994; Trenberth and Guillemot, 1995; Rasmusson and Mo, 1996). These analyses are also beginning to deal with atmospheric transport of heat (C_h) (Roads et al., 1998a,b).

Within GCIP, data assimilation methods for estimating C_q and C_h are being further developed and refined. Other sources of information, particularly for wind velocity, will be available for analyses of vapor and energy transport in

GCIP. Additional wind measurements are provided by the National Oceanic and Atmospheric Administration (NOAA) wind profiler network, which provides direct, high-resolution profiles of wind velocities, as well as the WSR-88D (Weather Surveillance Radar 1988-Doppler) velocity data that will be used to characterize low-level jets with high time and (vertical) space resolution. GCIP's innovative Commercial Aircraft Sensing of Humidity (CASH) program (Fleming and Hills, 1993), along with the GOES-8 (Geostationary Operational Environmental Satellite) radiation products, provide a link between GCIP and future EOS (Earth Observing System) era global observations.

Owing to the geometry of the surface drainage network, information on the net runoff (*N*) from a basin of any size may be estimated from measurements of discharge at a single river section. As of 1994, the U.S. Geological Survey's stream-gauging program routinely collected streamflow data for more than 7000 stations and possessed daily flow records totaling more than 400,000 station-years (Wahl et al., 1995). The disaggregation of the total discharge into areally distributed runoff 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 basin through the surface river network. Groundwater discharges from small basins can be significant, and this possibility must be considered case-by-case on the basis of local hydrogeologic conditions. Interbasin transport of water via pipelines, irrigation ditches, and water supply channels may also be a significant term in local water budgets.

Historically, large-scale area-averaged estimates of precipitation (*P*) have been based on interpolating, by various methods, point measurements from rain gauges. Precipitation is routinely observed by recording gauges at more than a thousand sites within the GCIP basin (Chang, 1981). However, simple interpolation of gauge data suffers from random sampling errors associated with the insufficient 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. The new network of WSR-88D radars (Crum and Alberty, 1993; Klazura and Imy, 1993) has the potential to improve precipitation estimates by vastly increasing the effective sampling density of precipitation. Ultimately, methods will be developed that optimally combine information from both gauges and radars.

The fluxes of water vapor (*E*) and sensible heat (*H*) between the land surface and the atmosphere are not readily estimated from routine observations. Specialized equipment and technical expertise are required to obtain accurate measurements, and such measurements are representative of a horizontal length scale of no more than 100 m. Consequently, evapotranspiration must be estimated as a residual in large-scale water balance studies, using equation (1.2) or (1.3). Another approach is the use of data assimilation systems that track the state of the land surface (soil water, in particular), computing surface fluxes in the process. Such systems can be driven by observations or analyzed fields of precipitation and surface radiation, and may also make use of discharge observations to adjust predicted land surface wetness. Whenever possible, the validity of estimates derived by balances or data assimilation must be tested, if only partially, by comparison with point measurements and theoretical estimates. In analogy to evaporation, surface sensible heat flux is not readily observed but can be derived as a residual from equation (1.5) or (1.6) or, potentially, by land surface data assimilation.

Prior to GEWEX and GCIP, surface radiation (R_l) estimates used in water and energy balance studies were typically based on empirical relations using long-term climatic means of relevant variables (Budyko et al., 1978; Henning, 1989). For the combined land-atmosphere system, satellite observations of top-of-atmosphere radiation (R) have been available for some time [e.g., from the Earth Radiation Budget Experiment (ERBE) in 1984-1987]. For the calculation of land surface and atmospheric energy balances, however, it is essential to know the partitioning of radiant energy between the land surface (R_l) and the atmosphere (R_a), as well as the temporal distributions of these quantities. The most promising technique for estimation of at least the time-varying surface solar radiation fields over the GCIP region may be to derive them from instantaneous observations of the cloud cover and atmospheric temperature and moisture profiles. Such estimates can be tested locally using direct radiative measurements. For example, the Surface Radiation Budget Network (SURFRAD) provides long-term, ground-based radiation monitoring at four widely dispersed sites in the Mississippi basin. The radiation issue is being addressed in a close collaboration among GCIP, Atmospheric Radiation Measurement (ARM), and other GEWEX projects.

Estimates of atmospheric vapor and heat storage rates (dq_a/dt and dh_a/dt), or tendencies, are readily made in conjunction with analyses of horizontal flux convergence, already discussed. Typically, the tendency terms are much smaller than the flux terms over periods of several days or longer. Atmospheric cycling of water and energy, of course, displays strong diurnal components; consequently, the tendency terms are important in the analysis of processes at the diurnal time scale. Furthermore, diurnal variations may have a significant impact on longer-term mean values.

At time scales longer than a few days, the change of water storage on land (dq_l/dt) is generally considered the most significant storage term in equations (1.1)-(1.6) and provides a mechanism for monthly to annual persistence of anomalies or "memory" in the land-atmosphere system. Storage variations in the soil water zone are almost always a significant component of dq_l/dt, and storage changes in the saturated zone, the snow pack, and the surface water network may also be significant, depending on local hydrogeologic and climatic conditions. However, each of these terms presents unique measurement difficulties, and their estimation is complicated by spatial variability. Some components of q_l could possibly be estimated by analysis and synthesis of available snowpack data (in situ and remotely sensed), records of lake and reservoir levels, and records of water table elevations. For example, the National Operational Hydrologic Remote Sensing Center (Carroll, 1997) uses airborne measurements of surface gamma radiation to infer snow water equivalent. Unfortunately, one key term—soil water—has not been observed sufficiently to enable its accurate estimation at large scales.

As a result of the complexities outlined above, large-scale estimates of dq_l/dt most readily come from water balance studies (e.g., Rasmusson, 1968; Roads et al., 1994), in which this term is inferred as a residual from equation (1.1):

$$dq_l/dt = C_q - N - dq_a/dt \tag{1.7}$$

As estimates of Cq improve, so will estimates of dq_l/dt derived from this balance equation. Competitive estimates may ultimately be provided by data assimilation systems, especially the land system discussed in Chapter 3.

The second land memory term in equations (1.1)-(1.6) is the terrestrial heat storage term, dh_l/dt. Here again, relevant measurements (soil temperature, in particular) are not routinely collected, except at scattered locations with varying protocols. Areal averaging is complicated by the spatial variability of soils, but the physics of heat storage in the soil is relatively simple and remote sensing can provide some information on changes in surface temperature. This storage term is of major importance at the diurnal time scale, when it is comparable to radiative and sensible and latent heat fluxes. Its magnitude is usually considered to be relatively small on monthly to seasonal time scales (e.g., in the computation of seasonal energy balances).

ACCOMPLISHMENTS

The GCIP strategy is to improve the large-scale data base not only with new observing systems, but also with new ways of processing available information. Data assimilation systems will improve the quality of information on such variables as atmospheric humidity and heat content, radiative fluxes, and precipitation; indeed, much progress has already been made in data assimilation system development and implementation. In addition, many model-oriented process studies supported by GCIP have already been initiated, and these will become increasingly tied to the analysis of GCIP data sets as the latter become available.

Precipitation Estimation

The Next-Generation Weather Radar (NEXRAD) network of WSR-88D radars is of central importance in the GCIP plan for observing precipitation. An essential requirement of GCIP is to assess the value of radar-derived precipitation estimates for quantitative climatological studies. Climatological analyses of two years of WSR-88D hourly precipitation data in the GCIP large-scale area–Southwest (LSA–SW) region have documented some characteristics of the estimates (Smith et al., 1996). Gauge-radar comparisons suggest that radars systematically underestimate rainfall at most sites, relative to rain gauge observations. Systematic differences found in radar-radar intercomparisons indicate that radar calibration is a problem at some sites. Contamination by anomalous propagation (errors associated with nonstandard atmospheric conditions) during nonraining periods (a major problem for the previous generation of operational weather radars in the United States) seldom appears in WSR-88D rainfall products, but contamination by anomalous propagation is still a major problem during raining periods.

Still, the WSR-88D system is superior to rain gauge networks for monitoring the space-time structure of heavy rainfall, which is essential to analyze the variability of soil moisture, evaporation, and runoff. In that regard, precipitation estimation based on GOES satellite imagery (Hsu et al., 1997) could also cover many regions where radar and gauges are unavailable (mountainous areas). It should be emphasized, though, that the accuracy of NEXRAD and satellite estimates is ultimately limited by the accuracy of gauge estimates, which are known to be affected by significant and systematic biases, particularly in snow situations. Compilation of relevant meta-data (histories of gauge type, exposure, site climate) are needed for gauge bias adjustments, which have so far been performed for about 1500 stations in the United States (Groisman et al., 1996).

The NOAA Core Project for GCIP is developing an integrated precipitation analysis combining WSR-88D, gauge, and satellite data. The current specification is that this product have a 4-km spatial and hourly temporal resolution. Unfortunately, the problems noted above must be addressed before one can produce a reliable high-resolution precipitation analysis for the Mississippi River basin. Still, preliminary versions already available on the Worldwide Web (WWW) are encouraging.

Radiative Flux Estimation

Estimation of surface radiative fluxes in GCIP is closely linked to several other projects, including several within GEWEX. One of the major tasks taken on by GCIP is the production of high-resolution radiation products for the GCIP area. These efforts have led to the production of hourly data sets for net shortwave radiation at the Earth's surface (Pinker et al., 1996; Tarpley et al., 1996). Currently, hourly estimates of net shortwave radiation are available on a 40-km grid on a near real-time basis. It is expected that this product will be valuable in the immediate future for studies of land surface process variability.

Estimation of the net surface longwave flux is considerably more difficult than estimation of the surface shortwave flux. Longwave flux depends on cloud base height and downwelling flux at the cloud base and on the low-level profiles of temperature and water vapor. No combination of observation systems currently provides all of this information. Thus, a net surface longwave flux product must merge both observations and model-assimilated fields. This is an active area of research.

GCIP, in partnership with the National Aeronautics and Space Administration (NASA) Clouds and the Earth's Radiant Energy System (CERES) project and the Department of Energy (DOE) ARM program, supports the CERES-ARM-GEWEX experiment (CAGEX). CAGEX provides detailed in situ and satellite measurements of vertical profiles of radiative fluxes, atmospheric temperature and moisture, and cloud properties for testing radiative transfer models and satellite retrieval algorithms [particularly for use with the National Centers for Environmental Prediction (NCEP) Eta model used in GCIP], and to provide data for local hydrologic and meteorological process studies. Preliminary data from an April 1994 campaign are now available from the GCIP Project Office.

Land-Atmosphere Interactions

Preliminary results from several GCIP studies of precipitation and cloud formation processes are available. Both observational and modeling studies have explored relations between spatial or temporal variations of land surface characteristics and corresponding variations in atmospheric processes, particularly cumulus convection and precipitation.

In one particular investigation, predictions of a boundary-layer model were confirmed by observations of the development of low cumulus at two GCIP locations; the model was then used to explore the sensitivity of cloud to land surface characteristics, again with supporting evidence from GOES and AVHRR (Advanced Very High Resolution Radiometer) data (Wetzel et al., 1996). The frequency of shallow cumulus convection during summer was found to follow large-scale relative humidity gradients across the GCIP region, with smaller-scale variations correlated with elevation and the scarcity of vegetation (Rabin and Martin, 1996).

Model studies have shown the importance of mesoscale circulation patterns induced by various types of surface heterogeneities. Vertical transport of water and heat by mesoscale circulation can equal the transport by turbulence. The analysis of one model experiment suggests that mesoscale circulation induced by landscape structure may concentrate precipitation on initially drier regions and thus tend to homogenize the surface moisture distribution (Avissar and Liu, 1996). In another study, precipitation enhancement was noted downwind of the ascending air (Seth and Giorgi, 1996). A preliminary model evaluation of the effect of land-use changes on climate in the GCIP region indicated systematic and substantial sensitivities (Copeland et al., 1996).

Atmospheric Water and Energy Transport

GCIP's regional data assimilation systems are now providing the improved analyses of atmospheric water and energy transports that are needed for further advances in understanding water cycling in the Mississippi basin. These data products will facilitate the analysis of water cycling at smaller spatial and temporal scales than have ever been previously 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.

The low-level jet in the planetary boundary layer close to the Rocky Mountains has been shown to be an important factor in controlling the moisture flux convergence and its diurnal variations. This, in turn, affects the diurnal cycle of precipitation, which appears to change character from mountain areas to regions under the influence of the jet (Helfand and Schubert, 1995).

Cloud-scale motions can have important large-scale effects on vertical water and energy transport, especially during summer. For example, condensation terms in the moisture and heat balance equations have different vertical structures at small or large scales (Roads et al., 1998b). Apparently, condensation of water vapor occurs just above the planetary boundary layer. The net heating, however, peaks higher in the atmosphere. The difference in vertical structure is associated with the interaction between vertical motions and latent heat release.

Characterization of Random Variability of Precipitation and Soil Water

Random, large-magnitude variations in precipitation complicate the tasks of analysis and prediction of water and energy balances. The spatial distribution of soil water, which is strongly influenced by precipitation, present a similar problem. For this reason, special efforts are made to characterize spatial and temporal variations in these variables. Scale-invariant descriptors of observed rainfall have been developed and related empirically to the pre-storm environment of mesoscale convective systems characteristic of the GCIP region (Perica and Foufoula-Georgiou, 1996). Studies of soil water variability have been conducted with both observed and modeled fields, which have been found to account for much of the temporal and spatial variance of Russian soil moisture data measured under natural field conditions (Vinnikov et al., 1996). Based on estimates of soil moisture distribution constructed from historical climate data and a soil water accounting model, spatial scaling properties of soil water in the GCIP have been explored (Guetter and Georgakakos, 1996).

RECOMMENDATIONS

Substantial progress has been made toward GCIP's objective of characterizing the variability of water and energy cycling in the Mississippi basin. Further progress will require increased care in the estimation of such critical variables as precipitation and surface radiative fluxes; certain other improvements in the use of available measurements could markedly enhance the value of GCIP. Rigorous investigations of local and remote forcing of hydroclimatic anomalies are needed to satisfy the GCIP objective of explaining the observed variations. Specific recommendations relevant to these and related issues are discussed below.

Develop Improved Estimates of Precipitation, Longwave Radiation, and Land Water Storage Using Existing Observational Networks

GCIP was planned with the expectation that NEXRAD would provide a high-resolution precipitation data set of high accuracy and consistency. Thus, the documented biases in WSR-88D products are a reason for concern. Because algorithms may be in a state of transition, it appears likely that improved estimates of rainfall will be obtainable in the near future by reanalysis of radar data. Polarimetric radar measurements would probably help in situations of heavy rainfall and with a variety of quality control issues. Full-scale polarimetric augmentation of WSR-88D cannot be expected in the GCIP time frame, but the necessary hardware is already in place at some sites. Research and development on its optimal use should be pursued in conjunction with work on improved WSR-88D rainfall estimation algorithms. As new algorithms are developed, the value of possible reanalyses should be assessed continually.

Radar algorithms for rainfall ultimately rely on rain gauge measurements for their development and continuing evaluation. For these and other reasons, it is essential to develop the highest-quality gauge-only precipitation data set. Data from each rain gauge should be included only if accompanied by adequate meta data characterizing the gauge site; some gauges that are used for operational applications may not meet the representativeness requirement for quantitative estimation of area-averaged precipitation, as attempted by GCIP. In this context, it is also important to adjust, where appropriate, for the bias associated with undercatch by precipitation collectors (Groisman et al., 1996); in some regions, the bias in annual precipitation measurements is comparable to the annual runoff (or equivalently the atmospheric water-vapor flux convergence). The estimation of snowfall is an especially difficult problem for GCIP. It is unlikely that useful snowfall data will be obtained from the WSR-88D during the GCIP program. At the same time, snow is the form of precipitation most severely affected by gauge biases. For the northern part of the Mississippi basin, these issues must be recognized in the preparation of precipitation data sets and in the context of GCIP water balance studies.

GCIP has a need for estimates of time-varying fields of longwave radiation. These should be improved by processing in situ and remotely sensed data on profiles of atmospheric properties using radiative transfer models. The strong influence of clouds and water vapor on longwave fluxes presents a major challenge (Ellingston et al., 1994). Improvement in knowledge of the vertical distributions of cloud and cloud properties, water vapor, and temperature could contribute to improvements in longwave radiation estimates. Engaging the participation of other GEWEX and related research projects is important to achieve this goal.

GCIP provides an opportunity, which should be pursued, to determine whether useful information on water storage on land can be obtained independently of the atmospheric water budget. It may be possible, for instance, to derive meaningful large-scale estimates of snowpack, surface-water, and groundwater storage from operational data products; these, in turn, might provide a lower bound on the annual change in total terrestrial water storage. The remaining term of importance, water in the unsaturated zone, is much more difficult to estimate because there is no continental-scale observation network, nor are there even any standardized methods. However, such measurements do exist at scales from individual sites to state networks (e.g., Hollinger and Isard, 1994), and new sites are currently being instrumented. The challenge for GCIP is to derive meaningful large-scale storage changes from these disparate data sources.

Promote Innovative Developments and Applications of Promising Measurement Technologies That Support or Complement GCIP

GCIP is making efficient use of existing operational data sources and measurement technologies. However, it seems prudent in an undertaking of this magnitude to promote both the development of new technologies and new applications of existing techniques to the problem of environmental measurements. For example, the CASH program (Fleming and Hills, 1993) being developed for GCIP and other NOAA programs uses commercial airlines to carry moisture sensors in addition to the current, pressure, wind, and temperature sensors. These innovative measurements will be used increasingly in the future to provide in situ high-resolution characteristics of atmospheric properties.

At the surface, recent field work on groundwater lysimetry (Van der Kamp and Maathuis, 1991; Bardsley and Campbell, 1994) offers the possibility of high-precision estimates of total land water storage changes (dq_l/dt) by observing pressure changes in confined aquifers or aquitards (Van der Kamp and Schmidt, 1995). Given the relatively large effective horizontal length scales of such a measurement (tens of meters and higher) and the relative difficulty of alternative measurements, the value of such an independent closure of the water balance to GCIP and to hydrology in general would be extremely high.

Carroll (1997) have developed innovative measurements of the natural gamma radiation from the surface to measure the amount of snow cover. Similar efforts are being initiated to relate background gamma radiation to the amount of soil moisture. Given the difficulty in estimating the snow water equivalent from satellite measurements of fractional coverage, such measurements may prove invaluable.

The value of isotopic measurements in investigations of water history and transport is well established, but potential applications to GCIP have not been pursued. Differing isotopic compositions of water (e.g., in precipitation) are indicative of differing source regions, transport, and residence times (Gat, 1996). Investigation of the isotopic composition of water in the GCIP region could potentially yield useful information on the dynamics of large-scale circulation and its history in the region. Information can be obtained by analyses of the isotopic composition of nonexchangeable hydrogen in the cellulose of trees over the lifetime of the trees, because the isotopic record in trees reflects the record of the water they utilize (Feng and Epstein, 1996).

Useful large-scale information on soil water could be obtained in the future by satellite-based microwave radiometry. Snow water equivalent and vegetation are already being remotely sensed, although more research is also needed in this area. Any acceleration of progress in these areas could be of enormous benefit to GCIP and its follow-on activities. In the GCIP time frame, it is especially important to coordinate soil water remote-sensing research with GCIP activities, to the mutual benefit of both. Airborne microwave sensors deployed in field experiments may provide information on the time-space variability of soil water that would otherwise be unavailable to GCIP. Reciprocally, GCIP and related activities could provide in situ soil water and relevant ancillary information that will magnify the value of such experiments.

Use Observations and Models to Evaluate the Local Factors and (in Collaboration with GOALS) Remote Influences That Govern Water and Energy Regimes in the GCIP Region

A major set of GCIP process issues concerns the dynamic interaction of atmosphere and land. What are the relative roles of land surface processes and remote forcing, such as ocean surface temperatures, in generating and modulating atmospheric and surface anomalies (precipitation, temperature, river discharge) in the Mississippi basin? Are anomalies in water storage and ocean surface temperatures effective predictors of atmospheric anomalies at monthly to interannual time scales? To what extent do human interventions (e.g., irrigation) influence the surface and atmospheric water and energy balances within the GCIP region? Additionally, there is a need to understand more fully the processes by which orography so strikingly controls precipitation at scales ranging from entire mountain ranges down to local orographic features. Some of these questions will have to be explored in conjunction with other projects, notably GOALS, to maximize the efficiency of research efforts.

Use Observations and Models to Assess Quantitatively the Impacts of Individual Land Surface and Atmospheric Processes on Large-Scale Water and Energy Transport

Key GCIP process issues concerning the land environment include the identification and quantification of the factors that control evapotranspiration in the absence of water stress and the interseasonal storage of water to support dry season evapotranspiration. The influence of extensive areas of shallow groundwater, swamps, or lakes on the dynamics of water and energy balances is yet to be characterized. GCIP also provides an opportunity to determine the predictive value of standard physical soil water transport theories at GCIP scales. To what extent does the water balance manifest a nonlinear dependence of runoff on rainfall intensity, and what is this dependence as a function of spatial and temporal scales? To what extent is soil infiltration capacity a factor in the water balance? How do seasonal freezing and changes in soil structure affect infiltration and runoff? Finally, do the details of land surface topography play a significant role in the area-averaged water balance?

GCIP can also contribute to the improved understanding of atmospheric processes, complementing related studies, for example, in the GEWEX Cloud System Study. What atmospheric processes control the structure of the low-level jet over the southern Great Plains? How does cloud-scale mixing affect large-scale water vapor and heat transport? How do mesoscale circulations contribute to local precipitation and larger-scale atmospheric transport?

2

Coupled Land-Atmosphere Models

Develop and evaluate coupled hydrologic-atmospheric models at resolutions appropriate to large-scale continental basins.

ATMOSPHERIC MODELS

Atmospheric general circulation models (GCMs) are one of our primary tools for diagnosis and prediction of weather and climate. However, GCMs contain many approximations. The basic equations are nonlinear and must be solved via approximate numerical techniques on model grids (see Arakawa and Lamb, 1977). With current supercomputers, GCM global grids have horizontal resolution on the order of 250 km, which is inadequate to describe many small-scale features of importance to the water and energy cycles. For example, cloud-scale motions transport moist warm air upward in narrow cloud-scale regions (kilometers) and, in turn, induce large-scale compensating subsidence (hundreds to thousands of kilometers). Various parameterizations have therefore been developed and are continuing to be developed to model this small- to large-scale interaction. However, small-scale precipitation patterns important to the surface water budget and to the occurrence of floods have not yet been adequately considered. Also, GCM vertical grids do not have the capability of describing small-scale vertical features in the planetary boundary layer that influence the transport of heat and moisture from an extremely heterogeneous land surface to the atmosphere, and accurate planetary boundary-layer parameterizations still have to be developed. The interaction of cloud water with the radiation field is also highly parameterized, and various parameterizations have been developed to model this interface.

Regional models are more compatible than GCMs with the cloud and boundary-layer scales. Regional models solve the same fundamental equations as do global GCMs and have the same basic parameterizations. However, since the geographic extent of the domains is much smaller, regional models can solve the equations at higher resolution (currently 30-50 km for most operational regional numerical weather prediction models). These regional models are usually nested in global models (or analyses), and more than one level of nesting can be incorporated. Finer-scale cloud-resolving models (CRMs) can simulate clouds with realistic representations of microphysical processes. A basic research technique in the GCIP coupled modeling effort is to use smaller-scale, high-resolution models and observations to improve the parameterizations of critical processes in larger-scale models. It should be noted, however, that climate simulations are not yet possible with CRMs because of the extensive computational requirements. GCMs and regional models will continue to play a key role in modeling long time scales and providing information about remote variations and their influence on moisture and energy transport into and out of smaller-scale models.

LAND SURFACE PARAMETERIZATIONS

Before GCIP, most of the atmospheric parameterization effort was concerned with atmospheric processes. Of great importance to GCIP, however, is how atmospheric models interact with and represent the land surface. Early GCMs did this by prescribing surface temperature and wetness, and hence the partitioning of incoming radiation. Subsequently, pioneering interactive land surface parameterizations (LSPs) were developed by Manabe (1969), and others soon followed. These LSPs were single bucket-type parameterizations, which ignored important nonlinearities, especially in the dependence of precipitation infiltration–runoff partitioning on soil moisture.

Later LSPs included vegetation effects. The Biosphere-Atmosphere Transfer Scheme (BATS) of Dickinson (1986, 1993), utilized in the early National Center for Atmospheric Research (NCAR) models, is a good example (Figure 2.1). Other models include those of Sellers (1986), Bonan (1996), and Cuenca et al. (1996). Many processes are now included in these LSPs. Just as the early weather models increased their number of levels to deal with the complexity of the atmospheric vertical structure, so too have LSP modelers increased the number of subsurface levels. This increased number of levels now allows a fast upper soil moisture layer, as well as a root zone and subsurface storage region. The vertical distribution of moisture through vegetation as well as ground diffusion are important components of the models. Also important are the vegetation characteristics (e.g., height, density, etc.) which affect variables such as interception, evaporation, radiation, and wind speed.

Although the land surface was previously thought to be important, atmospheric modelers mostly believed that it played only a minor role in climate variability. GCIP has helped to change this perception. The recent improvement in the new European Center for Medium-Range Weather Forecasts (ECMWF) model in depicting the 1993 heavy rainfall over the Mississippi and the attribu-

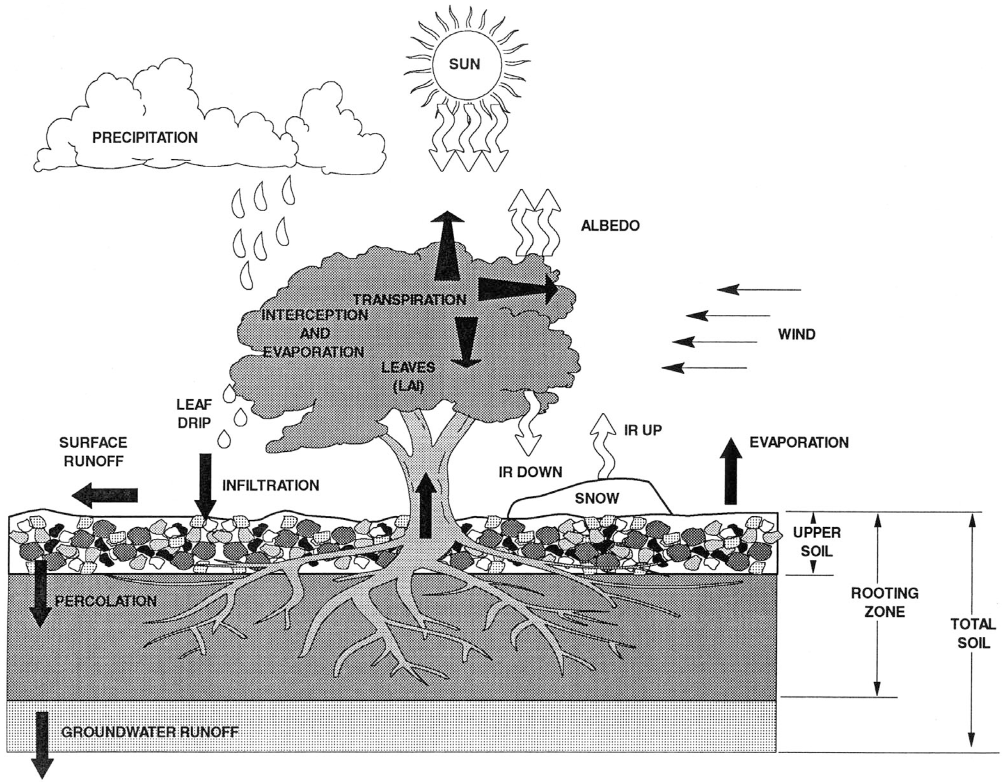

FIGURE 2.1 A typical land surface parameterization model (BATS), which accounts for vegetation, snow, and multiple soil moisture and temperature layers.

tion of that improvement to the new land surface scheme (Betts et al., 1993) have also increased the atmospheric modeling community's interest in the potential influences of the land surface. However, there are still many unresolved problems with LSPs. A major problem is subgrid parameterization of processes that control surface energy and water fluxes. LSPs take into account vegetation, soils, geology, topography, and climate characteristics at each grid point. LSPs eventually also have to provide a reasonable description of runoff to allow correct GCM simulations of soil moisture and evaporative fluxes, as well as to understand the influence of climate variability on river discharge. GCIP will be of special help here through its coordinated efforts between hydrologists and meteorologists.

HYDROLOGIC MODELS

Surface hydrologic models operate at the scales needed to represent key topographic, soil, and other surface features important for runoff generation (Lohmann et al., 1998). Usually, this is considerably smaller than the smallest grid size in GCMs and even most regional models. Because of the effects of snow and soil moisture storage, hydrologic models have much longer memories than do atmospheric models. Because the hydrologic response of the land surface is strongly affected by spatial heterogeneities in topography and soils at spatial scales as small as meters, hydrologic models applicable to scales much larger than hillslopes (e.g., hundreds of meters) have not been based on direct solution of the equations of surface and subsurface flow. Instead, the current generation of operational hydrologic models (e.g., for purposes such as flood forecasting) have used conceptual representations applicable to the scale of catchments defined by stream gauges (usually of the order of hundreds of square kilometers). These conceptual models typically represent the subsurface as a series of storage zones, with nonlinear parameterizations to describe two key nonlinearities: (1) the decreasing fraction of mean areal precipitation that infiltrates, dependent on spatially averaged soil moisture near the surface, and (2) nonlinear behavior in base flow as deep soil moisture decreases during dry periods. Of the conceptual hydrologic models, the Sacramento model (Brazil and Hudlow, 1981), widely used by the National Weather Service (NWS) River Forecast Centers, is perhaps the best known example.

Although conceptual hydrologic models have been operationally useful, they have two shortcomings from the standpoint of climate modeling and numerical weather prediction. First, they are specific to individual catchments and watersheds; before GCIP, no special attempts were made to develop a continental synthesis from these kinds of models. Second, they focus entirely on streamflow prediction and do not represent surface energy fluxes in a manner consistent with atmospheric models. For example, these models ignore diurnal variations, which most atmospheric global to regional models now take into account. Conceptual hydrologic model parameters, which are not directly observable, are commonly determined through a calibration process with the objective of fitting, as closely as possible, the model-generated runoff with observed runoff. So far, the usefulness of any distributed land surface cover data bases and remote sensing data in reducing the calibration requirements of conceptual hydrologic models has not been established.

Hydrologic models that explicitly represent topography, soils, and vegetation at the scale of digital topographic models (typically 30 or 90 m) have been developed over the past 10 years. Although these models address some of the shortcoming of conceptual hydrologic models, they have not yet been used to any significant extent for hydrologic prediction or for continental synthesis. There remain a number of important issues to be resolved before such models will be used for operational applications; the development of parameter estimation techniques is critical for their utilization.

There are important functional similarities between hydrologic prediction models and the LSPs included in general circulation and numerical weather prediction models. Both perform a water balance at the land surface. Although hydrologic prediction models generally do not perform a full surface energy balance, they do estimate evapotranspiration, which is related to latent heat flux by a scaling parameter. As indicated above, there is a distinction in that hydrologic prediction models focus on streamflow generation, whereas land surface parameterizations focus on surface energy fluxes, which in these models however also depend on variations in runoff. However, because both types model evapotranspiration, there may be an inherent inconsistency in approaches that attempt to use GCM or numerical weather prediction model output (e.g., precipitation) to drive hydrologic prediction models.

An important feature of GCIP is the attempt to bring together the diverse scales and processes represented in atmospheric and hydrologic models, and to deal with them in a common geographic and temporal framework in which all can be applied and evaluated. The atmospheric science community has begun to pay more attention to the incorporation of processes common to hydrologic models. The hydrologic community has also begun to expand the geographic extent of its models to continental-scale areas, as well as to incorporate full surface energy balances. One potential outcome of GCIP is to develop LSPs capable of predicting important hydrologic processes (especially streamflow) at continental scales and, in so doing, to provide a mechanism for updating key state variables (especially soil moisture) that control land-atmosphere moisture and energy fluxes on continental as well as basin scales.

ACCOMPLISHMENTS

Regional Focus

GCIP has provided a common geographic focus for the development and comparison of a number of atmospheric models ranging from:

- the coarsest-scale general circulation models (GCMs) such as NCAR's community climate model (e.g., Marshall et al., 1997) and NCEP's global spectral model (Kalnay et al., 1996);
- operational regional forecast models such as NCEP's Eta model (Black, 1994), the NOAA Mesoscale Analysis and Prediction System (MAPS) model (Bleck and Benjamin, 1993; see Figure 2.2), and the Canadian regional finite-element (RFE) model (Ritchie, 1991; see Figure 2.3); and
- regional climate models such as MM4 (Seth and Giorgi, 1996), Regional Area Modeling System (RAMS) (Pielke et al., 1992), and NCEP's regional spectral model (see Juang and Kanamitsu, 1994).

Macroscale hydrologic models being considered under GCIP include the surface water balance models from the office of hydrology (Schaake et al., 1996) and the macroscale hydrologic VIC-2L model described by Lohmann et al. (1998).

Land Surface Parameterization Improvements

Because of GCIP, these models are being improved. For example, considerable effort has been expended in developing new LSPs for regional analysis models. The NCEP land surface scheme, which originated with the LSP scheme of Pan and Mahrt (1987), was enhanced in the Eta model (Chen et al., 1996) and has since been transferred to NCEP's Global Data Assimilation System (GDAS). Enhancements included the acquisition of land surface data bases, including monthly vegetation type, green vegetation fraction, soil type, and albedo. The Eta LSP scheme now consists of two soil layers in which soil moisture and temperature are carried as dependent variables. In addition, intercepted precipitation and dew on the vegetation canopy and water in the snowpack are now carried as dependent variables. A similar LSP model is currently being implemented in MAPS. The RFE previously operated with a simple bucket, but as a result of the MacKenzie River GEWEX Study (MAGS), the corresponding Canadian GCIP project, this bucket formulation is also being upgraded to an even more comprehensive LSP known as CLASS (see Vberseghy et al., 1993).

It is important to remember, however, that LSPs are still not equivalent to hydrologic models in simulating streamflow. It remains to be seen whether LSPs can ever truly compete with the tuned hydrologic models used in river forecasting. For example, although it would be ideal if LSP parameters could be estimated from land surface physical characteristics alone, past experience indicates that direct relationships among model parameters and land surface characteristics are elusive. Research continues to show (Duan et al., 1997; Gupta et al., 1996, 1998; Koren et al., 1996; Schaake et al., 1996, Yapo et al., 1998) that the best hydrologic simulations are achieved by calibrating these parameters using local precipitation and surface meteorological and runoff data.

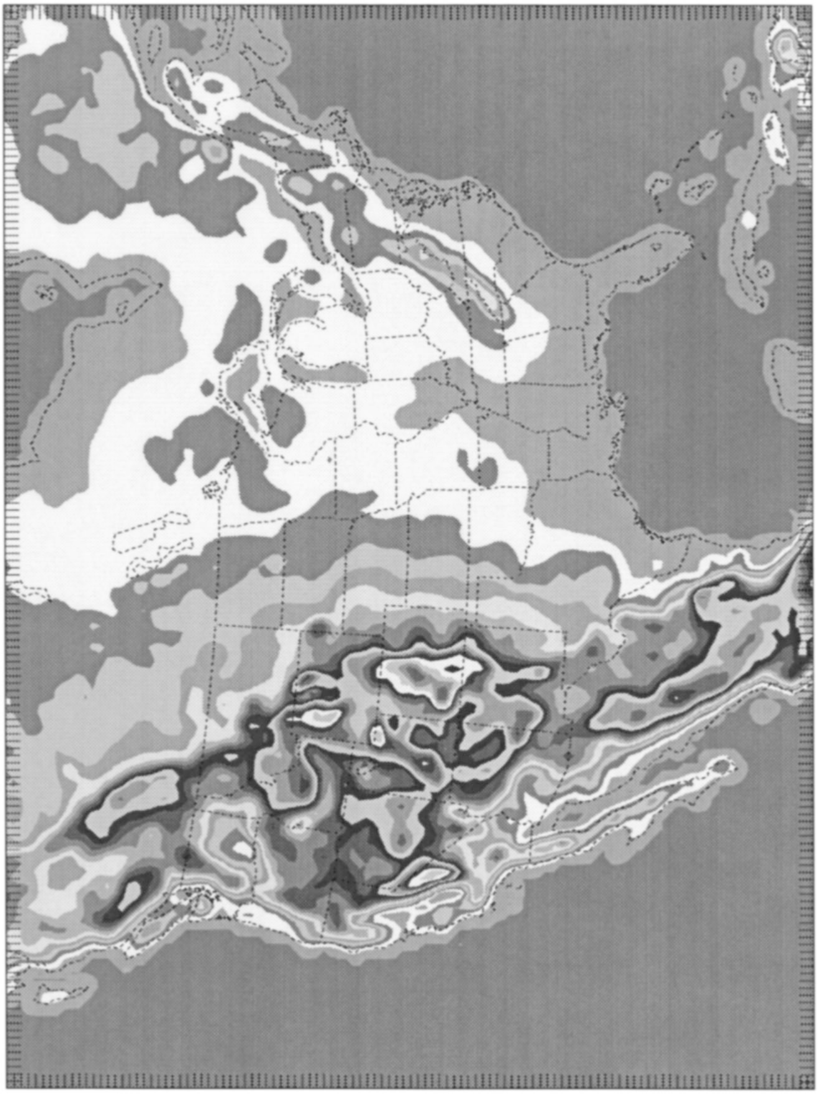

FIGURE 2.2 Representation of the topographical features that are resolved using the 40-km grid spacing of MAPS. 200-m contour interval.

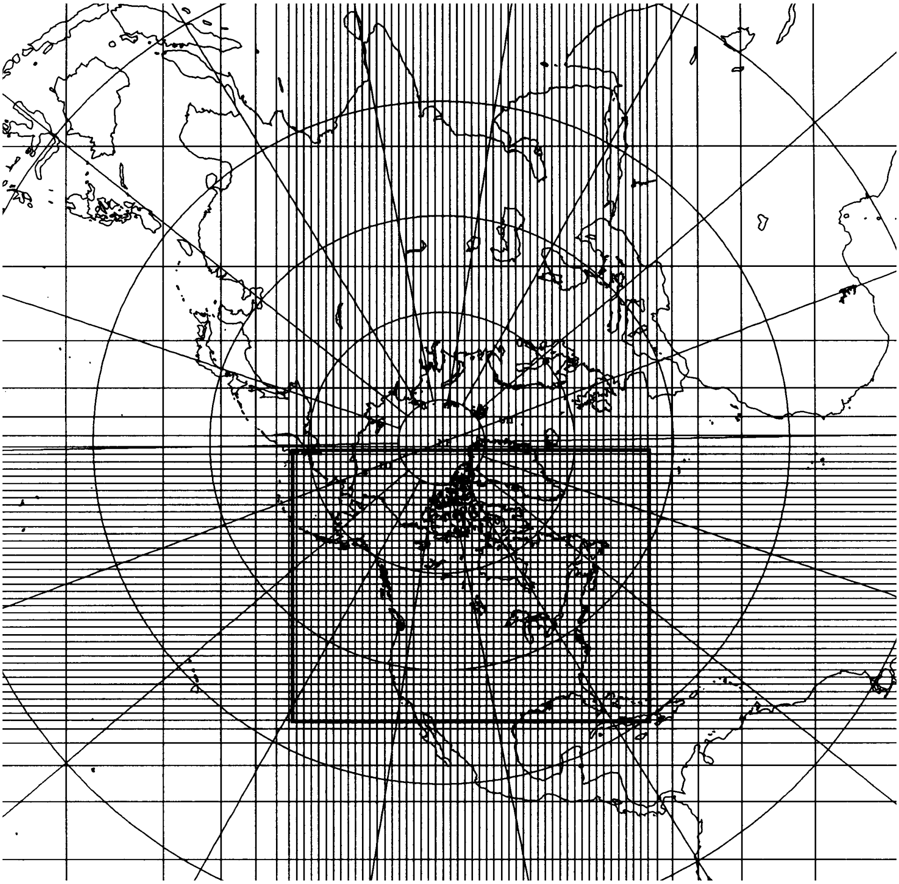

FIGURE 2.3 Variable-resolution horizontal grid of the Canadian RFE model on a polar stereographic projection. The resolution is 35 km in the central window (heavy rectangle).

However, hydrologic models and LSPs are on a converging course. In particular, new hydrologic models (see Abdulla et al., 1996) that simulate energy transfers have also made progress because of GCIP. Streamflow is now simulated in these models with an accuracy at least comparable to that achievable by the current generation of lumped conceptual models now used for operational purposes. Basically, GCIP and the other continental experiments have produced real innovations in the way regional to global models treat aspects of the land surface scheme, and the present segregation of hydrologic models and LSPs may soon be eliminated.

Project for Intercomparison of Land Surface Parameterization Schemes

GCIP helped to establish and supports the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) (see Henderson-Sellers et al., 1995), which provides a framework for evaluating LSPs. After early phases designed to evaluate certain elementary consistency measures using synthetic data, PILPS has formulated several sets of tests using local and regional observed data. For instance, common forcing data were provided at 30-minute resolution intervals for an agricultural site at Cabauw, Netherlands, for a full year. Because this was a drained field, runoff from the site is not the same as from a natural field. However, subsequent tests for a gauged catchment within the French Hydrologic-Atmospheric Pilot Experiment (HAPEX) field site provided an opportunity for the comparison of modeled and observed soil moisture and streamflow. There was a large spread between the model results and the available observations.

A new phase of the PILPS experiment is especially relevant to GCIP. PILPS 2c (Arkansas-Red River basin, or GCIP LSA-SW) will provide the most comprehensive hydrologic testing of LSPs to date. The scale of the application is consistent with the scale of numerical weather prediction (e.g., several hundred model grid cells), so some of the problems of scale mismatch inherent in testing surface fluxes with point data from land surface experiments such as the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) and the Boreal Ecosystems/Atmosphere Study (BOREAS) are avoided. PILPS 2c will also provide the first real test of the hydrologic performance of the current generation of LSPs as well as the first real test of macroscale hydrologic models.

Other Model Improvements

GCIP has done more than simply improve the representation of surface climate; it has also been instrumental in generating new and improved high-resolution operational regional analysis models that better describe the atmospheric climate. Cumulus convection parameterizations are continually undergoing modifications in all regional models. The treatment of the planetary boundary layer in regional models is also being updated continuously (e.g., Janjic, 1994) using data from field experiments such as FIFE and BOREAS and from large-scale eddy simulations. The parameterization depends on the type of land surface, the flow regime (whether stable or unstable), and the closure scheme. More realistic formulations of the free convection limit and the roughness length will lead to more accurate forecasts of surface temperature and wind. More realistic surface temperature and dew point predictions should also result from refined treatments of surface evaporation, snowmelt, and soil humidity analysis over North America. With the advent of the new land surface schemes and the GCIP data set, some of these previous planetary boundary layer (PBL) schemes will be further improved and will eventually replace the simpler schemes in global models.

Many global models still use simple relative humidity relationships to determine cloud cover. However, because of GCIP and related GEWEX research, the physical representation of clouds in regional models is being improved in operational regional models (Zhao et al., 1997). Like the RFE, the Eta model now includes a prognostic cloud parameterization scheme along with an additional predictive variable, the cloud water-ice mixing ratio, in the model's prognostic equations to represent both liquid water and cloud ice at every model atmospheric level. The model-predicted cloud water–ice mixing ratio and relative humidity are then used to estimate the cloud fraction at each model grid point. Precipitation is diagnostically calculated from the cloud water–ice mixing ratio. Calculation is done level by level, from the top to the bottom. All basic microphysical processes associated with the interactions between cloud water, cloud ice, rain, and snow are included in the precipitation calculation. The evaporation of precipitation under cloud bases is specially treated to allow the precipitation to fall, while it is evaporating, through the unsaturated layer to the ground. Horizontal cloud advection also allows the nonprecipitating condensate to be advected by the winds and by horizontal and vertical diffusion from one place to another until it evaporates.

Cloud water provides a negligible contribution to the total water and is thus ignored in most hydrologic computations; however, the contribution to the total water budget in the upper troposphere may be of interest. The predicted clouds in the Eta and RFE models are also used as input to the radiation parameterization. These parameterizations are expected to have a significant impact on precipitation and three-dimensional humidity forecasts. Energy budget calculations are expected to benefit from more sophisticated solar and infrared (IR) radiation parameterizations. Other observational programs, including Surface Radiation Budget (SRB), Baseline Surface Radiation Network (BSRN), and ARM, will be useful for providing validation data of the parameterized radiation fluxes within the GCIP area.

To summarize, the GCIP data set will contain new regional model outputs, over a basin covering most of the continental United States. Never before has so much high-resolution regional model output been available for developing a comprehensive investigation of the water and energy cycles in the atmosphere as well as the land surface over this large a continental area.

RECOMMENDATIONS

GCIP is developing some of the most advanced regional-scale models in the world. However, these advanced regional models need further development before large-scale hydrologic routing modules are included. Other parameterizations in these models, including clouds, precipitation, and radiation, also require special attention. Systematic comparisons, such as those being carried out by PILPS over parts of the Mississippi, are important for understanding model biases. Process studies, such as the way in which the land surface affects the Great Plains low-level jet, are also important because these features are not easily observed with the current sparse observational network. Specific recommendations relevant to these and related issues are discussed below.

Further Test and Compare LSPs

Model analyses discussed in Chapter 3 will provide part of the necessary validation for modeling studies; however, these analyses are partially dependent on the analysis model itself. Many land surface processes such as soil moisture and evaporation are strongly model dependent. It is important to understand how different models treat these and other processes under similar conditions. Field programs such as ARM and Cooperative Atmosphere-Surface Exchange Study (CASES) provide additional validation for models, and GCIP should actively participate in such programs.

Land surface parameterization constitutes one of the most critical areas for controlled comparison and validation. GCIP models have to participate in experiments such as PILPS to establish performance benchmarks that could then be applied to the rest of the GCIP domain. For example, one of the new PILPS experiments will cover GCIP's LSA-SW. Given the extensive GCIP data sets for other large-scale areas, it would be of interest to promote similar comparisons in these other LSAs.

Improve Methodologies to Disaggregate Regional Model Output to the Scales of Hydrologic Processes

LSPs and hydrologic models have many parameters that are tuned to the scale of the model. For example, a GCM LSP would use different parameter values than an LSP designed to work with local historical station data; recently Gao et al. (1996) showed that current GCMs simulate precipitation with reduced intensity and increased frequency, compared to local site data. Regional models deal with drastically different scales from either GCMs or station observations. We also know that LSPs could be developed at higher resolution than the atmospheric models in which they are embedded. It may be desirable to decrease the scale of the land surface parameterization even if computational restrictions prohibit a decrease in scale for the rest of the model. Developing LSPs and hydrologic models that will work with a variety of global to regional observational data would be useful for a variety of studies. For example, Gao and Sorooshian (1994) developed a stochastic precipitation disaggregation scheme that redistributes the GCM-calculated grid-average precipitation into a subgrid scale to improve the interaction between atmosphere and land surface. However, before we can develop scale-independent models, we have to understand the scale dependence of the input and output, as well as how to adjust these scales to give the best possible predictions.

LSPs capable of simulating streamflow, as well as state variables (soil moisture, surface temperature) and land-atmosphere fluxes, should be evaluated over the entire Mississippi River basin and its major tributaries. Complex modeling issues abound in runoff predictions. For example, the way water is partitioned into runoff and infiltration during the melting of snow and ice is a critical unresolved issue. Most LSPs follow the lead of prior-generation bucket models in effectively assuming that runoff instantly vanishes or, in some cases, goes directly to the ocean. LSPs with routing schemes that allow direct comparison of predicted and observed streamflow for major tributaries of the Mississippi would provide a unique means to validate the hydrological component of climate predictions. Limited work has been done with macroscale hydrological models, which typically operate at spatial scales compatible with numerical weather prediction or climate models. Some LSPs have attempted to take into account the surface heterogeneity in soils and vegetation as well as subsurface processes. LSP landscape features are in turn being used to describe the surface fluxes of heat and moisture into the planetary boundary layer. Runoff routing, however, is an important feature not widely present in most LSPs that deserves near-term attention.

Evaluate Model Representations of Atmospheric Mesoscale Circulations Induced by Landscape and Topography

The way in which the atmosphere interacts with the land surface is an evolving issue. Avissar and Liu (1996) suggest that mesoscale circulations induced by heterogeneous landscapes may concentrate precipitation on initially drier regions and thus tend to homogenize the surface moisture. Copeland et al. (1996) also indicate that the effects of land-use changes on climate within the GCIP region are systematic and substantial. Given the different PBL representations used in various weather and climate models, it is important to establish just how different the PBL schemes are and whether significant differences in turbulent transports occur. Comparisons of various PBL models have also begun for cloud-topped regimes (Moneg et al., 1996), and it would be useful to promote similar comparison activities for GCIP regions. A related problem is the depiction of the low-level jet (Stensrud, 1996), which is important for the transport of water vapor and heat in the Mississippi basin. This jet is analyzed quite differently by various models, especially in its nocturnal phase, which has not been well observed (Wang and Paegle, 1996). How this jet appears in different models, what its diurnal cycle is, and how important its transports are in comparison to the background large-scale transport are important scientific questions.

Improve the Parameterizations of Clouds and Precipitation in Regional Models

The scale mismatch inherent in the representation of cumulus convection in GCMs and large-scale forecast models requires that these processes be parameterized, rather than estimated explicitly. The resulting condensation and heating profiles have profound consequences on upper-level moisture and atmospheric diabatic heating processes. How should this convection be parameterized from cloud-scale models that explicitly model convection to large-scale hydrostatic models that handle convection mainly through parameterization? The GEWEX Cloud Systems Study (GCSS) (see Moncrieff, 1997) have begun to compare cloud systems over the tropical western Pacific; it would be useful to promote a companion study for the GCIP region. Scales and intensity of precipitation at the surface are also an issue. How should model precipitation be scaled to better match the characteristics of observed precipitation? How could orographic precipitation in large-scale models be adequately described?

Cloud formation and dissipation are important processes because of their effects on the atmospheric and surface energy balance. The patterns of cloud, precipitation, and surface temperatures, among properties, are generally quite inhomogeneous. How the distribution of such quantities affects radiative heating and whether GCIP models can adequately predict the distributions are unknown. The cloud modeling community has developed microphysical methods for describing clouds and precipitation. These microphysical methods are too computer intensive for large-scale models, but they have led to simpler ways of modeling clouds and precipitation that are just beginning to be incorporated into atmospheric models.

3

Data Assimilation

Develop and evaluate atmospheric, land, and coupled data assimilation schemes that incorporate both remote and in situ observations.

BACKGROUND

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 (NWP) model. Analytical accuracy is continuing to improve as an increasing diversity of high-resolution observations from new in situ and remote observing systems are incorporated. Analytical accuracy also progresses as initialization techniques and the underlying models used for the analyses continue to improve.

Less than 15 years ago, most numerical weather prediction models (global and regional) did not include the range of diabatic and hydrological processes that are now taken into account. It was thought that NWP models only had to carry dynamical atmospheric variables and that many physical processes, especially land surface processes, mattered merely for climate simulations. This philosophy changed after the spectacular success of the ECMWF medium-range forecasts (Kanamitsu, 1989). It is now well recognized that NWP models for short as well as long time ranges, including 4DDA must include the full suite of physical processes. In addition, predictions of these processes may, in most instances, constitute the best current global descriptions of them; although analyses are not observations, they are, in some sense, optimal inferences from these observations. Prediction of temporal variations in the horizontal and vertical structure of condensation and evaporation may be especially helpful since convection and boundary layer fluxes cannot be determined directly from current in situ observations over large enough domains. Even those quantities that are observed, such as precipitation or snowcover, are not measured very well, and comparisons between analyses and measurements can yield new insights.

GCIP's focus on assimilation of land surface variables should result in significant improvements in forecast accuracy and range. Snow water equivalent is beginning to be assimilated, but soil moisture remains a problem. We do not know how to estimate soil moisture from observations on a continental scale, much less how to specify its initial value for numerical weather prediction. Also unknown is how to assimilate subsurface temperature. Streamflow and precipitation measurements could provide additional information about how to update snow and soil moisture as well as the atmospheric dynamical fields that are implicitly dependent upon their values.

GCIP's focus on precipitation should also result in significant improvements in precipitation and streamflow forecasts and climatologies. Prior to GCIP, precipitation was reported only from individual stations. With the advent of GEWEX, the Global Precipitation Climatology Project (GPCP) began, and we now have global archives for a number of years (Xie and Arkin, 1996). GCIP is playing a major role in extending these coarse-scale global climate products (2.5°) to operational high-resolution (4-km) gridded precipitation for the continental United States (Baldwin and Mitchell, 1996). This analysis effort will further help to combine the disparate scales of atmospheric weather and climate with surface hydrologic scales.

GCIP ACCOMPLISHMENTS

Regional Model Analysis Archives

A number of model analyses, including the NCEP and the ECMWF global data assimilation systems, have been available since the late 1970s. NCEP's reanalysis (Kalnay et al., 1996) will further extend these analyses back to the 1950s. These analysis products are available at NCAR. Many scientists have used these and similar analyses to describe the global hydrologic cycle as well as the continental hydrologic cycle over the continental United States (e.g., Roads et al., 1994; Higgins et al., 1996).

Regional analysis systems (such as the NCEP nested grid model analysis system) were introduced in the 1980s to make better use of the high-resolution data available in certain regions (e.g., over the United States). However, regional analyses were archived only at NCEP and other numerical weather prediction centers and were not readily available to the community. GCIP has changed this; a number of analysis centers are participating in the GCIP project and are archiving their products on common horizontal grids (40 km on a Lambert-conformal projection). As discussed in Chapter 2, the NCEP regional Eta Model Data Assimilation Sys-

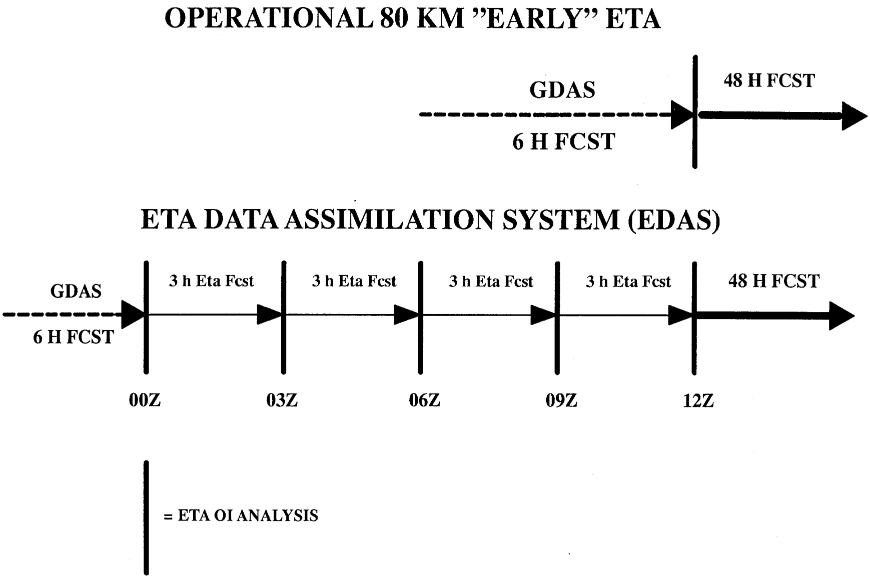

FIGURE 3.1 Data assimilation cycle for the Eta model. The early forecast is initialized from the GDAS. The Eta model currently allows 12 additional hours of spin-up. A continuously cycled data assimilation system has been developed for the Eta model and is undergoing final testing. Note: FCST = forecast; OI = optimal interpolation.

tem (EDAS) (see Rogers et al., 1996) and NOAA's MAPS (see Bleck and Benjamin, 1993; Benjamin et al., 1996) will deliver analysis products to GCIP. (It should be noted that MAPS is the experimental version of the model used for the NCEP Rapid Update Cycle Prediction.) The Canadian RFE (see Ritchie, 1991), used in the companion Canadian MAGS project, will also support GCIP objectives. For the first time, investigators will be able to analyze regional features at high resolution over a continent-scale domain on climatic time scales. This is a very timely development, when one considers the advent of high-resolution satellite measurements in the next century.

The RFE and EDAS regional analyses are currently initialized from the global analysis. However, since April 1, 1995 (GCIP archives), EDAS has allowed some additional time for the regional model to adjust the fast processes (e.g., convection) in the atmosphere. As shown in Figure 3.1, each EDAS execution spans a 12-hour assimilation period (four 3-hour cycles) that begins with a "guess" from the GDASs and ends with a 48-hour Eta model forecast from the final EDAS analysis. During this 12-hour cycle, EDAS assimilates a considerable variety of new data not incorporated in GDAS. In addition to surface stations, EDAS assimilates wind data from the radar profiler network in the central United States and automated observations of wind on commercial aircraft, known as ACARS (Automated Communication and Recording System) data. Recently, the assimilation of Special Sensor Microwave Imager (SSM/I) derived total column water vapor over oceans was implemented, to be followed in 1996 by the assimilation of GOES-derived water vapor profiles in clear areas over land and ocean.

In contrast to the current EDAS, the MAPS regional analysis system uses a continuous assimilation cycle for surface as well as atmospheric variables. MAPS currently uses all available surface data, aircraft observations (including temperatures), profiler (both the NOAA network and a number of boundary-layer profiles), radioacoustic sensing system (RASS) temperature profiles, and the horizontal velocity azimuth display (VAD) winds from the WSR-88D radars. These data are assimilated in an ongoing 3-hour cycle (which was changed recently to 1 hour). MAPS is also using a five-level soil vegetation model, and additional enhancements to most physical parameterizations are about to be implemented (Smirnova et al., 1996, 1997a). MAPS has a land surface scheme similar to the ETA model, and because of the continuous cycling the GCIP data base will now contain a regional-scale land surface-assimilated data set. A similar continuous assimilation cycle for EDAS is currently being introduced into operations.

Besides developing the regional analysis archives, GCIP was the driving force for developing useful augmentations to these model output products. In particular, a number of reduced data sets are being archived along with the full three-dimensional products. Model Output Location Time Series (MOLTS) will provide hourly time records of various model outputs at some 300 "station" sites (Figure 3.2). These products include time series of vertical latent heating and radiative heating profiles, soil moisture, soil temperature, precipitation, runoff, evaporation, snowmelt, and more. Many of these model sites are coincident with radiosonde sites. Another reduced data set is the Model Output Reduced Data Set (MORDS), which will provide vertical sums of the atmospheric budget variables as well as low-level atmospheric variables that interact with surface variables on a common 50-km grid. Also included in MORDS are horizontal slices at several atmospheric levels. This unprecedented level of postprocessing in the archives means that many researchers will now be able to effectively examine critical subsets of the gigabyte-to-terabyte archives associated with modern analysis systems without having to do an inordinate amounts of preprocessing themselves.

Land Data Assimilation System

The increase in spatial resolution in regional analysis models has affected the kinds of processes incorporated into both analysis and forecast models. Studies have begun to demonstrate the importance of surface inhomogeneities (gradients of soil moisture, vegetation type, soil type, cloudiness, and resulting surface temperature variations) in triggering mesoscale circulations. Such mesoscale circulations are often particularly important for initiating convection. Moreover

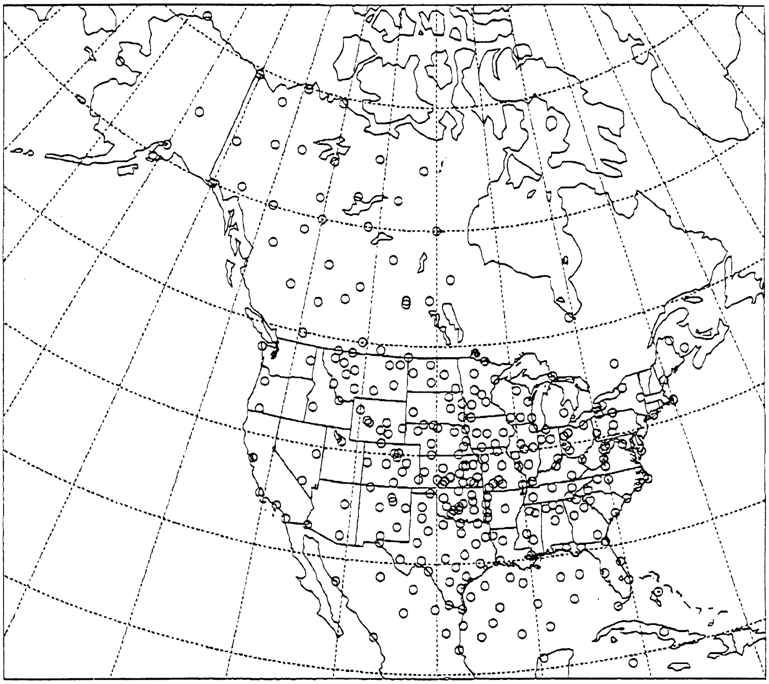

FIGURE 3.2 Geographic distribution of 300 MOLTS locations. Locations include all standard radiosonde and surface observations as well as derived quantities including vertical profiles of radiative and convective heating and latent heat release.

surface characteristics, especially soil moisture, may vary significantly over periods of only a few hours and influence the atmospheric circulation on the same time scale. In fact, assimilation systems are beginning to resolve scales at which surface influences are often equivalent to or even more significant than dynamical interactions in the general circulation of the free atmosphere. As discussed in Chapter 2, GCIP accelerated this recognition of the importance of land surface processes in weather and climate predictions.

In particular, GCIP provided the framework for developing companion Land Data Analysis Systems (LDASs) (K. Mitchell, personal communication, 1996). An LDAS is the land surface-hydrological component of the regional models that could be forced by observed or model fields and could cycle continuously on itself. Gridded precipitation fields provided by the precipitation analysis discussed below and hourly half-degree surface radiation fluxes inferred by the National Environmental Satellite Data and Information Service (NESDIS) from operational GOES-8 satellite observations could be used in place of model-predicted fields. Near-surface winds, humidity, and temperature data, which are needed as inputs to compute surface sensible and latent heat fluxes, could be provided by the regional models as well as observations. An independent LDAS could thus provide estimates of soil moisture, surface evaporation, surface sensible heat flux, and runoff that should prove to be more reliable than those generated by the operational assimilation schemes for the same surface variables. The LDAS could also be used to explore land surface climate scenarios available from GCMs. LDASs also form a potential bridge from LSP models of global general circulation models to hydrologic models of operational hydrology. It should be noted that a model-driven LDAS has been running in MAPS since April 1996 (Smirnova et al., 1997b).

Precipitation

GCIP also helped initiate the NCEP-OH (NOAA Office of Hydrology) operational national 4-km hourly precipitation analysis. This analysis is derived from the new WSR-88D (NEXRAD) radar-based precipitation estimates and hourly rain gauge observations combined by a multisensor precipitation analysis algorithm. This algorithm was developed initially for the regional OH River Forecast Centers. Through the efforts of NCEP and OH to develop centralized access to this information nationwide and through the work of Seo (1998a,b), the Hourly National Precipitation Analysis became available in real time on an experimental basis in May 1996. The experimental product shown in Figure 3.3 includes (1) a merged gauge-radar product; (2) a companion gauge-only product; (3) a companion radar-only product; and (4) a companion NESDIS GOES satellite-only product (Baldwin and Mitchell, 1996).

This high-resolution precipitation product is also being tested as a possible input to the Eta model assimilation. For example, Lin et al. (1997) showed that by incorporating precipitation and its influence on latent heating, subsequent predicted precipitation amounts as well as other model variables are improved.

RECOMMENDATIONS

GCIP is developing a comprehensive set of regional analysis archives from three regional analysis systems (Eta, MAPS, RFE). However, these regional archives are likely to be highly model dependent and must be compared with each other as well as with global analyses and field observations. Surface products will be one of the most innovative and potentially most problematic regional analysis outputs. These surface products need special attention, including comparison to output from hydrologic models and LDASs. LDAS simulations are just beginning and also require special attention. Finally, given all the scientific developments that will occur in the development of analyses for these surface and atmospheric variables, including longwave radiation and precipitation, it is espe-

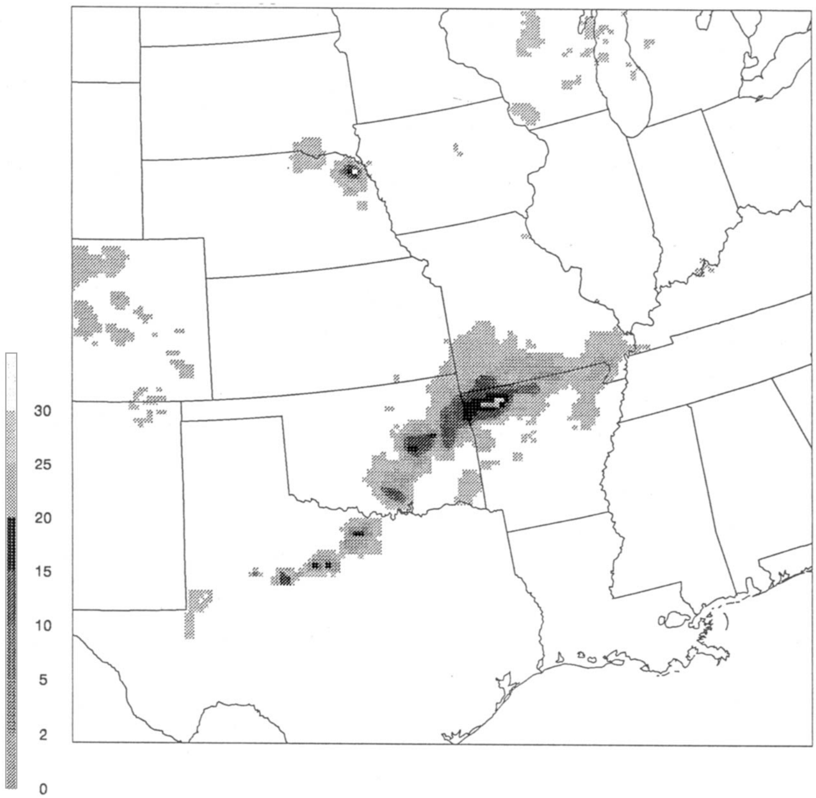

FIGURE 3.3 One-hour precipitation accumulation (mm) over the south central United States valid at 04 GMT, September 24, 1996, from the hourly 4-km multisensor gauge-radar NCEP National Precipitation Analysis (NPA). Only about one fourth of the NPA domain is depicted.

cially important that GCIP begins to plan for an eventual reanalysis of its products. Specific recommendations relevant to these and related issues are discussed below.

Archive and Develop GCIP Analyses and Forecasts for Comparison with GCM Simulations, Global Analyses, and Field Observations

Regional analysis systems being developed for limited-area NWP have great potential to assimilate data from high-resolution weather observing systems coming on-line in the near future over the United States. However, we need to know whether significant improvements result from current regional models or whether even higher resolution is required to provide noticeable impacts. Comparisons to global analysis products would be useful. Comparison to a range of observations, especially surface flux data, PBL profile data, and shelter-level temperature and dew point data from field projects such as FIFE (see Betts et al., 1993), HAPEX, SURFRAD, ARM-CART (see Charlock and Alberta, 1995), VORTEX, CASES, and BOREAS, could also be utilized to validate the regional 4DDA outputs. Additional data, such as satellite-derived surface skin temperatures, are being utilized at NCEP for model validation. Also, numerous surface measurements from cooperative stations that are not transmitted in time for incorporation into the operational analysis could also be compared to analyzed products.

Another problem is that the constant insertion of data into the analysis process keeps the analyzed climatological fields close to observations. However, the consequence of these frequent corrections is that the model increments or tendency terms are neither small nor random, and are sometimes dominant in regional hydrologic budgets (see Kanamitsu and Saha, 1996; Roads et al., 1998a). Although different model errors may compensate in different regions, reducing analysis increments in all regions is one clear measure of the quality of the model used for data assimilation (Roads et al., 1998b). It is important that this objective measure of analysis quality be retained in the archive. In addition, before GCIP, most climatological budgets were calculated twice a day from instantaneous analyzed fields. Nonlinear terms could be seriously aliased in this procedure, producing considerable errors in atmospheric water and energy budgets derived from instantaneous model output every few hours. Budget quantities should be accumulated at every time step and output values provided several times a day. Such cumulative results often combine contributions from several processes. It is important to keep separate accounts of these different contributions, since they cannot be unraveled afterward (except by redoing most of the original computation). For example, it would be important to archive horizontal and vertical advection terms, as well as implicit sub-grid-scale cumulus and planetary boundary-layer advection terms.

Analysis increments provide a description of some but not all regional model biases. Longer-term differences are not currently known since few regional models have been run for long time periods. It would be useful to run regional models for longer periods, like GCMs, to determine the characteristic time scales of the processes, especially processes at the land surface. In fact, one of the primary goals of GCIP is to show that improved modeling of the land surface-atmosphere interface in regional coupled models will improve predictions of weather and climate on a broad range of time scales from the diurnal to interannual. Some GCIP research has provided tantalizing evidence for this capability (Roads et al., 1998a), but more needs to be done. This research can be done initially with GCMs, but eventually it would be useful to determine how the heterogeneity of the land surface at GCIP scales contributes to the overall variability and predictability of atmospheric variables, including precipitation.

Diagnostic studies of rain-producing processes in limited-area and mesoscale model analyses are also needed to address another important aspect of GCIP science. The characteristics of convection and the vertical structure of rainclouds in various regional models are clearly different, and the GCIP community needs to understand how precipitation forms in these models and what the hydrologic balances are once it is formed. Understanding the vertical structure of the energy and water budgets and how they are treated in analyses as well as GCMs would be helpful for eventually developing better parameterizations for moist convection and boundary-layer processes. Developing a better understanding of precipitation characteristics would also lead to improved utilization of precipitation data as input to new atmospheric analysis schemes.

Develop and Distribute High-Resolution LDAS Products and Models

A completely satisfactory high-resolution land surface initialization scheme has not yet been developed for regional models. As mentioned previously, the EDAS and RFE analyses are currently initialized from coarse global analyses. The impact of using such coarse global initializations, especially for the land surface, is unknown but potentially important because of the long time scales inherent in land surface processes. It is essential that regional analysis models have their own land surface initialization, independently from a global model analysis, to permit the assimilation of high-resolution GCIP observations, rather than reinitializing from global analyses.

Much of the initial work on the stand-alone initialization of the land surface component of regional models can be carried out through LDAS studies. LDASs may also provide a promising approach to optimally determine land surface characteristics from available (incomplete) observations. Snow, soil (and perhaps lake), and vegetation water storage could eventually be part of the system. It is important to undertake an LDAS experiment with higher-resolution models as well as hydrologic refinements, especially with regards to the simulation of runoff. Although several problems remain to be solved, including anthropogenic influences on river flow through various water diversion projects (e.g., dams), a runoff model would be a definite step toward fulfilling GCIP's goal of developing a continental hydrologic information system, similar to the existing global weather information systems.

LDASs do not provide the coupling that may eventually be needed to properly represent land surface effects. Indirect methods, such as comparing weather predictions based on land surface analyses from LDAS and regional models, should be tested. For example, one could expect that the structure of the planetary boundary layer as well as atmospheric convection would be affected strongly by different initialization schemes for land variables. Basically, there is much to be learned from LDAS products, and the various regional centers producing such analyses should develop a dialogue with users that could exploit subsets of the data for testing future land surface and regional model schemes. Critical to this effort is the development of a GCIP data base of gridded data that could be used to force the LDAS systems.

Develop a Strategy to Facilitate Future Reanalyses of GCIP Data

Problems arise when using operational analyses to describe climate and climate variations because of successive upgrades to the analysis systems. Operational analysis systems are constantly being modified and improvements being implemented. For example, the optimal interpolation schemes used in EDAS and MAPS will be replaced next year with a three-dimensional variational analysis method, which will allow, in particular, the direct incorporation of satellite water vapor radiance data (McNally and Vesperini, 1996) and eventually other remote sensing variables such as radar reflectivity and global positioning system (GPS) signal data. It is important that these changes in analysis technique be clearly documented and in the archives. We need to know whether significant changes are due to climatic events or model enhancements.

Despite documentation of improvements in the analysis scheme, discontinuities and artificial jumps in the climatic record will impair the usefulness of GCIP analysis products for the study of long-term climate variations. Already, several global reanalysis programs are under way in an effort to produce consistent multiyear records of coarse-scale atmospheric and surface fields. Although the quality of data inputs may vary, these projects will at least use a consistent procedure to reanalyze data from the recent past. The GCIP archives should be organized so as to allow similar reanalyses. Combined global-mesoscale reanalysis systems could be an effective tool to investigate the relative influence of factors such as topography resolution, land surface physics, different observing techniques, precipitation, and temperature anomalies.

Other products would also benefit from a well-conceived reanalysis plan. For example, given that GCIP's 4-km precipitation analysis is produced in an operational (not research) context, it is essential to allow for a posteriori improvements of these archived operational rainfall estimates. Merging various precipitation data is also problematic as we infer area-averaged estimates (100 km^2) from kilometer-scale NEXRAD observations. Separate archiving of model-generated, gauge, radar (including separate components of the radar as well as the merged radar products), and satellite data sets is a requirement for assessing and eventually improving their quality. This is especially important for wintertime precipitation estimates, which are known to have large observational errors in both gauge and radar products (Groisman and Legates, 1994).

4

Data Collection and Management

Provide access to comprehensive in situ, remote sensing, and model output data sets for use in GCIP research and as a benchmark for future studies.

BACKGROUND

Over the Mississippi, weather and climate observations are made hourly or even more frequently depending on the particular weather situation or the particular observational system. Such frequent observations are obtained from pressure and temperature sensors and hygrometers in instrument shelters 2 m above the ground surface, from wind anemometers 10 m above the ground surface, from precipitation gauges at heights 1-2 m above the surface, and from stream gauges. Observations are made less frequently in the upper atmosphere by ascending radiosondes with temperature and moisture sensors, and remotely by radar and satellite-borne sensors. There also are new or less common instruments, such as the Automated Surface Observing System (ASOS), atmospheric profilers, weather radars, and satellite-borne sensors. In some cases a variable is measured directly (e.g., precipitation total from a precipitation gauge), whereas in other cases a value is estimated by interpreting a remotely sensed signal (e.g., continental estimates of snowcover from satellite radiance data). Many of the observations are made as part of a meteorological or hydrological network and are available in real time over the Global Telecommunications System (GTS), the primary source of data for the world's NWP centers.

ACCOMPLISHMENTS

Special Data Sets

The kinds of data available to GCIP efforts are illustrated by the data sets gathered for the fourth GCIP Initial Data Set (GIDS-4). These data were collected during the April to September 1995 Enhanced Seasonal Observing Period (ESOP-95) and include surface data from a variety of federal and state agencies, upper-air data, radar data, land characterization data, satellite data, and model output data. Additional ESOPs are being planned as GCIP emphasis moves from LSA-Southwest toward LSA-North Central, LSA-East, and eventually LSA-Northwest. The types of ESOP data gathered and disseminated will vary depending on data availability and needs within LSAs. For example, snow depth and areal extent measurements will be a special emphasis of the north central ESOP.

Most of the GIDS-4 data were collected by the University Corporation for Atmospheric Research (UCAR) Joint Office for Science Support (formerly known as the Office for Field Project Support) from existing data collection systems, although several unique data sets were derived from or supplement standard data (e.g., GIDS hourly and daily composites of precipitation and surface observations). ESOP-95 was also coordinated with the VORTEX project, and project data from both initiatives are available to all researchers. This combined data collection exemplifies the character of the climatological GCIP effort; GCIP is not planning specific field campaigns but instead intends to augment the GCIP continental and climatological perspective with data from individual field programs. Especially noteworthy is the successful cooperative data arrangement with the DOE's Atmospheric Radiation Measurement program, which will be included in the standard and LSA-SW ESOP data sets compiled for GCIP.

The GCIP Reference Data Set (GREDS) has been widely disseminated. GREDS includes a considerable amount of relevant background information, broadly characterized as data that will change little if at all during the next several years. This includes information on the physical geography of the GCIP region, along with cartographic information. GCIP is supporting additional efforts for characterizing soil physical and hydraulic properties. A soils data set is being developed from the U.S. Department of Agriculture (USDA) National Resource Conservation Service (NRCS) State Soil Geographic Database (STATSGO) and the county-level Soil Survey Geographic Database (SSURGO). This data set covers the 48 conterminous United States at a resolution of 1 km and contains information on texture, depth to bedrock, particle size distribution, rock fragment class and volume, porosity, hydrologic soil groups, and available water capacity. These data sets not only are useful to GCIP but also are useful to a wide variety of interdisciplinary studies.

Another retrospective data project being developed consists of pertinent data from two abnormal climatic events, the 1988 drought and the 1993 floods in the Mississippi River basin, which occurred just as GCIP was beginning its data collection efforts. These data will be used in conjunction with regional modeling efforts designed to understand these extreme events. Future data projects will include compiling high-quality hydrometeorologic data for even longer time periods (e.g., 30 years) to put ESOP and Enhanced Observing Period (EOP) data in their climatologic context and to assess the impact of climate variability on water resources. Data will include such variables as precipitation, air temperature, streamflow, and other available meteorological observations.

Four-Dimensional Data Assimilation Products

Model-derived four-dimensional data assimilation output for the GCIP program is being gathered from a number of atmospheric and hydrologic assimilation systems of various resolutions and with differing physics and data assimilation methodologies. Products are obtained from these global 4DDA systems, run by NOAA and Canada. Three principal mesoscale 4DDA systems used by GCIP are the NOAA-NCEP EDAS, the NOAA Forecast Systems Laboratory (FSL) MAPS, and the Atmospheric Environmental Service-Canadian Meteorological Centre (AES-CMC) RFE analysis system.

Although the full model outputs will be available, their very large volume (terabytes) will prohibit full examination by most users. Because of the immensity of these data holdings, GCIP is making a special effort to disseminate the essence of model output data. Postprocessed 4DDA output is available in two special GCIP data sets: (1) one-dimensional vertical profiles and surface time series at selected locations (MOLTS), and (2) gridded two-dimensional fields, especially ground surface state and flux fields and top-of-the-atmosphere flux fields (MORDS). Subdividing the 4DDA output into these component parts greatly facilitates dissemination of data sets to users. Forecast fields are also being archived and made available. As discussed in Chapter 3, forecast diagnostics are especially valuable in understanding how models adjust from initial conditions to conditions that are more compatible with the model physics.

Data Management and Service System

The GCIP project office is compiling information on data and metadata as they are collected at different centers, rather than assembling the information at one location (Figure 4.1). By directly accessing a distributed center, a user also receives further specialized information on the data sets (e.g., formats, metadata) directly from the source. This distributed data management approach minimizes the lag time before data are available to scientists.

The GCIP Home Page on the World Wide Web (*http://www.ogp.noaa.gov/gcip*) serves as the focal point for the Data Management and Service System (DMSS). This location is intended to provide links to existing directories such as NASA's Global Change Master Directory (GCMD) or to provide special facilities developed for the GCIP-DMSS to expedite data searches. DMSS facilities also provide information on experiment status, documentation, and references.

The DMSS consists of four primary data modules. The in situ data module provides data management and information resources for surface, upper-air, radar, and land surface characteristics using the UCAR Office of Field Project

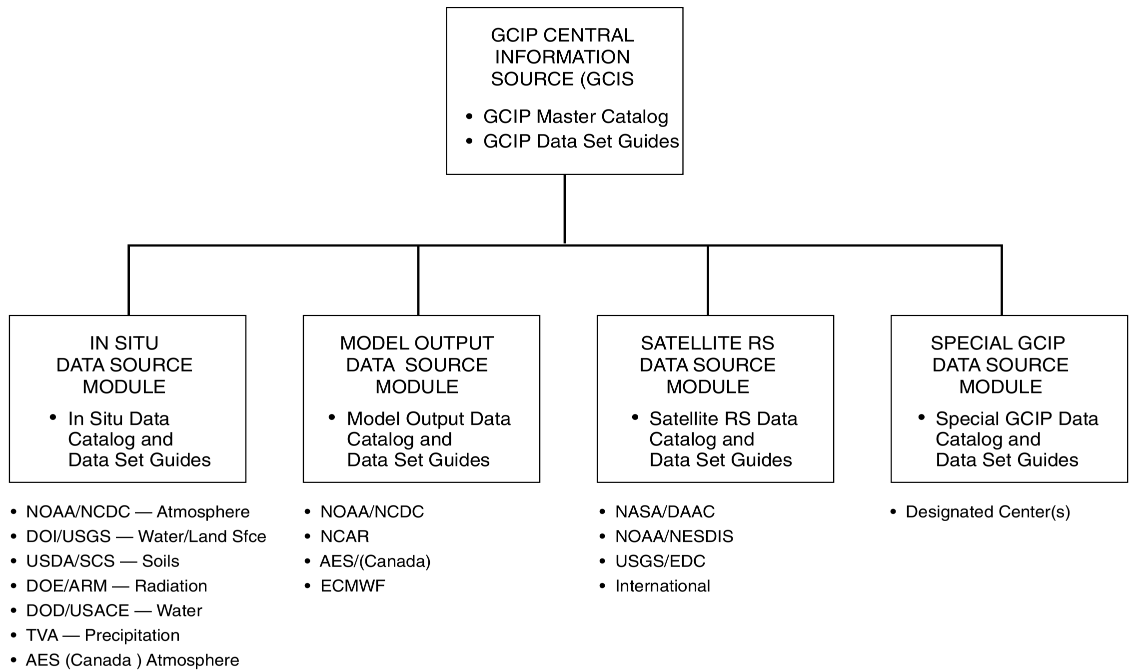

FIGURE 4.1 Organization of the GCIP Data Management and Service System. NOTE: DOD = Department of Defense; DOI = Department of Interior; EDC = Eros Data Center; RS = remote sensing; SCS = Soil Conservation Service; TVA = Tennessee Valley Authority; USACE = U.S. Army Corps of Engineers.

Support's Cooperative Distributed Interactive Atmospheric Catalog and the NOAA National Climatic Data Center's (NCDC) On-Line Access and Service Information System. Currently, data from the GIDS-1 and GCIP Integrated Systems Test (GIST) sets are available on-line, and data sites such as NCDC, DOE-ARM, and AES may be accessed. Activities planned for this module over the next several years include the following: (1) collecting data during the five-year EOP (1996-2000), including the ESOPs during this period; (2) providing "quick response" data sets (i.e., two-month lag) to the GCIP community; (3) continuing to provide GCIP data sets via on-line access and compact disk, read-only memory (CD-ROM); and (4) continuing to develop WWW enhancements to the module and establish links to other data centers and data sets.

The model output data module uses the NCAR Scientific Data Services as the infrastructure. Data sets provided by this module include output from the National Meteorological Center's (NMC's) numerical weather prediction model (Eta model) and its associated four-dimensional EDAS. All EDAS output is archived at NCAR. During the next several years RFE output from AES and MAPS output from NOAA-FSL will also be available through this module. MOLTS and MORDS will likewise be available here.

The satellite data module provides links to sites with remote sensing data sets. These include NOAA's NESDIS, the U.S. Geological Survey (USGS) Earth Resources Observation Satellite Data Center (EDC), and various international centers. It also previously provided a link to NASA's Data Acquisition and Archive Center (DAAC) at Marshal Space Flight Center. Work continues on improving the satellite data module, including compiling information about the GCIP data requirements and coordinating readily available data sets specified by principal research areas.

RECOMMENDATIONS

The GCIP data collection and management effort should add a scientific users' group to identify data sets of highest priority to GCIP researchers. The scientific users' group should recommend methods for the efficient archiving and reprocessing of high-volume NEXRAD data for climatological precipitation estimates. Methods to archive and access research data, especially remote sensing data sets created by individual GCIP scientists, also should be addressed. Specific recommendations relevant to these and related issues are discussed below.

Establish a Scientific Users' Group to Identify Priorities for the Data Sets Required to Achieve GCIP Scientific Goals—An Important Task for This Group is to Recommend an Archival Strategy for NEXRAD Data So That These Data Can Be Reprocessed Efficiently

The existing GCIP Data Collection and Management (DACOM) has done a commendable job of organizing the archiving of data sets, but now that GCIP is moving onto specific LSAs, it is important that science issues be the driving force for acquiring, archiving, and disseminating new GCIP data sets. This is the best way to ensure that GCIP science objectives are met.

The GCIP DMSS relies on the operational archives for very high data rate products, particularly raw data from the NEXRAD system for precipitation estimation. In fact, one of the prime drivers for GCIP being located in the Mississippi basin was the availability of data from these radars. Although these data are being archived, they are archived on an operational basis not designed for reprocessing of long time series of data from many radar sites. Retrieving a long time series of NEXRAD data from many sites is prohibitively expensive for GCIP or any other research project. The highest priority of this user's group should be to identify the levels of processing required, quality control issues, and practical schemes for the production, dissemination, and reprocessing of NEXRAD data.

Give Additional Attention to the Production, Archiving, and Dissemination of Remote Sensing Information

The GCIP-distributed DMSS relies heavily on operational systems subject to constraints and sometimes does not include GCIP data sets. Products that have not been derived as part of the operational system are not required to be archived and thus are not easily accessible through DMSS. The panel is particularly concerned that the Marshall Space Flight Center's DAAC has been closed, and no center has been identified to take over its responsibilities. Remote sensing information would be especially useful in supplementing in situ and model simulation data. In fact, some remote sensing information, such as the Normalized Difference Vegetation Index (NDVI) and snowcover, would be very useful in supplementing the in situ and model-assimilated data as more elaborate algorithms are developed to infer other land surface variables.

Investigate the Feasibility of Collecting Available Hydroclimatological Observations from Experimental Sites in Near Real Time

Field programs such as ARM, FIFE, and BOREAS have been invaluable for improving the quality of the models and data assimilation systems. However, except for the ARM site, no such data are available to the GCIP project as part of its standard operational archives. The information collected by these programs includes surface energy fluxes, soil moisture profiles, soil temperature profiles, planetary boundary-layer fluxes measured from towers, surface radiation measurements, and so forth, over the entire Mississippi basin. These flux measurements are a valuable resource for better parameterization of the surface and planetary boundary layers and for assimilation into operational models.

5

Application to Water Resources

Improve the utility of hydrologic predictions for water resources management up to seasonal and interannual time scales.

BACKGROUND

Management Issues

Proper management of water resources in large river basins, such as the Mississippi River basin, has the potential to benefit from improvements in scientific understanding of hydrologic processes, better modeling schemes (which can produce more accurate forecasts), and enhanced generation of data products, developed by programs such as GCIP. To realize how this will come about, it is important to understand what water resources management means from the perspective of an entire river basin. This includes an understanding of the wide variation in spatial and temporal scales at which the water resources are relevant because, in the final analysis, our ability to predict the availability of water in time and space under both "normal" and "anomalous" conditions will be critical for applications.

Most water resources management problems are either local or regional in nature. The complex hydrologic system of the Mississippi possesses a wide range of attributes, including numerous flood control structures, a network of navigation locks and dams, overlapping hydrologic and water resources management units, extensive groundwater and surface-water interaction and close proximity of the water table to the surface, and a wide range of hydroclimatic conditions along the basin. The average annual temperature varies from 5 to 10°C in the northernmost parts to 20-27°C at the mouth of the river. Similarly, the average annual precipitation varies between 50 and 100 cm in the northern parts of the basin and 150 and 180 cm in its southern parts. Seasonal variations in temperature and precipitation across the basin are even greater.

The regional nature of the management issue becomes apparent through a comparison of the water-use patterns, sources, and dispositions for three states on the Mississippi River basin (Figure 5.1). The selected states represent a north-to-south transect of the basin. In Nebraska for the year 1990, nearly 70 percent of the water consumption was for agricultural purposes. More than 53 percent of that amount was obtained from groundwater sources. Of the total water consumed, nearly 28 percent was returned to the river network. In Missouri, nearly 78 percent of the water consumption was for thermoelectric power generation. Almost 88 percent of the total water use came from surface-water sources, and 91 percent of the total was returned to the streams. As we move farther south to Louisiana, which is a more industrialized state, the primary water use (nearly 53 percent) was still for thermoelectric production, whereas 26 percent went for industrial applications. Of the total water use, nearly 86 percent was provided by surface-water sources, and almost 82 percent of the total was returned to the river network. Water quality/quantity resource and management issues for Nebraska (which is primarily an agricultural state) are likely to be different from those for Louisiana, where industrial consumption and instream use of water for cooling towers of power plants are prevalent.

Almost all water management decisions depend on relevant information and reliable predictions at different time scales. For example, short-term to extended weather forecast products generated by mesoscale models will enable farmers to know whether precipitation will provide the water required for the next irrigation cycle or whether alternative sources, such as surface-water diversion or groundwater withdrawal, must be arranged. At the seasonal time scale, reliable climatic predictions may enhance reservoir operation with respect to releases for water supply, power generation, and so forth. Furthermore, the ability to provide advance warning of the occurrence of floods will enable emergency and disaster relief managers to take timely and effective action toward saving lives and mitigating property damage (which can amount to billions of dollars). Prediction of droughts would also have a great impact on water resources management, for both instream and offstream uses. At the decadal time scale, the ability to predict regional tendencies toward warmer or cooler and wetter or drier conditions will be beneficial when establishing policies impacting the planning of water resources supply systems and socioeconomic issues such as migration, industrialization, and urbanization. The range of water resources concerns, depending on their temporal and spatial scales, is depicted in Figure 5.2.

Special mention should be made of the fact that a variety of water quality, wetland, fisheries, and aquatic ecosystem management issues are also affected by climate variability at the various space-time scales mentioned above. For instance, a different combination of land-use patterns on watersheds (i.e., deforestation, agricultural practices, urbanization, etc.) and human activities in rivers

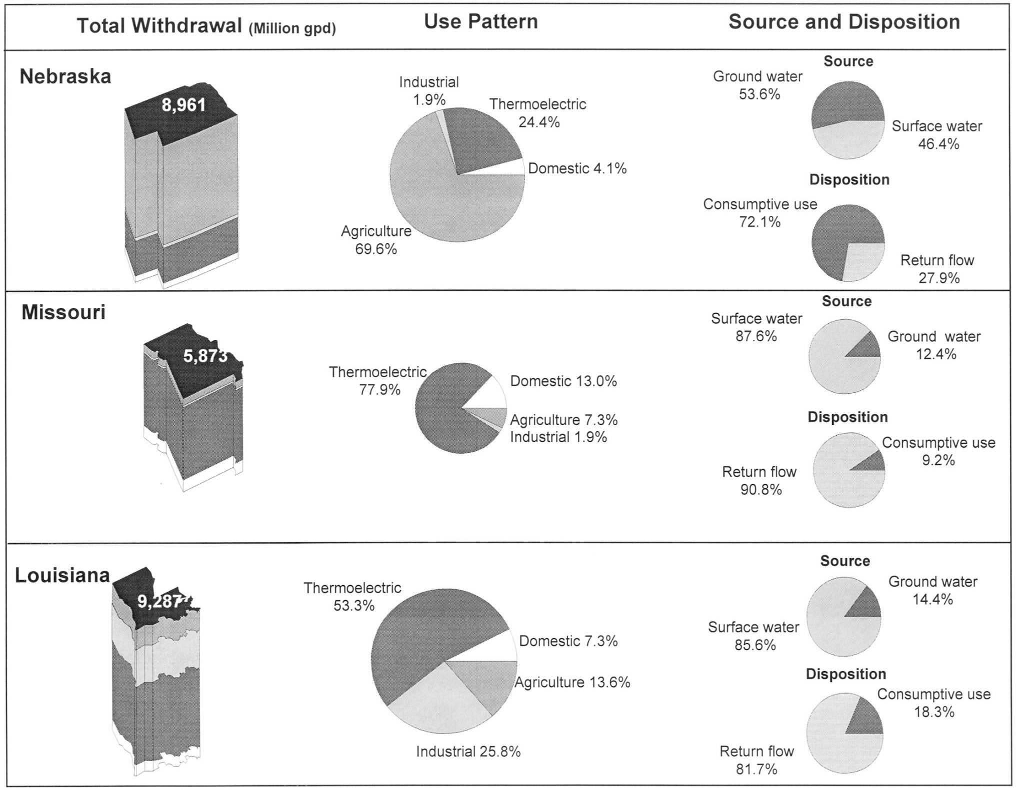

FIGURE 5.1 Comparison of the total withdrawals, use patterns, sources, and dispositions of freshwater in three states within the Mississippi River basin during the 1990 water year. Source: USGS (1993).

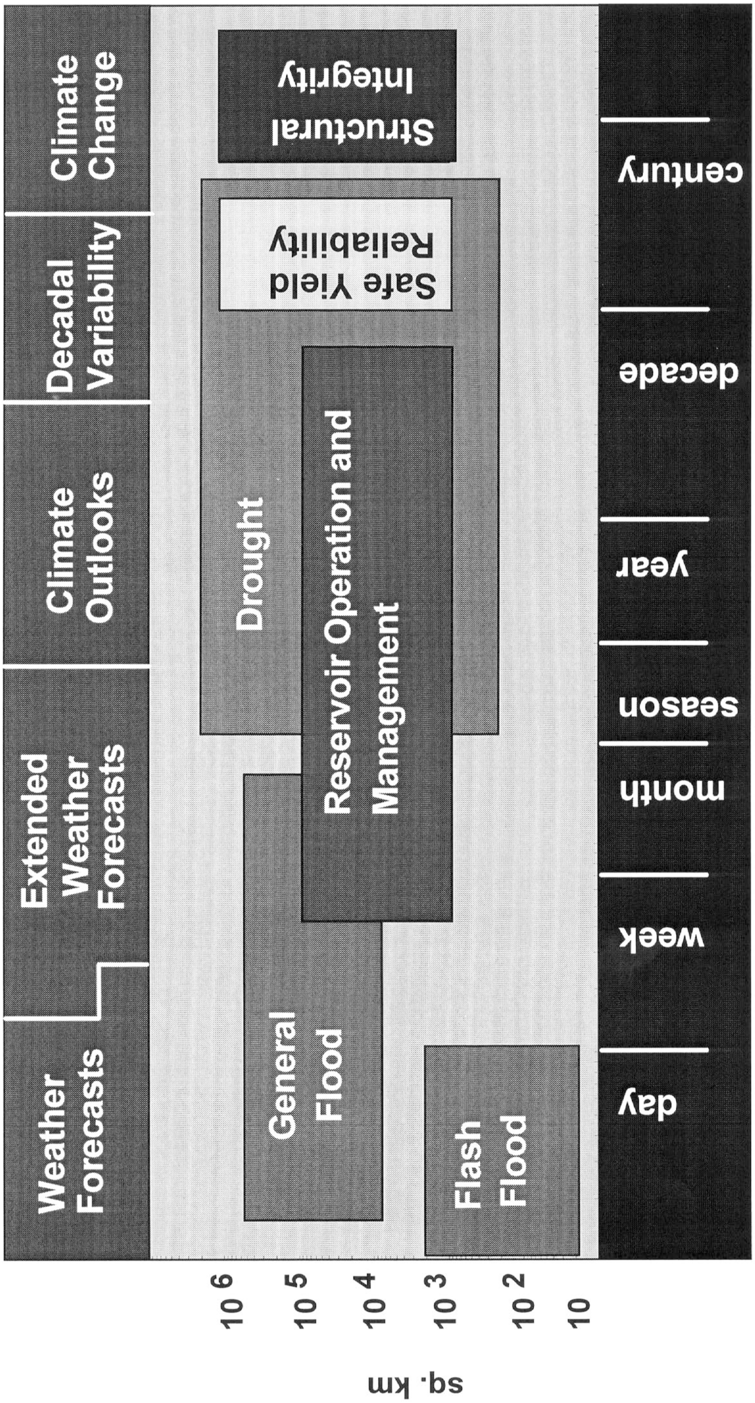

FIGURE 5.2 Characteristic spatial and temporal scale dependence of water resources management issues.

(i.e., construction of dams, levees, etc.) produces different responses to extreme hydroclimatic conditions, which alter the timing, magnitude, and nature of inputs of materials to wetlands and estuaries. An increase in the frequency or magnitude of overland flow (e.g., due to an increase in the severity of storm events) will alter the downstream transfer of sediments, organic matter, and nutrients. Given that aquatic ecosystems are sensitive to these alterations, proper management practices at all space-time scales will be critical to minimize the potential for long-term or irreversible damage.

A variety of both hydrologic-based models (e.g., precipitation-runoff, routing, sediment transport) and water resources management models are necessary to assist in the decision-making process for addressing issues such as urban flood studies, reservoir operation, drought management, erosion, and stream water quality monitoring, among other concerns. Depending on the nature of the data and information available and/or required, both deterministic and statistical models are in use. The deterministic models are commonly used to generate either short-term operational forecasts or future hydrologic scenarios. Management issues that deal with operational problems extending beyond several weeks (months, years, decades, etc.) and/or design scenarios (which are not necessarily time-dependent) have been handled using statistical and stochastic models.

Although GCIP's research program is not geared directly toward the development of water resources management models, GCIP's observational and modeling efforts are expected to enhance the front-end modeling tools, such as those mentioned above used for water resources management process. A particular role of GCIP in this regard could be to improve both the accuracy and the relevance of the hydrologic model-generated predictions that are used as inputs for water management. Hydrologic models that might receive the most benefit in this regard are discussed below.

Hydrologic Models for Water Resources Management

Deterministic Precipitation Runoff Models

The current generation of precipitation runoff models used for water management purposes is lumped rather than distributed, and their structures (e.g., process equations) have been determined by the availability of observations and the current state of knowledge about the processes. Among the most widely used models of this class are the NWS River Forecast Centers' Soil Moisture Accounting models (Hudlow, 1988) and physically based distributed models such as HEC-1 (Feldman and Davis, 1993). These models are applied to a variety of spatial and temporal scales, ranging from small plots to thousands of square miles and from hours or days to weeks, respectively. Better accuracy in the predictions provided by precipitation runoff models will come from two areas of progress: improvements in observed hydrometeorological inputs (principally precipitation) and improvements in the representations of land surface processes that mediate the storage, release, and redistribution of groundwater. In principle, the simulation of precipitation runoff performed by these models involves two phases: (1) the storm period and (2) the interstorm period. In the storm period, the problem is one of partitioning the precipitation between basin recharge and excess rainfall, which gets converted to direct surface runoff. Once a particular storm event occurs over an area, there may be a few days, weeks, or perhaps months before the next sequence of storms arrives. Thus, the main purpose of modeling interstorm periods would be to keep track of the various states of hydrologic processes. The primary state variables that require monitoring and updating are the soil moisture condition and snowpack (if any) over the catchment.

Accuracy of the precipitation observations required for storm period models is critical. It is well known that precipitation measurements from gauge recordings have a large amount of error associated with them. The errors are compounded further by the fact that data from sparse gauges are processed to obtain areal averages over a given basin. The potential benefits of NEXRAD precipitation estimates for rainfall runoff modeling purposes have been anticipated and discussed extensively in the literature (Crum and Alberty, 1993; Lindsey, 1993; Smith et al., 1996). Because a NEXRAD precipitation data base is one of the primary GCIP contributions, it will be of great benefit to the rainfall runoff modeling community.

Before runoff can take place, an initial amount of precipitation is lost to (1) interception by vegetation canopy and (2) capture by surface depressions. In hydrologic terms, these are known as initial losses. The initial losses, particularly canopy interception, can be rather significant, depending upon surface cover (Dunne and Leopold, 1978). For example, spring wheat can intercept anywhere between 10 and 35 percent of the gross precipitation. It is estimated that deciduous forests can intercept as much as 13 percent and coniferous forests as much as 22 percent of the gross precipitation. Depending on the catchment size, this can represent a very significant amount of precipitation that will not reach the ground surface to either recharge groundwater or to become surface runoff.

Once initial losses are accounted for, the most critical aspect of the storm period is the partitioning of precipitation between the volume resulting in direct runoff and the volume that goes to basin recharge. Essentially, two different types of partitioning mechanisms occur on a given catchment. These mechanisms are (1) infiltration excess (Horton, 1933) and (2) saturation excess (Dunne and Black, 1970). On a basin the size of the Mississippi River at any time, both of these mechanisms can occur. In fact, a substantial portion of the runoff generated in the Mississippi River basin may be due to saturation excess. Most hydrologic runoff generation models currently in use are based on the infiltration excess mechanism. Recently, models based on saturation excess (e.g., TOPMODEL, Beven et al., 1995) have been developed. The challenge for the future will be the development and application of models capable of computing runoff when both processes are accounted for simultaneously in a distributed fashion. In either case the volume of runoff generated during a given storm event is directly dependent on the initial surface and soil moisture conditions.

The changes in soil moisture over time are controlled by factors such as evapotranspiration, air and soil temperature, soil texture, land cover, topographic features, snow melt, and accumulation. These factors result in heterogeneous changes in soil moisture, which, if not captured properly and incorporated into these models, can have a profound effect on water balance calculations. For example, an underestimation of the available soil moisture would suggest that there is more storage capacity to hold water than is actually available. The result might be an underestimation of the magnitude of the flood volume. The opposite could also be true, resulting, for example, in the overestimation of the amount of water available in the soil. This may have implications in groundwater recharge, irrigation scheduling, and so forth.

Statistically Based Hydrologic Models

Hydrologists and water resources planners rely on a number of statistically based schemes to deal with structural design and long-term operational requirements of water resources systems. Several popular synthetic streamflow techniques (e.g., Fiering and Jackson, 1971) are used for both design and operation of water resources structures such as dams. Flood frequency analysis methods are used routinely to address floodplain management and zoning (Bedient and Huber, 1988). For example, the insurance industry relies on results obtained from the flood frequency analysis method to develop guidelines for flood-prone regions. Most municipalities, flood control districts, and state and federal departments of transportation rely on the results of flood frequency analysis to size culverts, drainage systems, bridges, and so forth.

The principle behind these statistical approaches is that when the probability distribution of historical streamflow is analyzed and the suitable distribution with the proper parameters has been identified, future scenarios can be generated. In the case of flood frequency analysis, emphasis is placed on the distribution of extreme values (i.e., floods). Inherent in these methods is their ability to help managers deal with future uncertainties based on a probabilistic understanding of the past. The key issue in climate change scenarios is whether we can rely on climate model simulations to produce relevant hydrological statistics for the future (or different climate conditions). Such statistics would answer the question of whether our hydrologic regimes (i.e., precipitation and streamflow) are, indeed, changing in character (Figure 5.3). The issues that would be of greatest concern to water resources planners and managers are (1) whether future streamflows are increasing or decreasing, due to wetter or drier climate in a fashion that fits the scenario shown in Figure 5.3A, or (2) while the mean streamflow remains constant, whether its variability is increasing or decreasing in a fashion that fits the scenario shown in Figure 5.3B.

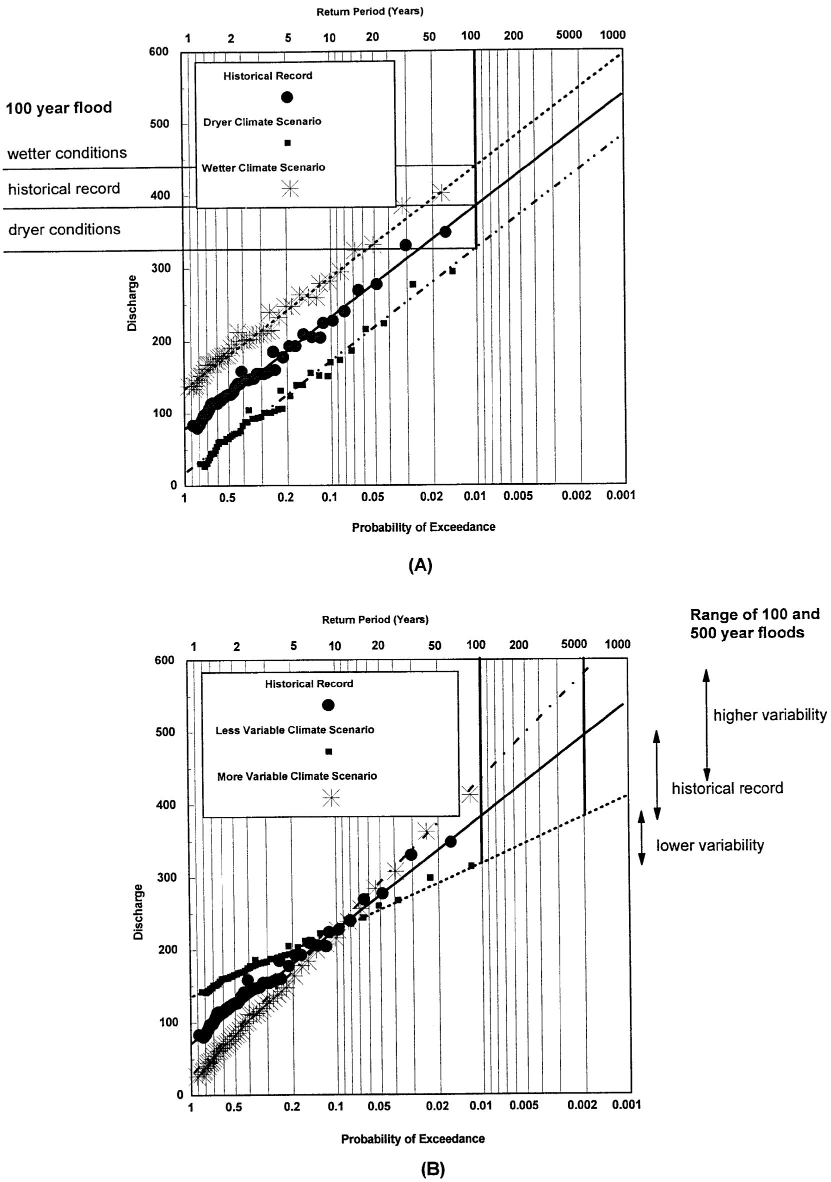

FIGURE 5.3 Conceptual representation of possible impacts of climate change on the maximum flood series. (A) Upward or downward shifts in the mean annual flood without changes in the variability of the series reflect an increase or decrease of the flood magnitude for all return periods. (B) A change in the variability of flood magnitude indicated by the different slopes of the frequency lines, while the mean annual flood remains the same, reflects opposite changes in the magnitudes of high- or low-frequency events.

ACCOMPLISHMENTS

GCIP research activities to date have not made direct contributions to water resources management. However, there is a great potential for useful interactions. Once a proper mechanism for closer cooperation with the water resources community has been established, the benefits of GCIP's budget studies (Chapter 1), model development (Chapter 2), data assimilation (Chapter 3), and collection and management (Chapter 4) will be better realized. The involvement of the Tennessee Valley Authority in the LSA-East detailed design workshop, held in Huntsville, Alabama (November 1996), is a step in the right direction.

RECOMMENDATIONS

It is anticipated that GCIP's observational and modeling efforts will enhance the front-end modeling tools used for water resources management purposes. However, the GCIP research program is not geared directly toward the development of water resources management models. At the present time, clear knowledge is lacking on the part of the water resources management agencies as to the potential benefits of GCIP research. In this regard, fostering an interactive dialogue between GCIP and the water resources management community in the Mississippi River basin is highly recommended. Specific recommendations relevant to these and related issues are discussed below.

Ensure That Hydrologic Data Sets Prepared Under GCIP Will Also Satisfy Modeling Requirements of the Water Resources Management Community

GCIP's comprehensive data base is placing a major emphasis on hydrologically related observations, such as precipitation, streamflow, and so forth. In order to ensure that the water resources community is able to take full advantage of this vast information, it is critical that the quality (accuracy and completeness) and resolution (in space and time) of hydrologic data be compatible with hydrologic modeling requirements. In this regard, the quality of the precipitation data from NEXRAD should be given a very high priority.

Develop Better Characterization and Estimation of Precipitation Partitioning in Rainfall Runoff Models

Although a significant amount of research has been directed toward understanding and modeling infiltration processes, particularly at the point scale, there has not been as much improvement in the partitioning procedure used in precipitation runoff models. Methods range anywhere from the simple Ø-index method—

which assumes a constant rate of infiltration (Singh, 1992)—to some conceptual approaches, such as the one used in the Stanford-type watershed model (Crawford and Linsley, 1966), or saturation-excess mechanics used in TOPMODEL (Beven et al., 1995). Because GCIP's focus is on water and energy balance studies, it follows that the partitioning of precipitation relevant to storm periods and applicable to catchment scales would benefit as well. GCIP should encourage the research community involved in precipitation runoff modeling to take advantage of the data and modeling activities sponsored by GCIP in order to improve the reliability and accuracy of the precipitation runoff models used extensively in operational hydrology and water resources studies.

Develop Strategies to Monitor, Model, and Archive Soil Moisture Data at Appropriate Spatial and Temporal Resolutions

The importance of soil moisture information to update the state of precipitation runoff models used for water resources forecasting purposes has been established in this chapter. At the present time, there seems to be no clear agreement about the definition, type, and resolution requirements (in time and space) of soil moisture among various scientific communities (i.e., climatologists, hydrologists, agricultural meteorologists, etc.). Given the strong land surface modeling orientation of GCIP and, hence, the importance of soil moisture information, GCIP should attempt to clarify these requirements in a manner suitable to the needs of various disciplines. It is through such an effort that the requirements for a space-based soil moisture global monitoring program can be best defined.

Combine GCIP's Physically Driven Studies with Statistical Approaches in Water Resources Management

One approach that should be considered is exploring changes in the probability distribution of extreme hydrologic events by means of climate model simulation. In this regard, climate models with high spatial resolution could be used to generate climate scenarios by varying plausible initial and boundary conditions on a regional basis. The ensemble of results could then be used to explore changes in the statistical properties of regional precipitation patterns, streamflow, runoff, and so forth. Clarifying the role that GCIP might play in furthering understanding of hydrological and meteorological variabilities on seasonal to interannual and decade to century time scales must be given high priority. Would any aspect of this new understanding improve our ability to more accurately predict changes in the parameterization of probability distributions used in statistical methods in hydrology? Similarly, could an understanding of elementary processes provide the capability to capture trends in the hydrologic regimes of a given region (e.g., moving toward wetter or drier climates in the next decade) or changes in their variability? This creates an opportunity for furthering cooperative research among the GEWEX, Climate Variability and Prediction Program (CLIVAR), and PACS communities.

Foster an Interactive Dialogue with Water Resources Management Agencies in the Mississippi River Basin

GCIP's research priorities and focus are geared toward improving the front-end hydrologic models and data bases used for water resources management purposes. However, to ensure that GCIP's modeling improvements and data products are useful to the water resources management community, it is important that a dialogue be established. Besides numerous local and state agencies, there are several large institutions and federal agencies with direct involvement in water resources decisions in the Mississippi River basin. Among these are the Army Corps of Engineers, the Tennessee Valley Authority, the Federal Emergency Management Agency, the Environmental Protection Agency, and so forth. It is not unusual to discover that some of these agencies are unfamiliar with GCIP and the potential benefits of GCIP research for their purposes. It is highly recommended that the GCIP program develop a strategy for (1) familiarizing the water resources management entities in the Mississippi River basin with the program and (2) seeking their input and advice on GCIP modeling and data activities and how these could be made more useful for their purposes.

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APPENDIX
A

Background and Linkages

WORLD CLIMATE RESEARCH PROGRAMME

The World Climate Research Programme (WCRP) was formed in 1979 to help develop the vast and diverse knowledge needed to understand the processes that determine climate and control climatic variations, and to develop methods to predict those aspects of climate variability or forced climate change that are indeed predictable. Since then, WCRP has become the principal international planning and coordinating mechanism for climate research throughout the world. WCRP has focused its effort on the physical climate system (atmosphere, ocean and sea ice, land surface hydrology, and continental glaciers or ice sheets), while a companion program, the International Geosphere Biosphere Programme (IGBP) emphasizes biological and chemical processes. The general objectives of WCRP are (1) to determine the extent to which climate can be predicted AND (2) to determine the extent of human influence on climate.

GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (GEWEX)

Water in its various phases plays a dominant role in nearly all aspects of the Earth's climate system. Water vapor is the most powerful contributor to the greenhouse effect in the Earth's atmosphere and the main vehicle of atmospheric energy transport. As a liquid, water sustains life on Earth, is accumulated in enormous quantity in the world's oceans, plays a major moderating role in the Earth's climate, and distinguishes our planet from all others in the solar system. As solid ice particles in clouds or snow on the ground, it reflects solar energy back to space. Condensation from vapor to liquid or ice heats the atmosphere, and evaporation cools the surface. To determine the net effect of water on our climate, the full cycle of evaporation, water vapor transport, cloud formation, precipitation, and runoff must be considered as an integral system, within which these "fast climate processes" interact on relatively short time scales, thereby involving large fluxes of energy. On the basis of this scientific paradigm, the WCRP formulated (WCRP, 1987) the concept of the Global Energy and Water Budget Experiment, an integrated multidisciplinary research program to study the interactions between the fast climate processes in the atmosphere and at the land surface, and the impact of these processes on exchanges of momentum, water, and energy with the slower components of the climate system.

GEWEX is an integrated program (Table A.1) to understand, model, and predict (1) radiative processed involving cloud, aerosol, water vapor, and their impact on radiation transfer and radiation flux divergence in the atmospheric column, and (2) hydrological processes, involving the transport and release of heat in the atmosphere, precipitation, evapotranspiration and land surface exchanges, groundwater storage, and runoff. GCIP is relevant to all elements in this program. The goal of GEWEX is to study and model linkages between the energy and water cycles on all time and space scales, using optimal combinations of in situ measurements and observations from space, especially the more informative data expected from the next generation of remote sensing instruments that constitute the International Earth Observing System (IEOS).

The overall objectives of the GEWEX program were expressed by WCRP as the following:

1. Determine the Earth's hydrologic cycle and energy fluxes using global measurements.
2. Model the global hydrologic cycle and assess its impact on the atmosphere, oceans, and land surfaces.
3. Develop the ability to predict variations in global and regional hydrological processes and water resources, as well as their responses to environmental change.
4. Foster the development of observing techniques and data management and assimilation systems suitable for operational application to long-range weather forecasts, hydrology, and climate predictions.

GEWEX is not an *experiment* in the traditional sense; rather it is an integrated *program* of research, observations, and science activities ultimately leading to prediction of variations in the global and regional hydrological regimes. Because of the magnitude of the effort, GEWEX is compiling information from several ongoing studies and will initiate investigations of its own, as needed, to improve modeling accuracy and the surface-atmosphere coupling in general circulation models. In fact, GEWEX initially encouraged a suite of exploratory

TABLE A.1 GEWEX Projects

Project Name	Description	Methodology	Status or Products
		Hydrometeorology and Land Surface Processes	
GEWEX Continental-Scale International Project	Intensive study of hydrological and energy budgets in the Mississippi River basin from 1995 to 1999	Develop new coupled land-atmosphere regional models based on a comprehensive data base of the Mississippi River basin using radars, profilers, and surface observing systems	• GIDS-1 CD-ROM (2/92-4/92) Atmospheric, hydrological, satellite, and radar composites; and surface data for central Mississippi River basin • GREDS CD-ROM—Topographic and land-use data • GIDS-3—GCIP integrated systems test data from Arkansas-Red River basin (on-line)
Global Runoff Data Center	Develop global streamflow data base for use in the development and verification of atmospheric circulation models	Compile river discharge data from 3300 stations located in 140 countries	• Daily and monthly flow data sets (on diskettes) • Gridded runoff data (in development)
International Satellite Land Surface Climatology Project	Provide global data, experiments, and modeling of land surface interactions, emphasizing satellite remote sensing	Develop new satellite measurement techniques and algorithms, conduct field campaigns, and develop global data sets for use in interdisciplinary science investigations	• 2-yr (1987-1988) global 1° × 1° land surface data sets • Updated data set for 1986-1995 at 0.5° × 0.5° planned for 1998
Regional Continental-Scale Experiments	BALTEX, GAME, LBA, MAGS: Intensive studies of specific hydrological regions	Improved observations and coupled land-atmosphere models	Data sets and improved model outputs planned

(continues)

TABLE A.1 Continued

Project Name	Description	Methodology	Status or Products
		Atmospheric Radiation Processes	
Baseline Surface Radiation Network	Provide highly accurate worldwide radiative flux measurements to validate satellite-based measurements	Develop instrument requirements, establish BSRN reference stations worldwide, and assemble a data base	• 12 stations reporting in 1995; 27+ planned
Global Precipitation Climatology Project	Provide monthly global estimates of area-averaged precipitation	Merge in situ daily gauge (6000 stations) with microwave and IR satellite land and ocean data into 10-yr global data set	• 7 yr (1986-1993)—2.5° × 2.5° blended precipitation data set • 1987-1988 1° × 1° gauge-only data set (ISLSCP CD-ROM)
GEWEX Water Vapor Project	Improve measurement of water vapor, and accuracy and availability of global data	Build global water vapor data set, establish reference stations, conduct intercomparison studies, and foster R&D for new RH RAOB sensor	• 5-yr (1988-1992) blended global water vapor and cloud liquid water data sets • 10-yr data set planned for 1997

APPENDIX B

Acronyms and Abbreviations

ACARS	Automated Communication and Recording System
AES	Atmospheric Environment Service (Canada)
ARM	Atmospheric Radiation Measurement program (DOE)
ASOS	Automated Surface Observing System (NOAA)
AVHRR	Advanced Very High Resolution Radiometer (NOAA)
BALTEX	Baltic Sea Experiment (northern Europe)
BATS	Biosphere-Atmosphere Transfer Scheme
BOREAS	Boreal Ecosystems-Atmosphere Study
BSRN	Baseline Surface Radiation (measurement) Network SRB Climatology Project (GEWEX)
CAGEX	CERES-ARM-GEWEX experiment
CART	Cloud and Radiation Testbed (ARM)
CASES	Cooperative Atmosphere-Surface Exchange Study
CASH	Commercial Aircraft Sensing of Humidity
CCM	Community Climate Model
CD-ROM	Compact Disk, Read-Only Memory
CERES	Clouds and the Earth's Radiant Energy System (NASA)
CLAVR	Clouds from the AVHRR
CLIVAR	Climate Variability and Prediction Program
CMC	Canadian Meteorological Centre
CRM	Cloud-resolving models
CSA	continental-scale area
DAAC	Data Acquisition and Archive Center (NASA)

DACOM	Data Collection and Management
4DDA	four-dimensional data assimilation
DMSS	Data Management and Service System (GCIP)
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
ECMWF	European Center for Medium-Range Weather Forecasts
EDAS	Eta Model Data Assimilation System (NCEP)
EDC	Earth Resources Observation Satellite Data Center (USGS)
ENSO	El Niño-Southern Oscillation
EOP	Enhanced Observing Period
EOS	Earth Observing System (NASA, MTPE)
ERBE	Earth Radiation Budget Experiment
ESOP	Enhanced Seasonal Observing Period
Eta	(Name of an NMC model using the Greek letter for the vertical coordinate)
FIFE	First ISLSCP Field Experiment
FSL	Forecast Systems Laboratory (NOAA)
GAME	GEWEX Asian Monsoon Experiment
GCIP	GEWEX Continental-Scale International Project
GCM	general circulation (atmospheric) model
GCMD	Global Change Master Directory (NASA-EOSDIS)
GCSS	GEWEX Cloud Systems Study
GDAS	Global Data Assimilation System (NCEP)
GEWEX	Global Energy and Water Cycle Experiment (WCRP)
GHP	GEWEX Hydrometeorology Panel
GIDS	GCIP Initial Data Set
GIST	GCIP Implementation System Test
GOALS	Global Ocean-Atmosphere-Land System
GOES	Geostationary Operational Environmental Satellite (NOAA)
GPCP	Global Precipitation Climatology Project (WCRP)
GPS	global positioning system
GREDS	GCIP Reference Data Set
GTS	Global Telecommunications System
HAPEX	Hydrologic-Atmospheric Pilot Experiment (France)
IEOS	International Earth Observing System
IGBP	International Geosphere-Biosphere Programme
IGPO	International GEWEX Project Office
IOP	intensive observational period
IR	infrared
ISA	intermediate-scale area
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project

LBA	Land Biosphere-Atmosphere program (Brazil)
LDAS	Land Data Assimilation System
LSA	large-scale (study) area (GCIP)
LSA-SW	LSA-Southwest
LSP	land surface parameterization
MAGS	MacKenzie River GEWEX Study
MAPS	Mesoscale Analysis and Prediction System (NCEP)
MOLTS	Model Output Location Time Series
MORDS	Model Output Reduced Data Set
MTPE	Mission to Planet Earth (NASA)
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climate Data Center (NOAA)
NCEP	National Centers for Environmental Prediction (NOAA)
NDVI	Normalized Difference Vegetation Index (AVHRR)
NESDIS	National Environmental Satellite Data and Information Service
NEXRAD	Next-Generation Weather Radar system (see also WSR-88D)
NMC	National Meteorological Center (recently changed to National Centers for Environmental Prediction, NCEP)
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRCS	Natural Resource Conservation Service
NWP	numerical weather prediction
NWS	National Weather Service
OH	Office of Hydrology (NOAA)
PACS	Pan-American Climate Study
PBL	Planetary Boundary Layer
PILPS	Project for Intercomparison of Land Surface Parameterization Schemes (GEWEX)
RAMS	Regional Area Modeling System
RASS	radioacoustic sensing system
RFE	regional finite element
RS	remote sensing
SCS	Soil Conservation Service (recently changed to Natural Resource Conservation Service (NRCS)
SRB	Surface Radiation Budget
SSA	small-scale area
SSM/I	Special Sensor Microwave Imager (DOD, DMSP)
SSURGO	Soil Survey Geographic Database (USDA)
STATSGO	State Soil Geographic Database (USDA)
SURFRAD	Surface Radiation Budget Network (NOAA)
TIROS	Television and Infrared Observation Satellite
TKE	Turbulent Kinetic Energy

TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rain Measuring Mission (NASDA-NASA)
TVA	Tennessee Valley Authority
UCAR	University Corporation for Atmospheric Research
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USWRP	U.S. Weather Research Program
VAD	velocity azimuth display
VORTEX	Verification of the Origins of Rotation in Tornadoes Experiment
WCRP	World Climate Research Programme
WSR-88D	Weather Surveillance Radar 1988-Doppler (see also NEXRAD)
WWW	World Wide Web