GEWEX America Prediction Project

GAPP SCIENCE BACKGROUND

A World Climate Research Programme Research Activity

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1. INTRODUCTION

Society's expectations for skillfull seasonal predictions have increased dramatically around the world and particularly in the United States as a result of the success in forecasting the 1997 ENSO and its impacts. Seasonal variations in climate are driven by feedbacks from the land to the atmosphere as well as the larger scale oceanographic forcing. The role of land in the hydrologic cycle is very complex and only now are we beginning to understand it. Recent advances in understanding have come through large field experiments that study the influence of land on the atmosphere at continental scales; through an improved capability of modeling land-atmosphere interactions, and, imminently, from a suite of new earth satellite systems designed to measure the properties of the earth's surface at high resolution on a global basis.

This document describes the scientific basis for a new World Climate Research Program known as the GEWEX Americas Prediction Project (GAPP). It is aimed at addressing the role of land in seasonal prediction based on an integration of this emerging understanding, and new measurement technologies and modeling capabilities.

To a large extent GAPP is an extension of the highly successful GEWEX Continental-scale International Project (GCIP) that completed its observational phase in March 2001. This new phase and emphasis are needed to realize GCIP's and now GAPP's ultimate mission, namely "to develop a capability to predict variations in water resources on time scales up to seasonal and interannual as an integral part of a climate prediction system" (NRC, 1998a). This mission remains a challenge that will only be addressed through the development of a more comprehensive understanding of land surface processes and their interactions with the atmosphere, the exploitation of new technologies, and the infusion of this new knowledge on land-atmosphere interactions into a global prediction system.

A number of recent influential studies and reviews have highlighted the need to develop a prediction capability that effectively includes land surface processes. The National Research Council's (NRC) Pathways report noted, "the relatively simple problem of coupling land hydrology to the atmosphere remains elusive and yet is quite important" (NRC, 1999a). An NRC hydrology report noted that "the development of scientific capability to detect and predict changes to the water cycle in response to natural and human-induced climate variability is a key priority research area" (NRC, 1999b). A recent USGCRP Water Cycle study has indicated that a central question is "to what extent can variations in the global and regional water cycle be predicted?" (Hornberger et al., 2001) and urges the federal government to launch a new initiative in this area.

The GAPP initiative outlined in this Science Plan and Implementation Strategy extends the GCIP approach developed in the Mississippi River Basin to other climate regions of the USA and also advances the program focus from analysis to prediction, thereby better positioning the hydrometeorological community to achieve the GAPP mission. In addition, GAPP has been designed to infuse the emerging understanding and capabilities of the climate community into a climate prediction system that fully incorporates land surface processes and hydrology. Furthermore, GAPP will develop stronger links between the climate community, which makes these predictions, and water resource managers who will utilize climate predictions.

This GAPP Science Plan and Implementation Strategy outlines the project's approach to building and delivering a land component for climate models and a capability to monitor and predict the components of water and energy budgets on all time and space scales. In addition, this ability to predict on climate time scales will be coupled to the needs of water resource managers to ensure that a future prediction system provides long-term national benefits from the management of this critical resource.

2. BACKGROUND

2.1. The Emerging Water Crisis

The demand for water by the public in the USA is growing by an estimated 1.6% per year, although the effects of this increase are currently being offset in some regions by decreased demands for irrigation water. Increases in water demand are occurring in cities where urban growth is fueling the demand for domestic water; in localized areas of industrial growth where expansion requires more water for hydroelectric production and industrial cooling requirements; and, generally, in water management with increased requirements for ecological needs, recreation, and navigation on larger rivers. Neither the water supply nor the demand for water are evenly distributed across the country. Regional water supplies vary with climate zone, ranging from relatively plentiful supplies in the East and Pacific Northwest to very scarce supplies in the semi-arid Southwest. As population and industrial demands increase, these new requirements for water are increasingly difficult to satisfy and society becomes much more vulnerable to long term droughts. This trend is particularly important in the southwestern US where annual water demands are rapidly approaching the average annual supply. In other areas, such as the Midwest, the economic implications of summer droughts are very large because irrigation demands for water cannot be met during these periods and the risk of crop failure becomes very high. Often, during dry periods, supply deficits are met by "mining" groundwater, a practice that has an alarmingly limited lifetime and severe environmental consequences. Furthermore, the policy framework needed to redistribute water through interbasin transfers has not been fully developed.

In the face of these growing regional demands for fresh water and growing supply uncertainties, such as a possible long-term trend towards decreased supply or increased year to year supply variability due to climate change, it is important that water managers have access to the best possible information on current and predicted states of water resource availability. As shown by Georgakakos et al. (1999), the use of accurate seasonal prediction information formulated in probability terms for one reservoir in Iowa could lead to savings of more than $2 million per year. These savings could be multiplied across the country with the production and appropriate use of accurate climate predictions at seasonal to annual time scales. However, for these benefits to be fully realized two obstacles need to be overcome. First, an ability must be developed to produce reliable hydrologic forecasts with lead times up to a year and with the range of uncertainties clearly specified. Second, water resource managers must be convinced of the benefits of relying on the forecast information based on its relevance and perceived accuracy. GAPP will focus on providing the scientific basis for accurate forecasts based on land-atmosphere, land process and hydrology studies on time scales up to seasonal and annual. It will also assist in building ownership within the water management community for these predictions, so that conditions will be favorable when a comprehensive national or international climate prediction system is ready for implementation.

2.2. The GCIP Legacy

The Global Energy and Water Cycle Experiment (GEWEX) was initiated in 1988 to examine the global and regional energy and water budgets. In 1994 the pilot phase of the first and most critical of its five continental scale experiments known as the GEWEX Continental-scale International Project (GCIP) was launched in the Mississippi River Basin. The other four GEWEX continental scale experiments include the Baltic Sea Experiment (BALTEX), which considers land-atmosphere-ocean interactions for the Baltic Sea and its drainage basin; the Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA), which considers the effects of tropical forests on the atmosphere; the GEWEX Asian Monsoon Experiment (GAME), which considers the role of land in determining spatial and temporal characteristics and the intensity of the Asian monsoon; and the Mackenzie GEWEX Study (MAGS), which considers cold region processes and their influence on runoff into the Arctic Ocean. These projects complement GCIP, and together they form a comprehensive assessment of land-atmosphere interactions on a global basis.

Since its full implementation in 1995, GCIP has produced numerous results that have clarified the nature of land-atmosphere interactions. Some of these advances have had benefits for GCIP's primary funding agencies, NOAA and NASA. As outlined in the NRC GCIP Review (NRC, 1998a), Lawford (1999), and elsewhere GCIP has played a leading role in showing, among other things:

1) Regional water balances cannot be closed with sufficient accuracy using radiosondes to estimate moisture convergence and divergence. High frequency outputs from modern-era 4-D atmospheric data assimilation systems are needed to close regional water budgets with the degree of accuracy required for GEWEX.
2) During the summer, the presence and vigor of vegetation has a significant influence on evapotranspiration rates and the quantity and distribution of convective precipitation, while soil moisture has an influence on the intensity and location of downstream precipitation.
3) The statistical properties and sub-grid variability of precipitation patterns can be characterized with non-linear algorithms, resulting in significant improvements in hydrologic predictions.
4) The spatial scale and pattern of land surface heterogeneity can have significant effects on the nature of mesoscale convection and the magnitude of local moisture recycling.
5) Land surface schemes have been substantially improved by developing better model representations of snow, vegetation, soil moisture, runoff and ground frost.
6) Land surface evapotranspiration and evaporation from the Gulf of Mexico are the primary moisture sources for summer precipitation in the Mississippi River Basin.

The full legacy from these insights and developments includes improved land surface models (SSiB, BATS, NOAH, etc.) now being used in climate studies and weather prediction by the academic and operational communities. In addition to incorporating these processes into models, GCIP has developed an infrastructure for the conduct of model intercomparison studies through the Project for the Intercomparison of Land Surfaces Parameterization Schemes (PILPS). Furthermore, a new Land Data Assimilation System being developed through GCIP by NCEP, the Goddard Space

Flight Center (GSFC) and a number of univeristies holds the promise of providing initial fields for climate models based on the assimilation of extensive surface data sets, including soil moisture and variables derived from radiance measurements acquired from existing and next generation satellite data products as well as radar and in-situ precipitation measurements.

Among GCIP's major contributions have been improvements in NCEP's regional data assimilation capabilities and the archival of consistent gridded fields from a variety of models of aerological and hydrological variables over the continental U.S. on a systematic daily schedule. These archives are 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. GCIP has also facilitated integration of data from a variety of sources, including upper-air radiosondes, surface weather stations, rain gauges and stream gauges. It is also assembling a five-year (1996-2000) research quality data set of precipitation radar (based on NEXRAD WSR-88D), as well as supporting data from wind profilers and automatic weather stations. A companion project to develop a short wave radiation product for the same time period is now being funded through NASA. New observations of soil moisture have also been initiated under GCIP sponsorship and will become part of the nation's climatic information system.

Within GCIP, a number of strategies for the implementation of large-scale field experiments have been developed. GEWEX views GCIP as a flagship for its other continental scale experiments and, in many ways, these experiments have been modeled after GCIP. From a science management perspective, GCIP has drawn the meteorological and hydrological communities closer together in order to study land surface and hydrologic processes and their atmospheric interactions. Through the contributions of operational and developmental numerical weather prediction centers (NCEP and FSL) to its data assimilation activities, GCIP has made optimal use of the extensive data sets gathered routinely throughout North America and incorporated them into data sets for climate research. This initiative has also facilitated the transfer to operations of new modeling techniques developed in academia. In the future, GAPP will build on the strengths that GCIP has developed, while expanding the community that participates in the project, and build stronger links between the prediction and observational research communities.

The GCIP coupled modeling research was predicated on the hypothesis that the creation of regional-scale coupled models that simultaneously represent both relevant atmospheric and the land-surface processes, and the validation of these models against observations from GCIP, will improve our ability to:

a) predict variations in weather and climate at time scales up to interannual; and
b) interpret predictions of weather and climate in terms of water resources at all time scales.

GAPP will build its modeling efforts on the same hypothesis.

The implementation of model development in GCIP has followed two paths as described in the GCIP Implementation Plan (IGPO, 1993) and shown in Figure 2.1. On the "research" path are the longer term modeling and analysis activities needed to achieve the GCIP coupled modeling Research Objective, namely "to develop and evaluate coupled hydrologic-atmospheric models at resolutions appropriate to large-scale continental basins" (NRC, 1998a). GCIP focused on those research activities that created, calibrated, and applied coupled models of the atmospheric and hydrologic systems with priority given to research to improve climate prediction and to improve hydrological interpretation of meteorological predictions at time scales up to seasonal.

As GCIP progressed, the "operational" path adopted new modeling methodolgies, and developed and implemented the improvements needed in the operational analysis and prediction systems to produce the model assimilated and forecast output products for GCIP research, especially for energy and water budget studies. The regional mesoscale models also served to test components of a regional climate model and provided output for the evaluation of a coupled hydrologic/atmospheric model during the assimilation and early prediction time periods as a precursor to developing and testing a coupled hydrologic/atmospheric climate model. The output from three different regional mesoscale models was routinely compiled as part of the GCIP data set.

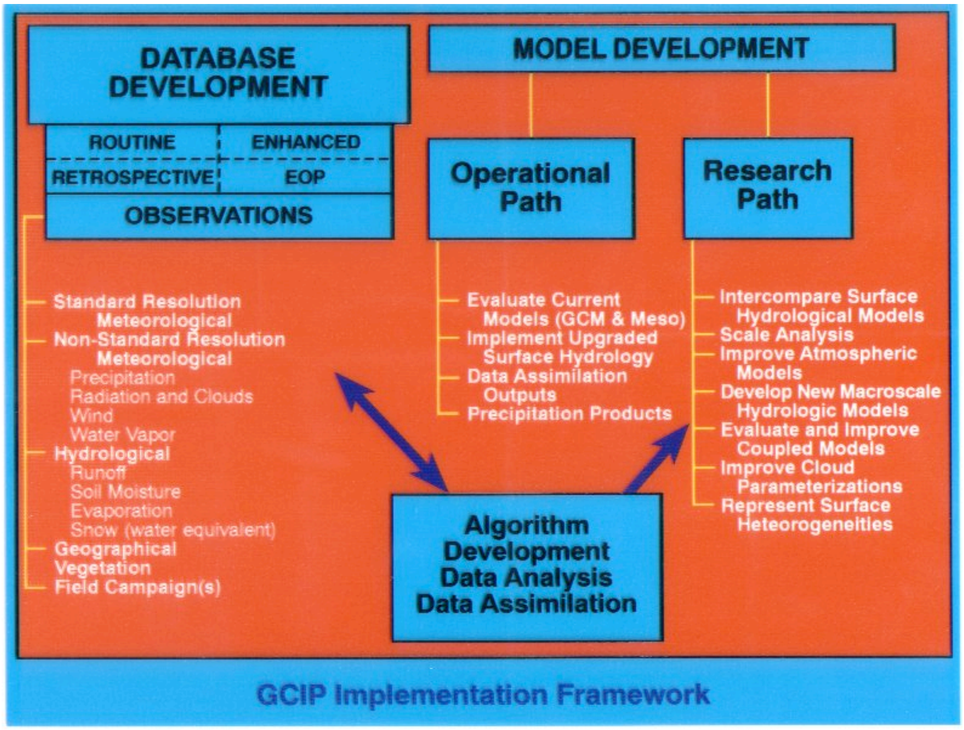

Figure 2.1. Research and operational paths for model development in GCIP.

2.3. The Programmatic Context

Prediction on a seasonal basis can be achieved partially with empirical tools or, as many contend, more completely with coupled dynamic models. Under some environmental conditions, empirical techniques have been useful in predicting precipitation anomalies, however, by their nature, these statistical approaches are only one step in developing the detailed understanding required for dynamic seasonal prediction. High-powered computers and new earth-observing satellite systems are creating opportunities to develop an understanding of the physical processes and dynamics responsible for climate anomalies over land. Although this research is not restricted to GEWEX, many of the initiatives that adress this need have developed through the GEWEX Continental Scale Experiments (CSEs).

At the national level, the US Global Change Research Program has recently recognized the importance of water and through an External Science Group has developed a Water Cycle Science Plan. This plan identifies three major global water cycle questions that the federal government is expected to address over the next decade. These questions are as follows:

1) What are the underlying causes of variation in the water cycle on both global and regional scales, and to what extent is this variation induced by human activity? To address this question work is needed to quantify variability in the water cycle and to develop techniques for separating natural variability from that which is human-induced.
2) To what extent are variations in the global and regional water cycle predictable? This question can best be addressed by demonstrating the range of predictability of variations in the water cycle over a range of space and time scales and to establish a scientific basis for making predictions and estimates of uncertainty useful for water resource management, natural hazard mitigation, decision making and policy guidance.
3) How will variability and changes in the cycling of water through terrestrial and freshwater ecosystems be linked to variability and changes in the cycling of carbon, nitrogen and other nutrients at regional and global scales? To address this question, observations and experiments will be needed to characterize the coupling and feedbacks of water, carbon and nitrogen cycles. In addition, a quantitative, predictive framework will be developed through the synthesis of concepts from different disciplines that utilize these data sets.

At the time of writing, the USGCRP and the Climate Change Research Initiative (CCRI) are working together to identify federal climate research priorities for the next three to five years and in the longer term. GAPP interfaces with the USGCRP Global Water Cycle program whose mission is “to enhance understanding of water cycle processes and provide better predictive capability to improve managment of water systems for the benefit of people and the environment.” The CCRI has a strong focus on research initiatives directed at reducing the uncertainties in climate change prediction. Since many of these uncertainties arise from interactions between the water cycle and the climate system, studies of these feedback processes could be viewed as priorities. GAPP will contribute to reducing these uncertainties by providing new knowledge related to the effects of land, surface hydrology, boundary layer processes and clouds and land use changes of the climate system, and incorporating this knowledge into global climate models.

GAPP will be funded by NOAA and NASA as one of several specific water cycle initiatives under the USGCRP. Accordingly, GAPP will ensure that its research contributes to the federal response to the research questions posed above. In particular, GAPP will address questions related to prediction and monitoring in areas that relate to the GAPP mission.

With the advent of new satellite systems such as EOS and ADEOS II, the World Climate Research Programme (WCRP) is implementing the second phase of its GEWEX program. Within the USA a strong national program involving NASA, NOAA and other agencies is needed to deliver the integrated program on the prediction of continental scale water and energy budgets that GEWEX envisions. Furthermore, to fulfill the expectations of WCRP, GEWEX will rely heavily on a follow-on to GCIP that emphasizes improved predictability based on an enhanced understanding of land surface processes at seasonal, and regional and global scales. GAPP is designed to meet this need.

CLIVAR, with support from dynamic models, is successfully contributing to the understanding of how tropical sea surface temperatures can be used in seasonal predictions during ENSO years. However, prediction studies also show that the evolution of climate over land areas for the annual cycle is dependent on initial moisture conditions and on the models' ability to predict the precipitation that, in turn, forces soil moisture and the land surface boundary conditions as the simulation unfolds. Given the importance of land memory processes in influencing regional climate, particulalry in the summer, GAPP will also give a high priority to the incorporation of land surface processes into global climate models. To fully achieve this objective, however, GAPP and the GEWEX Hydrometeorology Panel will need to work closely with the global components of the GEWEX and CLIVAR programs to plan and develop a comprehensive prediction system. In particular, GAPP will focus on incorporating high to medium resolution (10-50 km scales) land and land-atmospheric processes into Land Surface Models (LSMs) for both regional and global application. However, GAPP must also be regional and local in order to develop strong ties with the water resource community at the watershed/river basin scale and to effectively cope with the hydrologic aspects of predictability questions. This result will be achieved by building on existing infrastructure (e.g., NOAA's Office of Hydrology) as well as creating new ways of addressing prediction problems. GAPP's participation in the UNESCO/ WMO Hydrology for Environment, Life and Policy (HELP) initiative will also contribute to realizing this objective.

GAPP will provide leadership in linking relevant GEWEX and CLIVAR activities by developing joint regional land surface modeling activities that are integrated with CLIVAR/ VAMOS/PACS oceanographic and experimental research. In December 1998, sixty countries met in Paris to commit themselves to undertaking CLIVAR. Based on agreements at that meeting, CLIVAR is looking to GEWEX to provide the necessary land surface modeling for improving global prediction systems. Accordingly, GAPP will work with appropriate projects and committees in GEWEX and CLIVAR to develop the process understanding and model parameterizations needed for global climate models and seasonal forecasting. These studies will focus on land-ocean-atmosphere interactions and the influence of large-scale circulation patterns on mesoscale processes. Together with CLIVAR/VAMOS/PACS, GAPP will provide the scientific basis for an end-to-end prediction system for America's water resources.

GAPP addresses recommendations contained in the recent NRC Review (1998a) and the Overview to the NRC Pathways Report (NRC, 1998b). As noted earlier it builds on the valuable experience, models, data sets and expertise that have been developed through GCIP; actively contributes to the new initiatives of the GEWEX Hydrometeorology Panel (GHP) in developing global applications and coupled (land-atmosphere) models, and addresses the needs of resource agencies to have access to the latest information and technology. GAPP will report periodically on its success in pursuing its new strategy and will provide a final synthesis of its findings and experience in 2007 at its conclusion.

Precipitation patterns also are dependent on the feedback from land areas to the atmosphere, particularly during the summer when the atmosphere is more weakly forced by the ocean. During the 1990s, it was not possible to observe patterns of global soil wetness to the extent required for seasonal prediction. However, through programs in NASA (satellite data) and DOE (high-speed computers) this situation is changing. With the anticipated computing power and data collection capability these agencies are acquiring, GAPP should be able to realize significant gains in precipitation and soil moisture prediction skill by incorporating new land data and process understanding into much higher resolution climate models than are currently available.

In setting its strategic objective in 1995, the GHP anticipated the development and demonstration of a coupled global ocean-atmosphere-land model for climate prediction within the first five years after the millennium. Its strategic objective is stated as, "Working with other WCRP Initiatives by the year 2005 predict changes in water resources and soil moisture on time scales of seasonal to annual as an integral part of the climate system." The CLIVAR Implementation Plan identifies the land surface process studies and resultant coupled land-hydrology component of a global climate model as GEWEX contributions. It is expected that the GHP efforts in coupled land area-hydrologic and atmospheric modeling will make a significant contribution to a coupled global ocean-atmosphere-land model for climate prediction.

2.4. The Climate Change Imperative

As the scientific community grows more confident in its assessment of climate change arising from greenhouse warming, and calls for action by the public and government become more pressing, the demands for unambiguous assessments of the effects of climate change on regional temperature, precipitation and runoff patterns will increase. In addition, the requirements for an adaptation strategy to deal with the effects of these regional changes are likely to increase. The reports of the Intergovernmental Panel on Climate Change (IPCC) are the basis for the current projection that greenhouse warming will lead to an intensified hydrologic cycle, with an increase in the frequency of severe floods and droughts.

However, the 1995 report also recognizes that one of the main sources of uncertainty in these assessments is the inability to model complex land-atmosphere interactions in global climate models. Vegetation, soil moisture, snow cover and runoff all play important roles in the climate system that cannot be fully simulated by the current generation of climate models. GCIP has already made incremental improvements in regional land-surface models by incorporating more physical processes and through model intercomparison studies. Models developed for climate prediction studies must include all of the physics needed to simulate climate time scales; consequently GAPP models will meet the scientific standards for Global Climate Models (GCMs) used in climate change studies. GAPP will continue to improve the representation of land-surface processes and land-atmosphere feedbacks in these models, and in collaborationwith GHP and CLIVAR, GAPP will work towards a well-tested, robust, universal land-surface model to support these critical climate change modeling applications.

3. GAPP OBJECTIVES

In order to achieve its overall mission, GAPP will pursue two primary objectives, namely:

1) To develop and demonstrate a capability to make reliable monthly to seasonal predictions of precipitation and land-surface hydrologic variables through improved understanding and representation of land surface and related hydrometeorological and boundary layer processes in climate prediction models, and
2) Interpret and transfer the results of improved seasonal predictions for the optimal management of water resources.

These objectives will be achieved by undertaking a series of modeling and diagnostic studies, collaborative field projects, and observing activities. In particular, studies in support of the first objective will be structured to:

a) Improve the understanding of land surface, precipitation, radiation and hydrologic processes over a continental domain at space and time resolutions appropriate for future climate and related hydrologic models,
b) Identify, quantify and model the feedbacks between land surfaces (e.g. soil moisture and snow cover) and the atmosphere including monsoonal circulations and other large scale circulation patterns (e.g., The Pacific North American teleconnection pattern) that contribute to the predictability of continental precipitation, soil moisture, vegetation and runoff on climate time scales,
c) Develop the process understanding, algorithms and parameterizations, data sets (including new satellite data sets), and data assimilation products necessary for transferring models from data rich to data sparse areas, and for the formulation of improved Land Surface Models (LSMs) for a broad range of applications including vegetation and biogeochemical cycling, and
d) Develop a sophisticated high-resolution transportable land surface and boundary layer model with feedbacks that represent all the climate regions of the Americas, and the world.

The second objective will be achieved by projects carried out in close cooperation with water resource organizations and will rely heavily on the experimental prediction products generated by GAPP and other seasonal prediction experiments (e.g. by NOAA's Office of Hydrology, Climate Prediction Center (CPC), CLIVAR, International Research Institute (IRI)). This objective will be attained by:

a) Developing an understanding and quantitative description of scale relationships between hydrometeorological variables for use in techniques to make outputs of climate models relevant to water resource managers through downscaling, calibration and probability distribution functions,
b) In collaboration with international programs such as HELP, developing the scientific basis for hydrologic predictions and resource assessment systems that can be used for planning water and ecological resource strategies and projects,
c) Undertaking demonstration projects to evaluate and implement applications of seasonal predictions in operational water resource management, and

d) Assessing the consequences of land use change and other environmental manipulations that cause potentially significant changes in regional climate and hydrology.

In order to achieve these objectives GAPP will rely on modeling and diagnostic studies and special coordinated field campaigns and data set development initiatives. GAPP will consist of the following seven components with time phased activities within each of these components: 1) Predictability of Land Processes, 2) Orographic Influences on the Regional Water Cycle, 3) Predictability of the North American Monsoon, 4) regional prediction, 5) assessing the transferability of predictability and prediction systems, 6) incorporating predictability into predictions systems, and 7) the role of predictions for water resources and related applications. The relationships between these seven components are shown in Figure 3.1.

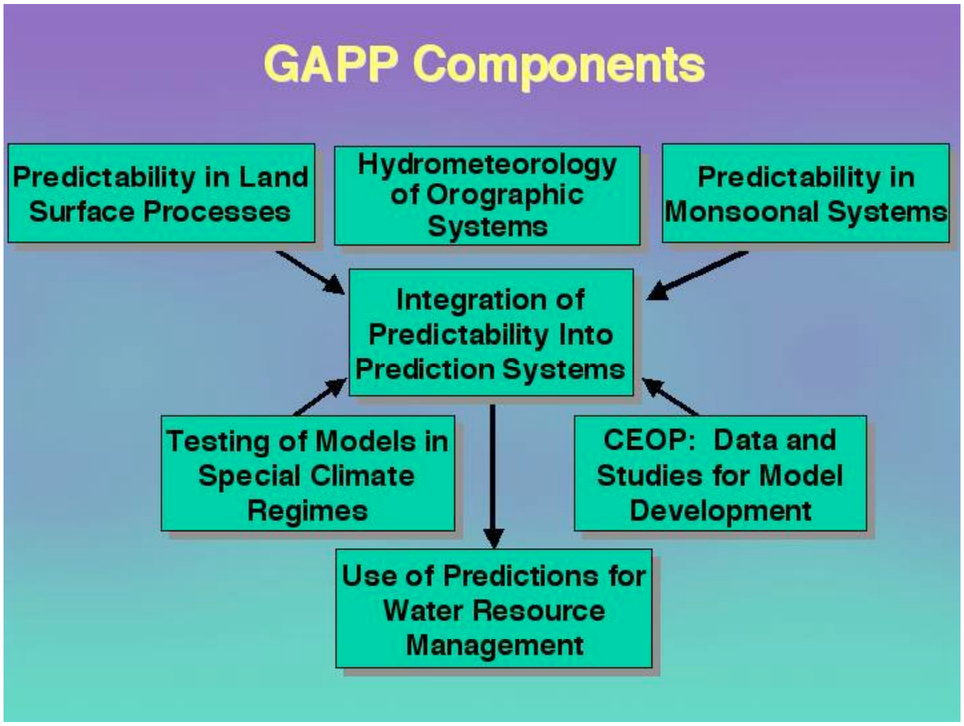

Figure 3.1. Relationship between the various elements of the GAPP Initiative.

4. CONTRIBUTION OF LAND-ATMOSPHERE INTERACTIONS TO PREDICTABILITY

4.1 Rationale

To fulfill the first objective of GAPP, it is necessary to identify, adequately understand, and capably model those land-surface features, phenomena, and processes that can contribute to improved monthly to seasonal predictions of precipitation and hydrologic variables. GAPP will address this goal in a study area that includes the Mississippi River basin previously studied under GCIP, the southwestern US, and the western Cordillera. This extended study area provides an opportunity to investigate hydrometeorological interactions in more extreme environments than were sampled under GCIP, where water resources are particularly important. The surface water balance of the semi-arid Southwest, for instance, is markedly different from other regions of the U.S. where water is more plentiful. This aridity is reflected in the surface energy balance and the relative importance of ground-water processes. Snow and ice cover and topography are important influences on precipitation in mountainous regions throughout the west, and seasonal changes in soil-moisture status and vegetation are significant features of the land-surface/atmosphere interactions in the semi-arid southwestern U.S.

Land-memory processes will receive particular attention in GAPP, but it is recognized that the land surface and the atmosphere are a tightly coupled system that evolve together on both diurnal and seasonal time scales (Betts, 2000). Existing understanding from GCIP and other studies provides guidance on which aspects of the coupled land-atmosphere system are most likely to be associated with predictability. The storage of water near the surface as soil moisture and its storage on the surface as snow and ice cover are land-memory processes that can affect both the overlying atmosphere and runoff in streams or to ground water. Moreover, research suggests that the nature and seasonal progression of growing vegetation also represents a land memory because the current distribution and growth status of plants, which partly reflects past climate, controls current surface energy, moisture, and momentum exchanges. In addition, topography, although not a land memory process as such, has a well-recognized influence on precipitation and hydrologic flows and, depending on the time of year, can determine whether precipitation falls in liquid or solid form.

Topography, snow cover, soil moisture, and vegetation all form an interactive system. For example, a large winter snowfall may produce more spring soil moisture as it melts, delaying the spring warming of the surface. This factor in turn will affect the timing and rate of initiation of growth of plants. Denser vegetation will provide more surface to intercept snow, but at the same time shade snow on the ground. Higher peaks receive more snowfall. Thus it is not possible to study each of these elements of land surface hydrology in isolation. Nevertheless, we express the scientific questions below specifically for each element to focus our research program. The planned research activities, however, will take into account the complexity and interactions of the system that we are studying.

4.2. Scientific Background and Questions

Topographic influences, land-memory processes (snow/ice cover, soil moisture, and vegetation status), and semi-arid hydrometeorology are discussed in greater detail in the following sections.

4.2.1 Topographic Influences

Sub-regional scale variability of topography has a marked influence on atmospheric convective processes and a strong control on surface hydrological flows. The interaction between atmospheric and hydrologic processes and topography necessarily involves questions of both temporal and spatial scale, as well as identification of significant, controlling topographic parameters, such as elevation, slope, and aspect. Such topographic parameters can be readily derived from digital elevation models at various spatial scales in the GAPP study area. On the other hand, precipitation data in mountainous areas are often poorly sampled by ground stations and poorly measured by radar. This factor places significant demands on analysis techniques and underlies the need for additional, strategically placed, ground stations.

Precipitating convective cloud systems in GAPP, and the North American Monsoon (NAM) system in particular, raise key issues involving interactions among the large-scale flow, topography, land-surface processes and convective cloud systems. These issues are of concern for both global and regional models. If adequately forced at lateral and lower boundaries, regional models with an adequate parameterization of the precipitation processes should be able to represent orographically generated precipitation reasonably well. However, key issues are associated with the initiation and life-cycle of convection over the North American Cordillera and the eastward propagation of organized convection that are not well understood and have not been properly represented by existing parameterizations.

Fundamental to GAPP and the North American Monsoon Experiment (NAME) are the indirect and remote effects of the North American Cordillera that are more complex than direct orographic forcing. Indirect effects include the orographic influences on the initiation of convection and heat-generated mesoscale circulations in mountainous terrain. Remote (far-field) effects involve traveling mesoscale systems not represented by existing (single-column) parameterizations. These research issues can be addressed using a hierarchical modeling approach based on (parameterized) regional-scale and (explicit) cloud-resolving models (Liu et al. 1999a, 1999b, 2000) that stem from oceanic convection studies (Grabowski et al. 1998; Wu et al. 1999). These models provide statistically meaningful results that contribute to the development of both GCMs and statistical models.

When hydrologic models capable of describing the horizontal movement of water are coupled to regional atmospheric models, the resulting coupled models can represent the hydrologic response of catchments to topography. Testing the performance of such coupled hydrometeorological models is a priority for GAPP. However, statistical models of the influence of topography on precipitation, particularly at subgrid scales, are also required. Such models can be used to determine whether coupled hydrometeorological models provide realistic simulations, and they can downscale precipitation patterns within the grid squares of coupled hydrometeorological models.

Statistical analysis of the interaction of precipitation with topographic parameters involves calibrating appropriate, single-point statistical models to the observed temporal variability (Hutchinson, 1991a, 1995a). Such models can conveniently separate long-term average precipitation patterns from anomaly patterns. These separate components can have different spatial scales and different topographic dependencies. This approach can be advantageous when using observations to calibrate topographic dependencies to support the spatial and temporal interpolation and statistical simulation of precipitation patterns. It can also help to identify key statistical parameters associated with longer-term change and predictability. Because orographic precipitation depends not only on the synoptic scale circulation, but also on mesoscale flows, the regional reanalysis can provide useful information to further improve statistical models of orographic precipitation.

So far, most statistical analyses of the interaction between precipitation and topography have focused on the temporal interpolation of long-term monthly mean precipitation (Daly et al., 1994; Hutchinson, 1995b). This approach can be used to describe long-term average seasonal variability, which in turn is closely associated with patterns of natural vegetation. Moreover, interpolated monthly mean precipitation can also be considered to be one of the important parameters in a temporal-statistical model of precipitation. Monthly mean precipitation patterns are strongly modulated by topography. Elevation is usually the primary factor, but its influence varies spatially, thus invalidating the use of simple regression equations between precipitation and elevation (Chua and Bras, 1982; Hutchinson, 1995b). However, spatially coherent elevation dependency can be calibrated by using robust multivariate spatial analysis techniques such as thin plate smoothing splines (Wahba and Wendelberger, 1980; Hutchinson, 1991b, 1995b).

These techniques and others have indicated that the relative impact of elevation on precipitation patterns is two orders of magnitude greater than the impact of horizontal position (Hutchinson, 1995a, 1998; Running and Thornton, 1996). Thus, precipitation patterns usually reflect a topographic landscape that is exaggerated in the vertical, leading to a significant influence on precipitation patterns by relatively modest topographic features (Bindlish and Barros, 1996; Barros and Kuligowski, 1998). The spatial resolution of this dependence has been estimated as 4 to 10 km (Daly et al., 1994, Hutchinson, 1998). Slope and aspect also affect precipitation patterns at a similar spatial resolution (Hutchinson, 1998). Further study is needed to clarify the scales of the topographic dependency of precipitation. These scales may vary for different precipitation averaging periods and for windward and leeward precipitation generating processes (Barros and Kuligowski, 1998; Buzzi et al., 1998). More studies are needed to develop and calibrate robust spatial and temporal statistical models (e.g. Pandey et al., 1998; Widmann et al., 2002), dynamical models (e.g. Rhea, 1978; Barros and Lettenmaier, 1993), and subgrid parameterization (e.g., Leung and Ghan, 1995; 1998) capable of representing the interrelationship between precipitation and the complex, extreme topography in the western U.S.

Statistical analysis shows that precipitation anomaly patterns arising from large-scale synoptic weather patterns display relatively broad spatial coherence and are relatively insensitive to topography (Hutchinson, 1995a). Such patterns are more readily represented in mesoscale meteorological models and are amenable to analysis in relation to broad scale circulation patterns (Walsh et al., 1982; Klein and Bloom, 1987; Lyons, 1990). It is fortunate that the statistical properties of such patterns can be more readily determined from less dense networks. Once determined, these anomaly patterns can be added to the background (long-term mean) topography-dependent patterns to generate more complex statistical models of precipitation patterns. Interpolating precipitation in this way can provide a data series that is appropriate as the input to hydrological models with a monthly time-step (Alley, 1984; Arnell, 1992; Pandzic and Trinic, 1992). Study is needed to identify the relative sensitivity of long term mean and anomaly patterns to the factors that affect long-term change and predictability. It will require close attention to the statistics of precipitation and due recognition of appropriate physical constraints where these can be identified.

Among the questions relating to predictability issues associated with topography that will be addressed under GAPP are the following:

1) Is it possible to define a robust statistical relationship between topography and precipitation across the entire GAPP study area? Specifically:
2) How sensitive are the parameters in such a statistical relationship to geographical location and interannual variability?
3) Are the parameters in such a statistical relationship different for liquid and frozen precipitation?
4) How does the influence of topography on precipitation, including its influence on whether precipitation falls in liquid or solid form, the displacement of precipitation by upstream blocking, and the formation of mesoscale convective systems, modify the magnitude and timing of hydrological flows in watersheds of differing spatial scale?
5) Can coupled land-atmosphere and regional climate models adequately reproduce the observed statistical relationships between precipitation and topography across the entire GAPP study area?

4.2.2 Snow, Ice and Frozen Soil

Snow processes are important in climate and weather prediction models because of the unique characteristics of snow, specifically its high albedo, low thermal conductivity, and the fact that snow and ice cover often exhibit considerable spatial and temporal variability. The control exerted by snow and ice on energy and water exchanges between the atmosphere and the underlying soil are therefore markedly different to other surfaces. In addition, the timing of snowmelt and the subsequent fate of melted water play an extremely important role in the hydrological response of catchments, especially in the western U.S.

Several studies have investigated the development and validation of snow submodels in climate models (e.g., Loth et al., 1993; Lynch-Steiglitz, 1994; Yang et al., 1997; Schlosser et al., 2000; Slater et al., 2000). These stand-alone model evaluations are encouraging but reveal that there are significant observational problems when validating snow/ice models. There are, for instance, challenges in accurately specifying the model forcing data. Measuring snowfall is difficult, especially in windy conditions.

It is also difficult to specify a threshold temperature to characterize when precipitation falls as snow rather than rain, and although it is difficult to measure downward long-wave radiation, it is important to do so because this component is the dominant wintertime radiation flux (Yang et al., 1997). In the past, acquiring validation data has been problematic and data have been scarce. There has been a general lack of measurements of snow temperature and density, and snow water equivalent and snow depth are often sampled infrequently, which makes model validation difficult, especially during the (often rapid) snow ablation period. Fortunately this problem is being mitigated to a significant extent by data collection under the MAGS and ARM-SHEBA projects.

Yang (2000; also see http://www.atmo.arizona.edu/~zly/snow.html) reviewed the snow/ice models used in weather forecasting, climate research, watershed modeling, and process studies. There are numerous snow/ice models, but the models that were used in the Schlosser et al. (2000) intercomparison study show substantial mutual disagreement because there is currently limited understanding of many important snow/ice processes. Poorly understood processes include the time-evolution of snow albedo, the representation of patchy snow/ice cover, sublimation, snowmelt and re-freezing, the retention and transport of melt water, and, not least, the mutual interaction between the snow/ice processes and the soil and vegetation processes within a comprehensive land-atmosphere model (Yang et al., 1997; Schlosser et al., 2000; Slater et al., 2000).

When coupled to climate models, snow/ice models do seem to be able to capture the broad features of the seasonal snow regime such as seasonal variations in the snow line. However, a convincing explanation of the still significant discrepancies in simulations of snow cover remains illusive because of the complex feedbacks between precipitation, air temperature, radiation, topography, vegetation, and snow. In the case of global models, for instance, the reasons for the frequent delays in modeled snowmelt at high latitudes in Eurasia and North America are not known (Yang et al., 1999), and similar unexplained weaknesses are also observed in regional climate model simulations for areas such as the Pacific Northwest U.S. (Leung and Ghan, 1999).

Thus, there are many difficult challenges remaining in the development of adequate representations of snow accumulation and snowmelt processes before predictive coupled hydrologic-atmospheric models can be expected to successfully reproduce the observed relationship between spring snow pack and subsequent summer rainfall in the southwest U.S. (Gutzler and Preston, 1997). By investigating the development of both uncoupled and coupled snow/ice models in regions with and without strong topography and by studying the potential climate predictability associated with the snow/ice memory in the North America context at catchment to regional length scales and at time scales up to seasonal, GAPP may meet this requirement.

Although there have been many studies of the effect of liquid soil moisture on climate, the effect of frozen soils on land surface processes and the climate system has received little attention. However, approximately 60% of the exposed land surface in the Northern Hemisphere experiences seasonal freezing and thawing (Zhang et al., 2000) which often lasts several months and may reach depths of 2 to 3 m, while about 24% of northern hemisphere continents are classified as permafrost regions (Zhang, et al., 1999). Much of the GAPP study area experiences seasonal freezing which last several months, notably the upper Mississippi River basin and the Rocky Mountains (Zhang and Armstrong, 2001). Because of the latent heat of fusion, freezing and thawing wet soil involves a very substantial uptake or release of energy, so soils that freeze and thaw have, in effect, a large heat capacity. Freeze-thaw cycles influence the thermal and hydrological properties of the soil and this attribute has a significant impact on surface energy and moisture balances (Kineshita, 1982; Williams and Smith, 1989; Yershov, 1998) and, hence, on the climate system. Freezing soil increases its thermal conductivity and hence the soil heat flux, but it reduces its hydraulic conductivity and infiltration, thus increasing runoff, although near surface soil moisture may still increase due to restricted deep drainage. The existence of a thin frozen layer at the surface essentially decouples the moisture exchange between the land surface and the atmosphere. Soil freeze/thaw has a great impact on the onset of plant growth in the spring, on the regional carbon cycle and ecosystems and on the infiltration rates of spring snowmelt.

There are substantial inter-seasonal fluctuations in the area covered by snow in the Northern Hemisphere, and recent studies suggest there has been a decrease over the last 20 years (Armstrong and Brodzik, 1999) as air temperature has increased (by almost 1 °C in the case of North America). On the one hand, if the area with snow cover is reduced, the areal extent and thickness of frozen soils might well increase. On the other hand, increased temperature may itself result in less frozen soil. Data sets on snow cover extent, depth, and snow water extent are becoming more available at the National Snow and Ice Data Center (http://www.nsidc.colorado.edu) to aid study of this phenomenon.

Among the predictability questions associated with snow and ice cover that will be addressed under GAPP are the following:

1) When operating within comprehensive land-atmosphere models in an uncoupled mode, can snow/ice submodels adequately represent the observed seasonal evolution of snow cover and snow water equivalent at catchment and regional scale and, when linked by horizontal routing models, can they correctly simulate the effect of snowmelt on the hydrological response of catchments?
2) When operating with observed snow cover and snow water equivalent imposed as a lower boundary condition, can regional climate models adequately reproduce observed relationships between snow/ice cover and regional climate?
3) Can coupled regional hydrometeorological models that include snow/ice submodels adequately reproduce the observed seasonal evolution of snow cover and snow water equivalent at catchment and regional scales and the associated hydrological response of catchments?
4) In regional models, what are the model criteria that should be used to specify frozen precipitation?
5) How can the timing, duration, areal extent, and depth of seasonally frozen and thawed soils best be detected using remotely sensed data?

6) What is the response of seasonally frozen soils to changes in air temperature and snow cover extent? What is the impact of soil freeze/thaw status under snow cover on spring soil moisture after snowmelt.

4.2.3 Soil Moisture

The land, biosphere, atmosphere, and oceans are coupled together in an Earth system in which there is variability over a wide range of time and space scales. Variability and memory in this system are due to the cycling of water between reservoirs and may be strengthened by the development of feedbacks in the linkages between the reservoirs. Although the land fraction of the Earth is fairly small (30%), its distribution into large contiguous areas and its distinctive hydrothermal inertia cause significant variations in regional climatic systems.

Hydrologic states that have long memory, such as soil moisture, may serve to integrate past atmospheric forcing and enhance prediction skills for regional climates. Fennessey and Shukla (1999), Atlas et al. (1993), Bounoua and Krishnamurti (1993a,b), Xue and Shukla (1993), and Oglesby (1991) presented examples of numerical experiments, based on general circulation models, that indicate the sensitivity of climate simulation to initialization of surface soil moisture. Early studies by Delworth and Manabe (1993) showed that the presence of an interactive soil-moisture reservoir acts to increase the variance and add memory to near-surface atmospheric variables such as humidity, while Milly and Dunne (1994) identified and analyzed shifts in the atmospheric general circulation and hydrologic cycle in response to soil water storage capacity. Koster and Suarez (1996, 1999) introduced statistical measures to distinguish between inherent climate variability and variability due to the presence of land memory in the form of soil moisture.

The presence of feedback mechanisms can enhance land-memory phenomena. Thus, if positive feedback mechanisms are present in the coupled land-atmosphere system, an initial anomaly can persist through reinforcement at both climate and weather time scales. Cook and Ganadeskian (1991) and Cook (1994), for instance, showed that, following an initial soil-moisture anomaly, precipitation and the tropical general circulation are altered in ways that tend to reinforce the perturbed surface conditions. Brubaker et al. (1993) and Entekhabi et al. (1992) identified one such feedback mechanism that can reinforce surface anomalies. They found that when local precipitation is partially derived from local evaporation, reduced evaporation leads to reduced precipitation that, in turn, leads to further drying. Scott et al. (1997) and Vinnikov et al. (1996) demonstrated the importance of both soil-moisture reservoir size and the recycling of precipitation. However, there are conditions under which such simple feedback loops are not established. Thus, the relative roles of local versus external forcing for hydroclimatic anomalies over North America depend on factors that may either favor or counter drought or flood conditions (Giorgi et al., 1996).

On weather and storm event time scales, there is also evidence that initial soil conditions can reinforce the development of precipitating weather systems. At the regional scale, soil-moisture availability has substantial influence on elevated mixed layers and on associated “lids” on atmospheric instability that act to focus the release of convective instability and hence determine the distribution of the regional precipitation in time and space (Benjamin and Carlson, 1986; Clark and Arritt, 1995). Such coupling was clearly demonstrated by numerical modeling in GCIP (Paegle et al., 1996; Beljaars et al., 1996; Betts et al., 1996; Liu and Avissar, 1999a,b). These mechanisms are believed to have played a significant role in the Mississippi River floods in 1993. Castelli and Rodriguez-Iturbe (1993) showed that growth of baroclinic instability could be enhanced by anomalies in surface fluxes. Using numerical mesoscale atmospheric models, Chang and Wetzel (1991) and Fast and McCorcle (1991) showed that the evolution of summertime weather systems in the Midwestern U.S. is critically dependent on so-called "dryline" conditions where sharp gradients in soil moisture are present.

Thus, it is apparent that, in certain conditions, land memory in the form of the soil-moisture store, perhaps reinforced by positive feedback mechanisms such as recycling of precipitation, has significant effects on atmospheric variability and predictability and can lead to greater persistence of weather and climate anomalies. Delineation of the conditions under which soil-moisture state is important to the evolution of weather and climate, coupled with ways of estimating the initial soil-moisture state based on in situ and satellite observations and the realistic simulation of the subsequent evolution of that soil-moisture state in predictive models, should allow the extension of atmospheric forecast skills.

Among the predictability questions associated with soil moisture that will be addressed under GAPP are the following:

1) When operating in an uncoupled mode with observed (as opposed to modeled) precipitation, can the soil-vegetation-atmosphere transfer schemes used in climate prediction models adequately represent the observed seasonal evolution of soil moisture (and associated variables such as surface temperature) at catchment and regional scales in the GAPP study area? Furthermore, when coupled to horizontal routing schemes, can these models correctly simulate the hydrological response of catchments?

2) Does the use of off-line calculations of soil moisture improve predictions of regional seasonal climate and hydrological responses in the GAPP study area?

3) Are there ways of estimating the initial soil-moisture state in GAPP's regional hydrometeorological models based on in situ and satellite observations at catchment and regional scales, and does the use of such initialization methods improve the ability of these models to predict regional climate and hydrological responses in the GAPP study area?

4.2.4 Vegetation and Land Cover Dynamics

Vegetation plays a major role in determining the surface energy partition and the removal of moisture from the soil by transpiration. Representation of the vegetation's response (i.e., the change in live biomass) to atmospheric and hydrologic influences is currently weak in models used to give monthly to seasonal predictions of precipitation and hydrologic variables. GAPP should undertake research to better represent heterogeneous vegetation covers in models and to represent the seasonal evolution of vegetation.

There has been substantial progress in representing heterogeneous vegetation by specifying area average parameters on two fronts, one being essentially empirical and the other theoretical. The empirical approach (e.g., Mason, 1988; Blyth, et al., 1993; Noilhan and Lacarrere, 1995; Arain et al., 1996, 1997) is to create a coupled surface-atmosphere model, and to postulate and test hypothetical rules (often called "aggregation rules" see Shuttleworth, 1991) that give parameters applicable at larger scales by combining the parameters that control surface exchanges for small plots of uniform land cover. The theoretical approach (e.g. L'Homme, 1992; McNaughton, 1994; Raupach, 1995; and Raupach and Finnigan, 1995, 1997) is to adopt the equations that are accepted as reasonable descriptions of land-atmosphere exchanges for small plots of uniform land cover and to assume that such equations can also be used to describe the area-average behavior of heterogeneous cover, and to derive theoretical equations that link the parameters required at large scales with those that apply for individual small plots. Ongoing research under GCIP is investigating the sensitivity of model predictions to improved representation of heterogeneous vegetation cover. GAPP will address the requirement to extend such studies into new areas of the U.S.A.

Most meteorological models either prescribe a seasonal evolution in vegetation parameters or assume that they are constant. Assimilating satellite observations is one way to provide a more realistic representation of current vegetation status in model simulations, and there is now great opportunity to develop this approach with data from the recently launched Earth Observing System. However, when using this approach, care is needed to avoid creating inconsistencies between the space-time distribution of soil moisture and the assimilated vegetation biomass growth pattern.

The assimilation of satellite data is appropriate in weather forecasting applications, and it is an excellent approach for studying model mechanisms, for providing fields for model initialization, and for documenting the regional vegetation "climatology". However, it is less appropriate in the context of freestanding, monthly to seasonal climate prediction models. In this case, the alternative approaches are (a) to impose prescribed seasonal patterns of the evolution of vegetation based on the previously observed cycle of vegetation climatology, or (b) to incorporate the growth and senescence of vegetation in an interactive vegetation model. This last approach would provide a tool for addressing the land memory aspects of vegetation.

Incorporating dynamic vegetation into a land-surface model is a relatively new development, but research in this area has already provided important insights. Claussen (1995), for instance, used an interactively coupled global atmosphere-biome model to assess the dynamics of deserts and drought in the Sahel. He found that the comparison of atmospheric states associated with these equilibria corroborates Charney's (1975) hypothesis that deserts may, in part, be self-inducing through albedo enhancement. Ji (1995) developed a climate-vegetation interaction model to simulate the seasonal variations of biomass, carbon dioxide, energy, and water fluxes for temperate forest ecosystems in northeastern China. Foley et al. (1998) directly coupled the GENESIS GCM and IBIS Dynamic Global Vegetation Model through a common treatment of land-surface and ecophysiological processes. They found that the atmospheric portion of the model correctly simulates the basic zonal distribution of temperature and precipitation (albeit with several important regional biases) and that the biogeographic vegetation model was able to capture the general placement of forests and grasslands reasonably well.

An interactive canopy model (Dickinson et al., 1998) has been added to the Biosphere-Atmosphere Transfer Scheme (BATS: Dickinson et al., 1986, 1993) to describe the seasonal evolution in leaf area needed in atmospheric models and to estimate carbon fluxes and net primary productivity. This scheme differs from that used in other studies by focusing on short time-scale leaf dynamics. Tsvetsinskaya (1999) introduced daily crop growth and development functions into BATS and coupled it to the National Center for Atmospheric Research (NCAR) Regional Climate Model to simulate the effect of seasonal crop development and growth on the atmosphere-land-surface heat, moisture, and momentum exchange. She found that the coupled model was in better agreement with observations than the earlier non-interactive mode. Lu et al. (2000) developed and implemented a coupled RAMS/CENTURY modeling system and, in the context of GCIP, successfully applied it in the central U.S. to study the two-way interactions between the atmosphere and land surface at seasonal-to-interannual time scales (Lu, 1999). All these early attempts suggest the value of including two-way feedbacks between the atmosphere and biosphere in meteorological models to create the soil-vegetation-atmosphere transfer schemes (SVATS) with “dynamic Vegetation” (IV), hereafter called IV-SVATS.

Among the predictability questions associated with seasonally changing vegetation cover that will be addressed under GAPP are as follows.

1) How can the representation of the dynamic biophysical properties of vegetation and heterogeneous land cover be improved and validated in predictive models?
2) Do currently available SVATS with vegetation dynamics realistically simulate the seasonal cycle of vegetation growth and senescence in the several ecohydrological regions present in the GAPP study area?
3) Assuming that IV-SVATS do give realistic simulation, does their introduction into GAPP’s regional coupled models improve the simulation of climate variables in the GAPP study area at catchment to regional length-scales and at time-scales up to seasonal?
4) How does the simulation of IV-SVATS into GAPP’s regional models influence the modeled relative contribution to precipitation of advected moisture relative to the contribution from local evapotranspiration, and how does it influence the relative importance with respect to predictability of precipitation arising from sea surface temperature anomalies and land-memory processes?

5. OROGRAPHIC EFFECTS

5.1 Rationale

The Western Cordillera imposes pronounced surface influences upon North American weather. These mountains determine locations of lee cyclogeneses in winter and spring; the associated elevated heat source anchors the summer monsoon; the deflecting effects channel moisture corridors and low-level jets; and the upwind slopes that are favored sites for winter snow packs contribute runoff to North American rivers.

Although many orographic influences represent semi-regular, and therefore potentially predictable elements of the seasonal cycle, it is necessary to quantify contributions of local and remote thermal and dynamic effects in order to advance simulations of related circulation patterns, precipitation, and land hydrology. Some climate elements, such as the North American monsoon, are probably dominated by regional distributions of surface and latent heating. Other components, including the winter Rockies anticyclone, must also be strongly modulated by mechanical deflection. Both thermal and dynamic effects influence the transition seasons of fall and spring, but their relative magnitudes remain to be determined.

Winter and transition season events are particularly important for the hydrology of the western U.S.A. Unlike most other monsoonal areas of the world, it is the winter and transition seasons that provide most of the precipitation of this region. The accumulation of snow in these mountains is a disproportionate source of streamflow in the region, over 70 percent of which originates from the winter snowpack. This natural storage, which induces a lag of as much as six months between winter precipitation and its appearance as streamflow, is of critical importance to water management in the region. In view of the importance of winter and transition season precipitation, this chapter emphasizes these seasons.

5.2 Atmospheric circulation and precipitation variability -- scientific background

5.2.1 Large-Scale

Paegle et al (1987) show a regular phase-locking of monthly averaged lower-tropospheric circulations in western North America. Observed deviations from the monthly averaged climatology are strongly affected by orography. Mo et al. (1995) suggest that the anomalously wet Mississippi Basin pattern of the summer of 1993 was due to unusually strong and persistent westerly currents over the Rocky mountains. The anomalous westerlies produced a topographic response similar to the observed anomaly in a simplified model. Pan et al (1999) demonstrate the important role of quasi-stationary, monthly averaged anomalies to both the lee-side Low Level Jets and associated precipitation anomalies simulated in a relatively complete model for the 1988 drought and 1993 flood.

It is reasonable to suppose that orography plays an important role in the seasonal evolution of the climatology. The relative roles of different anchoring mechanisms, however, have never been clearly quantified. The mechanical blocking effect of topography produces an anticyclone above the highest mountains for strong westerly flow (Charney and Devore, 1979, Nogues-Paegle, 1979) and a cyclone in this location during weaker westerlies. This pattern is broadly consistent with lower tropospheric circulation changes from winter to spring (Paegle et al., 1987), although the circulation centers are not positioned over the highest orography in either season.

There is much evidence for strong local thermal forcing, particularly in summer when the western Cordillera forms a heated, elevated plateau (e.g. Smith et al., 1997). This mechanism is likely to be less relevant in winter. Some studies also suggest linkage of seasonal North American circulation re-arrangements to regional re-arrangements of tropical latent heating of the Amazon Basin and the eastern Pacific (Paegle et al., 1987). The possible relevance of several local and remote dynamic and thermal influences upon the climatology underlines the complexity of the forecast problem. High research priority should be placed upon diagnostic and prognostic studies designed to sort out the relative effects in different seasons.

Perspectives gained from vorticity dynamics can be particularly illuminating. In the presence of mountains, barotropic models that are founded upon the principle of vorticity or potential vorticity conservation are capable of explaining a substantial portion of the large-scale seasonal rearrangements. These models have been used to describe the scale dependence of topographic influences as well as lee-side flow characteristics. Charney and DeVore (1979) and Nogues-Paegle (1979) point out abrupt reversals of relative vorticity that may occur when the zonal flow fluctuates about near-resonant values for stationary, orographically forced Rossby waves.

5.2.2 Local-Scales

Major gaps remain in our understanding of the natural evolution of clouds and precipitation in mountainous terrain, especially at horizontal scales less than 100 km. Most measurements of air motions over complex orography (Neff, 1990) lack the spatial resolution to identify small-scale features like gravity waves, barrier jets, cold air pools, convergence zones, channel and blocked flows. These phenomena interact with cloud and precipitation development above the western Cordillera. Atmospheric stability also plays an important role. In winter the atmosphere is generally stable during pre-frontal periods and becomes less stable after the front passes. Stably-stratified flows excite waves that interact with cloud and precipitation development, whereas post-frontal periods are dominated by convective clouds that also interact with the orographic flow. A portion of the energy associated with these disturbances radiates away from the mountains as transient gravity waves, while some of the response may be orographically-bound in a semi-steady state.

Recent studies have addressed the role of blocking in determining the distribution of precipitation relative to a barrier (Yu and Smull 2000; Neiman et al. 2001). One of the goals of the CALJET and PACJET experiments (California Land-falling Jets and Pacific Land-falling Jets) of 1997/98 and 2000/01 on the U.S. West Coast in winter was to document this behavior using coastal wind profilers and rain guages and offshore observations from island-mounted wind profilers and from a NOAA P-3 aircraft. These observations have shown that a convergence line sets up offshore of the coast and initiates upward vertical motions offshore rather than only on the windward slope. This results in heavier precipitation at lower altitudes than would otherwise occur (Neiman et al. 2001). A key issue scientifically is the relative importance of blocking that can create an upstream-propagating internal bore, versus offshore advection of cool continental boundary-layer air through gaps in coastal terrain, as well as modulating effects of differential diurnal heating due to the land-sea contrast. Better understanding of these processes would translate to better forecasting of local precipitation if the likelihood of blocking could be assessed ahead of time. Such forecast improvements would be of particular value to emergency managers and highway departments.

Enhanced vertical motions resulting from low level lifting of air by orographic barriers that further excite gravity waves, often lead to the development of clouds and precipitation. Gravity waves can penetrate through deep layers and significantly influence the location, intensity, and microphysics of precipitation reaching the surface. Little effort has been directed towards understanding the effect of gravity waves on cloud and precipitation development. As a result, the interactions between air motions, cloud, and precipitation development on the smaller scales (10 to 100 km) are still poorly understood. When mountain waves induce cloud development, the clouds can modify the thermodynamic profile of the atmosphere and in turn the gravity wave structure. For example, condensation reduces atmospheric stability, thus decreasing gravity wave frequency; i.e. increasing the vertical wavelength of mountain waves (Barcilon et al., 1979; Durran, 1990). For flow over complex terrain, the combined effect of these mechanisms is still poorly understood.

Smith (1979) and Cotton and Anthes (1989) reviewed wintertime orographic flows and precipitation. Although numerical models have demonstrated an ability to provide realistic simulations of certain mesoscale flows and weather systems (Cotton and Anthes 1989), an accurate prediction of the amount and, to a lesser extent, the location of precipitation in mountainous regions has remained elusive. Mesoscale convective systems occur in the lee of the Rockies and commonly provoke severe weather and flash floods there during spring and summer. It has been suggested (Tripoli and Cotton 1989a, b) that these systems are accompanied by thermally driven solenoidal circulations and that their development is favored over the Rockies. The mountain/plains solenoidal circulation has been implicated in the formation of long-lived mesoscale convective complexes over the central United States (Davis and Weissman, 1994; Olsson and Cotton, 1997a, b). These weather elements also interact with the leeside, Great Plains low-level jet, particularly during the night when the jet and leeside convection both reach maximum strength (e.g. Nicolini et al., 1993).

5.2.3 Role of Coupled Land Surface-Atmosphere-Ocean Interactions

Some seasonal anomalies of precipitation in regions of the western Cordillera, appear to be connected to ENSO fluctuations. Cayan et al (1999) studied a group of La Nina and El Nino years for the period of 1949-1995. They conclude that over the U.S. Southwest, mildly wet days are more frequent in typical El Nino years and very wet days are even more frequent in such years. They also find that higher streamflow values are much more frequent in typical El Nino years and conclude that streamflow patterns are accentuated replica of precipitation patterns. The pattern over the Pacific Northwest and northern Rockies shows a reverse correlation with El Nino. Here mildly wet days are less frequent in typical El Nino years and very wet days are even less frequent during El Nino years. High streamflow values are much less frequent in this portion of the Rockies during El Nino events.

The local streamflow signal is strongly reflective of ENSO related atmospheric anomalies, but less clear for those rivers that have important tributaries over a broad latitude belt. For example, the Green river tributary of the Colorado river originates in the northern Rockies and may correlate with dry El Nino episodes, while lower-latitude tributaries of the Colorado are wetter during El Nino and this trend tends to weaken the net ENSO signal for the Colorado River proper (Cayan et al; 1999; Piechota et al, 1997).

Although streamflow anomalies in large river basins such as the Columbia River in the Northwest and Sacramento-San Joaquin basin in California reflect the basin mean ENSO temperature and precipitation anomalies, the effects of ENSO on streamflows in the subbasins and smaller mountain watersheds are more complex. For example, Leung et al. (2003) show that mesoscale patterns of ENSO precipitation anomalies can be controlled by the interactions of changes in large-scale circulation during the different phases of the ENSO cycle with topography. Such interactions may lead to complex spatial distribution of ENSO precipitation and streamflow anomalies within the larger river basins that vary in magnitude and sign. Leung et al. (2003) and Ralph et al. (2003) show examples of observed streamflow anomalies that are evident of the role of topography in modifying the large-scale ENSO climate signals.

While atmosphere-ocean interactions such as the ENSO cycle and its effects on climate and hydrology have been studied quite extensively in the past decade, and recent studies have begun to investigate the role of topography in controlling local to regional scale climate variability, the effects of land-atmosphere interactions on cold season hydrometeorology in regions of complex terrain have received relatively little attention. Snow can affect atmospheric stability through albedo effect and snowmelt can influence atmosphere conditions through changes in soil moisture and surface fluxes. Because of limitations in model resolution and land surface models, snowpack is often not well simulated by global and regional climate models. Remote sensing and data assimilation of snow can offer a significant opportunity for improving model representations of snow processes and advancing the understanding of the effects of land-atmosphere interactions on hydrometeorology and its prediction in the western cordillera.

5.2.4 Role of Inland Lakes

While orographic uplift provides the major surface forcing of precipitation on the western sides of mountains, other surface mechanisms are also locally important. The Great Salt Lake, for example, appears to enhance cold-season precipitation to its lee. The lake effect is difficult to distinguish from local topographic uplift in observations, but diagnostic and model studies (Steenburgh et al, 2000; Onton and Steenburgh, 2001; Steenburgh and Onton, 2001) clearly point to a lake influence in pronounced events. The Great Salt Lake depth increased by about 10 feet from an average prior depth of about ten feet, and horizontal area increased substantially after an unusually wet period in the early 1980s. The lake covered an even larger area and was several hundred feet deep approximately 18,000 years ago when it was referred to as Lake Bonneville and spanned much of present-day Utah, eastern Nevada, and southern Idaho.

This largest inland body of water of the western United States has strong surface interactions with climate variations that contribute to the water cycle of the semi-arid west and presents potential hazards to local development. During its modern recorded maximum of the mid-1980s, the lake inundated portions of interstate highway 80, the major east-west land route through the Central Rockies, and its surface elevation was within 1 foot of the lowest runways of the largest airport of the Great Basin. An effect that is thermodynamically similar to the lake influence may be noted over extensive moist salt flats located west of the Great Salt Lake. These salt flats retard surface drying because of the reduced saturation vapor pressure of salty brines and reduce surface temperature response because of the high conductivity and heat capacity of wet soils. Large differences of skin temperature have been noted between wet salt flats and adjacent regions of dry soil. These surface variations are usually neglected in models, and neither the Great Salt Lake, nor the surrounding mountain ranges, are adequately resolved by most models, particularly in climate simulations. Both topography and these other surface variations affect simulated mesoscale circulations (Astling, 1990), and their inadequate resolution may contribute to the relative minimum of forecast accuracy of precipitation over the central Rockies found by Gartner et al. (1996) and by McDonald (1998) in operational forecast models.

5.2.5 Role of Maritime Mountains

In mountainous maritime regions of the western U.S., the interaction of topography, precipitation, and temperature, both at the time scale of individual storm events and over the winter season, strongly influences streamflow, and the potential for damaging floods (Westrick and Mass, 2001). Unlike the higher elevation mountain ranges in the western interior, much of the Coast and Cascade ranges lie in the so-called transient snow zone, where the form of precipitation transitions between rain and snow many times over the winter season. In the northern Cascade Mountains, the transient snow zone is usually taken to be roughly 300-900 m, whereas farther south in California it is higher, perhaps 1200-1800 m. Below the transient snow zone, most precipitation occurs as rain over the winter period, whereas above the transient snow zone, it is mostly snow. Figure 5.1 shows the seasonal streamflow signature for representative catchments in the three zones. The difference between the seasonal hydrograph of the lowland stream, which peaks in winter more or less in phase with the precipitation maximum, and the high elevation catchment, which peaks in late spring near the time of maximum melt energy, is apparent. The transient catchment shows a more complicated behavior, which reflects both the influence of a low elevation zone that is primarily rain-dominant, and a higher elevation zone where a repeated cycle of snow accumulation and melt occurs throughout the winter. This accumulation and melt cycle can have a critical effect on the potential for flooding, which often occurs (especially for catchments on the west slopes of the maritime mountain ranges) due to a combination of intense rainfall and snowmelt.

In western Washington and Oregon, and northern California, many of the largest floods have had a significant component of rain-on-snow. Furthermore, many of these floods tend to occur in late fall or early winter, often after accumulation of an early season snow pack which melts rapidly (Kattelman, 1997; Harr, 1981).

The mountainous coastal zone of the western United States has experienced several major flood events in the past decade, resulting in more than 6 billion dollars of damage and loss of dozens of lives (Percy, 2000). Flooding in the Russian River basin in California during winter 1994-95 caused $800M dollars of damage; over $1 Billion in damage resulted in the Pacific Northwest in February 1996 when the Columbia and Willamette Rivers crested 10-20 feet above flood stage (Colle and Mass 2000) and during the 1997-98 El Nino floods, landslides, and agricultural damage due to heavy precipitation produced losses totaling $1.1 billion throughout the U.S. (Changnon 1999).

Such events involve interactions between large-scale atmospheric flow anomalies, orographic precipitation enhancement, and surface hydrology effects. For example, extreme flooding events in the Pacific Northwest are most common during the fall and are frequently preceded by heavy snows that reach unusually low elevations (e.g. Colle and Mass, 2000). The subsequent development of moist southwesterly large-scale flow with connections to the subtropics, known colloquially as the "pineapple express", results in heavy precipitation and a rapidly melting snowpack as the snow line retreats to higher elevations. Due to high freezing levels, orographically enhanced precipitation over the Coast Range and Cascade Mountains falls predominantly as rain during these events. During the 5-9 February 2000 flooding event, liquid precipitation in the lower and higher elevation regions of the Pacific Northwest ranged from 10-25 and 35-75 cm, respectively. High freezing levels further augmented this rainfall with the melting of 10-30 cm of water equivalent snowmelt (Colle and Mass, 2000). During flooding events in California rainfall rates over mountainous terrain of as much as 50 cm/day have been observed, and the influence of melting is less.

The threat of major flooding in California in winter season storms is highlighted by the fact that over the last 30 years, storms have caused loss of life and property in the west coast states at an annually averaged rate comparable to the impacts of earthquakes in this earthquake prone region (roughly 10 lives lost and $1 billion damage annually). These coastal storms can reach hurricane intensity, as indicated by surface winds in excess of 100 knots in several recent storms, 24-hour rainfall of 12 inches or more in 1998, and 22 inches in 3 days in 2001, for example. A National Academy of Science study (NAS, 1995) reported that Sacramento, CA has one of the greatest flash flood threats in the nation as a result of likely extreme rainfall in the American River watershed and the relative capacity for flood control. Finally, NWS summaries of the spatial distribution of probable maximum 24-hour precipitation indicates the potential of more than 48 inches of rain in 24 hours in the mountains above Los Angeles (NWS, 1999), one of the highest values in the nation, if not the highest. One storm in that area produced 26 inches of rain in 24 hours. The spatial distribution of precipitation in these intense events is largely driven by orographic processes in the proper synoptic-scale context where maritime air is forced over coastal mountains, and better prediction of these events could play a major role in emergency response, flood control and other key areas.

5.2.6 Role of Microphysical Processes

The Western Cordillera hosts a hydrological system characterized by highly localized snow packs that dot the ambient landscape and define headwaters, flow rates and storage zones of regional streams and rivers. The horizontal dimensions of many such snowpacks are on the order of a few tens of kilometers. This is similar to the horizontal displacement of hydrometeors in their descent from cloud to surface, and the local distribution of snow-loading on adjacent slopes is determined by influences affecting the fall rate, including cloud microphysical processes, as well as cloud-scale to mesoscale wind fields. Chen (2000) illustrates the extreme variability of wintertime snow-rates over the central Great Basin.

A correlation exists between the temporal and spatial evolution of clouds and the complexity of the terrain (Rauber et al., 1986; Rauber and Grant, 1986; Marwitz, 1986; Deshler et al., 1990; Huggins and Sassen, 1990; Super et al., 1989). Marwitz (1986) compared cloud and precipitation evolution in winter orographic clouds over the Sierra Nevada and San Juan mountains and found significant differences in flow dynamics and microphysical processes between the two mountain ranges.

A very recent finding from a seasonal rainfall study on the coast of Northern California that included specialized vertically pointing radar measurements indicates the importance of "warm rain" processes in orographic winter-season coastal storms. Using the radar data to identify the signature of a radar bright band, the study found that roughly 38% of all precipitation at the wet site chosen had no discernable bright band. This suggests that ice processes likely play a minor role in these events, even though some of the cases produced rainfall at a rate known to produce flooding in the area. This result was from the CALJET experiment during the strong El Niño of 1997/98. In a follow-on study, during PACJET-2001 at the same site but during a weak La Niña, only a very small percentage of precipitation occurred without a brightband. The presence of warm rain processes in this region, and the contrast in local microphysical conditions during opposite phases of ENSO is a critical and exciting arena of new research.

Understanding microphysical processes and their complex interactions with the dynamics in winter storms in mountainous regions can be substantially enhanced using numerical modeling that is supported by field programs. Modeling studies help to understand the roles of various microphysical processes on heat and moisture budgets of clouds and their role on precipitation development. Several levels of cloud microphysical treatment have been attempted, but it is not yet clear how detailed these calculations must be to provide acceptable simulations of cloud processes and quantitative precipitation forecasting. Gaudet and Cotton (1998) showed significant improvement in precipitation prediction skill with the use of bulk microphysics. However, the simulations produced excessive precipitation at low-levels and too little at higher elevations. In addition, systematic biases have been found in real-time MM5 simulations over the Cascades which tend to produce too much precipitation on the windward side and too little on the lee side (Colle et al., 1999). This bias also was observed in the 10 km Eta model (Colle et al., 1999). These biases may be related to incorrect representation of microphysical processes in the model parameterizations. Important parameters found to be sensitive to the development of precipitation are, for example, fall speeds of hydrometeors and the definition of the cloud droplet spectra. Interaction of the dynamics with microphysical processes may also play a role.

5.3 Hydrologic implications

Orographic processes exert a strong influence on the hydrology of the West. In the western interior, the lowlands between the Rockies and the Cascades and Sierra Nevada are areas of low precipitation and high evaporative demand. Therefore, runoff production from these areas is extremely small, and substantial runoff usually occurs only during infrequent occurrences of intense precipitation. In the southwestern most portion of the region, monsoonal conditions can lead to extreme flooding in lowland areas (almost always, however, exacerbated by orographic intensification in the uplands). Outside this area of monsoonal influence, runoff from lowland areas is mostly associated with very infrequent convective storms, often in summer.

On the other hand, the mountainous areas of the west mostly experience winter dominant precipitation, the amount of which varies strongly with elevation. The elevation gradient affects the land surface water balance in two ways. First, evaporative demand is reduced with elevation due to lower temperatures, and second, precipitation is orographically enhanced. The result is that relatively small high elevation areas are the source of most of the region's streamflow. The role of these high elevation areas has long been recognized. For instance, snow surveys conducted to measure the water equivalent of the mountain snowpack have been used to forecast spring and summer streamflow since the 1930s, when the method was first applied by Church to the Carson River in Nevada (Clyde, 1939).

5.4 Objectives

The central goal of GAPP orographic precipitation studies is to improve the ability to predict the spatial distribution of precipitation in the complex terrain of the western U.S., and to forecast precipitation for intermediate (seven to fifteen days) to long range (monthly to seasonal). The specific steps include: 1) Quantify regional and remote surface processes that determine the regular annual cycle in the Rocky Mountains and Cascade and Coast Ranges; 2) Examine predictability of the average seasonal cycle and of differences from the average. 3) Explore model methodologies required to simultaneously resolve global to local catchment scales. These goals will emphasize the winter and transition seasons, and are intended to complement NAMS objectives outlined in Chapter 6.

5.5 Scientific Approach

The above stated objectives will be addressed by building on ongoing research, which will be extended through the initiatives outlined below.

5.5.1 Collaboration with ongoing research

The relatively well-defined forcing of mountains helps to simplify the dynamics, particularly in the case of stable wintertime flows. Such winter storms present a broad range of active microphysical processes and as such provide a fixed natural "laboratory" for studying the dynamics and microphysics of cloud systems (Banta, 1990). These concepts have motivated a number of scientific studies and field programs. Recent field programs include the Arizona Program (Klimowski et al., 1998; Bruintjes et al., 1994), COAST (Bond et al., 1997), CAL-JET (Ralph et al., 1999), and MAP (Houze et al., 1998) which focused on precipitation in the Alps. These programs mainly emphasized orographic surface forcing interacting with cloud dynamics, but other surface forcings associated with lakes and variable soil moisture are also relevant in certain regions of western North America.

The California land-falling Jets experiment (CALJET) of winter 1997/98 (Ralph et al. 1999) and the Pacific Land-falling Jets experiment (PACJET) of winter 2000/01 (Ralph et al. 2001) have explored issues related to improved understanding and prediction of land-falling winter storms that emerge from the data sparse Pacific ocean and strike the U.S. West Coast. These efforts have focused on physical process studies, observing system assessments, and forecast applications development. Of critical importance to understanding and predicting these storms are (1) distinguishing the roles of the low-level jet, air-sea interaction, orographic blocking and precipitation, (2) targeted observations for operational forecasting, (3) testing of new observations, and (4) the impact of seasonal-to-interannual variability on storm characteristics. The operational applicability of CALJET and PACJET has led to requests from the operational community and from forecast users that PACJET be conducted each winter. If this comes to pass, then each winter there may be an opportunity to enhance field activities associated with GAPP along with those of PACJET.

The Intermountain Precipitation Experiment (IPEX) took place in February 2000 and was centered over the Great Basin (Steenburgh, 2000). This experiment was partly motivated by the observation that the Eta model Quantitative Precipitation Forecast (QPF) skill is lower over the Intermountain West and eastern Rocky Mountains than over any other region of the U.S. (Gartner et al., 1996). Its base of operations was selected in part by the need to distinguish the surface roles of topography and lake effects upon precipitation in the Central Great Basin and partly by the proximity of an extensive mesonet of surface-based stations (Horel et al., 2000). This experiment and the MAP initiative place an emphasis upon cloud microphysics thought to be important on small scales characterizing highly corrugated local topography.

GAPP orographic precipitation studies will also benefit from the IMPROVE (Improvement of Microphysical PaRameterization through Observational Verification Experiment) field experiment in the Pacific Northwest. IMPROVE (improve.atmos.washington.edu) is intended to improve quantitative precipitation forecasting (QPF) in mesoscale models through comprehensive observational verification of model-parameterized cloud and precipitation microphysics. Two field campaigns were conducted. The first was a frontal precipitation study over the northeast Pacific Ocean offshore of Washington State carried out in January/February 2001. The second was an orographic precipitation study in the Cascade Mountains of central Oregon in November/December 2001.

IMPROVE is motivated by deficiencies in the microphysical parameterizations in mesoscale numerical weather prediction models when applied in regions of complex terrain, especially mountainous maritime environments. One focus is on the bulk parameterization of grid-resolved cloud microphysics and precipitation. IMPROVE aims to provide an observational basis for a comprehensive evaluation of the underlying assumptions and predicted hydrometeor distributions of these schemes, and to use such tests to improve the parameterizations. IMPROVE is designed to obtain concurrent in situ and remotely sensed observations of cloud and precipitation microphysics, thermal structure, and 3D wind fields over the Olympic coastal area of Washington (2001) and the Oregon Cascades (2001). The IMPROVE experimental design will utilize the NCAR S-Pol radar, as well as in situ and aircraft observations. Some modest hydrologic enhancements to the experimental design are planned as well.

5.5.2 Identification of sources of seasonal cycles

GAPP will promote studies designed to explain what determines the annual cycle of water cycle processes over North America as well as deviations from that cycle. Since the possible surface and atmospheric forcings span a broad range of local and remote thermal and dynamical effects, it is impractical to address this problem through field programs of limited duration and areal coverage. Consequently, these studies will rely heavily on model predictions. The relative contributions of dynamic and thermodynamic orographic effects require further quantification. Important elements of summer to winter variability are present in global models of relatively low resolution (e. g. Nogues-Paegle et al., 1998). Such models may be used in inexpensive configurations to study local and remote surface forcing of the semi-stationary wave patterns characterizing the climatology of each season. If dynamic effects dominate the winter-time orographic influence, the west coast anticyclone should be largely unaffected by the presence or absence of surface heat flux over the Rockies, but depend essentially upon the presence of this mountain range. A series of experiments can be designed to address this question, and their results will have obvious relevance to explanations of the seasonal evolution and form the basis for understanding deviations from this evolution.

5.5.3 Identification of sources of anomalies and precipitation predictability

Precipitation prediction is among the most difficult forecasting problems and even with vastly improved observations and numerical models in recent times, skill in precipitation forecasting has been improving very slowly (Fritsch et al., 1998). Olsen et al. (1995) show that prognostic skill levels for heavy precipitation events are highest in the winter, and attribute this to the larger-scale character of cold season precipitation events. The role of topographic organization of precipitation is more difficult to evaluate. Gartner et al. (1996) demonstrate that the highest equitable threat scores over the conterminous USA.for the meso-Eta model are found around the West Coast, although there is an extensive data-sparse region to the west. One possible explanation for this skill enhancement may be orographic organization of precipitation and related predictability enhancement. This explanation would also imply relatively high skill scores over the central and eastern Rockies, but Gartner et al. (1996) find that here the meso-Eta model has relatively low skill.

In some respects, the problem of monthly and seasonal precipitation prediction may be simplified by the averaging inherent at these extended ranges. Precipitation outlooks accompanying the last strong El Nino were remarkably good. However, neither the ENSO signal, nor the prospects for predictability enhancement, were always regarded as useful elements to extra-tropical prediction. Indeed, the observed extra-tropical ENSO signal is quite variable. For example, the weak warm event of 1976-1977 was marked by substantial winter drought over most of the West, while strong warm events of 1992- 1993 and 1997-1998 were accompanied by serious flooding. Earlier model studies emphasized the role of natural variability and the difficulty in sorting out ENSO related signals at higher latitudes (e.g. Geisler et al., 1985). Estimates of predictability based on model simulated signal and noise gave generally pessimistic views about the prospects for dynamical seasonal prediction in mid-latitudes (Chervin, 1986). Efforts at deterministic extended range prediction (Miyakoda et al, 1983, 1986) displayed feasibility of monthly dynamical prediction, but it was realized that the deterministic predictability of the first ten days was the basis of dynamical predictability of the monthly mean. This fact led to further skepticism regarding extended range predictability.

Many earlier models did not produce realistic extra-tropical height anomalies in relation to tropical SST anomalies (reviewed by Lau, 1997). More recent modeling efforts (e.g. Shukla et al, 1999) display much higher skill in seasonal prediction of the Pacific-North American flow anomalies in the presence of large tropical SST anomalies. The skill enhancement is presumably related to model improvements, and it is reasonable to postulate that continued model advances should allow further predictive improvements. This supposition forms the working hypothesis for GAPP, and available evidence suggests that the winter and transition seasons may be especially well suited for its exploitation. The GAPP research community can both benefit from past model advances and contribute to model evolution, as outlined below.

5.5.4 Explore and Develop Model Methodology

Many of the requisite model developments for regional hydrometeorological processes are similar to those addressed in other modeling sections on monsoons and summer precipitation. In view of the monthly to seasonal forecast requirement, it is necessary to include global forecast capability. In addition, the relatively poor Eta model precipitation forecasts at 29 km resolution over the extreme topography of the central Rockies (Gartner et al., 1996) suggest a need for exploratory forecasts at much higher resolution. Such simulations may require non-hydrostatic treatment and prognostic cloud microphysics.

The optimal model configuration would contain all necessary features in a global, variable resolution treatment or global model with two-way interactive high resolution nests that can focus on a number of watershed catchments. This capacity is currently available only in early developmental stages, particularly for versions that include non-hydrostatic dynamics and prognostic cloud microphysics in a fully global treatment. Real-time three-dimensional prototype regional/mesoscale precipitation prediction studies for Colorado have been conducted for more than six years (Cotton et al., 1994). These simulations used the CSU RAMS with bulk microphysics (Walko et al, 1995) at horizontal grid resolutions between 16 and 80 km. Bruintjes et al. (1994) completed research simulations of heavy precipitation events with horizontal grids as fine as 2 km. These simulations also used bulk microphysics and non-hydrostatic dynamics with interactive grid-nesting. Good correlation between model precipitation dynamics and observations were obtained. The results indicated that a seeder-feeder mechanism enhanced precipitation that contributed to flash flooding. Accurate simulation of gravity wave-cloud interactions and precipitation development required horizontal grids of 2 km.

It is important to know the spatial and temporal variations of aerosol and CCN concentrations as they affect microphysical processes of precipitation development in clouds. Studies including aerosol and CCN as field variables in microphysical parameterizations in numerical models are necessary. This approach may eventually allow dynamic adjustment of the microphysical parameterization to differing aerosol and CCN characteristics and could produce a more robust model and reduce the need for tuning parameterizations with changes in airmass. In addition, investigations are needed to determine whether parameterizations based on a number of well-tuned case studies provide robust solutions that capture natural precipitation phenomena in a consistent manner.

Knowledge and experience gained through field experiments and real time weather forecasts need to be incorporated in models that are used in climate and hydrologic predictions. Currently, model resolutions are limited by current computing resources, and model parameterizations do not scale properly over a range of spatial scales, consequently there is a need to investigate the effects of model resolution and model representation of topography in climate models. The validity and utility of alternative approaches to modeling orographic effects such as statistical and dynamical models and subgrid parameterizations of orographic precipitation also should be explored.

5.5.5. Identification of sources of hydrologic prediction errors

The primary source of hydrologic prediction error usually is error in precipitation, hence the GAPP focus on improving predictability of precipitation should have ancillary benefits for streamflow forecasting, and its use in water management. However, aside from this general understanding, the hydrologic response of mountainous watersheds in partially or highly snow-dominant watersheds represents a complicated interaction of initial soil moisture (and its seasonal and interannual persistence), the spatial distribution of precipitation and its form, and the timing and spatial variability of energy available for snowmelt. Therefore, concurrent with the GAPP emphasis on field data collection and mesoscale modeling, companion hydrologic studies will be undertaken to provide data sets and methods suitable for diagnosing hydrologic predictions. These data sets and studies will focus on a) the role of timing and spatial distribution of snowmelt on runoff production in mountainous areas; b) the extent to which seasonal soil moisture carry-over (from the end of the summer season through the following winter) affects runoff generation during winter storms and spring snowmelt, and c) the sensitivity of runoff generation to evapotranspiration, particularly changes that would be associated with lengthening of the snow-free season. The resulting data sets, in combination with mesoscale reconstruction of precipitation and associated hydrologic model forcings, will provide the basis for diagnosis of hydrologic model predictions, and evaluation of improved runoff parameterizations.

6. NORTH AMERICAN MONSOONAL CIRCULATIONS

6.1 Rationale

Documenting the major elements of the warm season precipitation regime and their variability within the context of the evolving land surface-atmosphere-ocean annual cycle is a fundamental and necessary first step towards improving warm season precipitation prediction over the United States. Monsoon circulation systems, which develop over low-latitude continental regions in response to seasonal changes in the thermal contrast between the continent and adjacent oceanic regions, are a major component of continental warm season precipitation regimes.

6.2 Scientific Background

The North American warm season is characterized by a monsoon system [hereafter referred to as the North American monsoon system or NAMS] that provides a useful framework for describing and diagnosing warm-season climate controls and the nature and causes of year-to-year variability. A number of studies during the past decade have revealed the major elements of the NAMS, including its mean seasonal evolution and interannual variability. Its broad scale features and variability are described together with a literature review in Appendix C.

The NAMS displays many similarities (as well as differences) with other regional monsoons, most notably the southern and east Asian monsoon complex and the Australian and West African Monsoons. While the NAMS is less impressive than its cousins, it still has a tremendous impact on local climate. Of significance to GAPP is the fact that the NAMS affects much of the USA, and in particular the GAPP large-scale study areas. Notable features of the NAMS include major low-level inflow of moisture to the continent (from both the Gulf of California and the Gulf of Mexico), a seasonal increase in continental precipitation, and a relatively warm troposphere over the monsoon region resulting in a “monsoon high” in the upper troposphere. There are also significant regional fluctuations in precipitation (including both increases and decreases) that arise as a result of coastal geometry, topography and latitudinal distribution of the continents.

A fundamental and distinguishing property of the NAMS is the prominence of the diurnal cycle. The strong low-level inflows of moisture from the Gulf of Mexico mentioned above are strongly tied to the diurnal cycle. Moisture transport from both oceanic source regions primarily occurs via diurnally-varying low-level jets. Diagnosing the causes and variability of these jets is essential for achieving improvements in the simulation and prediction of warm season precipitation in the GAPP study area. The necessary scientific steps in this regard are outlined in Section 6.2.3.

6.2.1 North American Warm Season Precipitation regime

There are fundamental differences between the North American cold season and warm season precipitation regimes. The upper tropospheric mid-latitude westerlies are much weaker during the warm season, as are the extratropical storm tracks, which shift poleward to a mean position near the US-Canadian border. In the eastern tropical Pacific the ITCZ and equatorial cold tongue intensify as the tropical precipitation maximum over the Americas shifts from Amazonia to the eastern Pacific-central American region. To the north, there is clear evidence of increased continental-scale control of the precipitation regime over the U.S. and Mexico. The energy at smaller spatial scales increases (e.g., terrain related diurnal variability and convective precipitation related to terrain and coastline features), and much of the continent becomes an atmospheric moisture source, i.e. evaporation exceeds precipitation.

The structure of the low-level circulations that supply moisture from the tropics along the Gulf of California and from the Gulf of Mexico, the precipitation patterns and associated divergent circulations, and the moisture and energy budgets over the core North American monsoon region remain largely unvalidated and incompletely understood. Dynamical understanding of the seasonal march of rainfall and its variability over the NAMS domain is incomplete. The meteorological observation and analysis system for this region must be improved to describe and understand relationships among low-frequency anomalies of the warm season precipitation regime and the nature and frequency of significant weather events such as hurricanes and floods.

Precipitation is an intermittent process. Individual precipitation events occur in association with synoptic, diurnal, and mesoscale atmospheric circulation systems. The number and/or intensity of these events over a month or season can vary substantially from year to year. Part of this time-averaged variability appears to be a response to subtle variations in the distribution of tropical sea surface temperatures (SSTs), but the mid-latitude response to these tropical anomalies is regionally and seasonally dependent. There is also persuasive evidence that variations in land surface conditions, particularly soil moisture and vegetation, can also play a significant role in warm season precipitation variability, including over mid-latitude continental-scale areas. Because these land surface anomalies are themselves largely determined by fluctuations of precipitation, it has been suggested that there are important feedbacks between the atmosphere and land surface that can be either positive (in which case climate anomalies are self-sustaining) or negative (self-suppressing). Diagnosis of these feedback pathways will require significant advances in the quality of observations and modeling of the NAMS domain.

6.2.2 Role of Land Surface-Atmosphere Interactions

The relative importance of land and ocean influences on North American precipitation changes with the seasons. The influence of the land surface is strongest during the warm season, when the continents are warmer than the surrounding oceans and surface evaporation is large and varies greatly as a function of terrain and vegetative cover. It should be noted that the influence of SST anomalies on cold season precipitation can indirectly affect warm season rainfall, since they play a role in determining the initial springtime soil moisture conditions and vegetative cover, which in turn can feed back upon the warm season climate through their influence on surface air temperature and evaporation.

The land surface has many memory mechanisms beyond soil moisture, especially over the western US. Snow extends surface moisture memory across winter and spring. Vegetation in semi-arid regions is a seasonally evolving, interannually variable atmospheric boundary condition that affects momentum transfer, radiation, and heat and moisture fluxes. In addition, aerosols are an important atmospheric constituent in southwestern North America. Aerosols from urban anthropogenic sources attenuate and reflect short wave radiation. Fires (both natural and man-made) and their associated particulates have pronounced seasonal and interannual variability. Dust is an important factor in the spring and early summer. The atmospheric circulation is often weak in southwestern North America, enhancing the residence time and effect of aerosols. The large and variable radiative impacts of aerosols as well as anthropogenically-driven trends in aerosols in the region must be understood.

It is important to recognize that, depending on the variable and the time of the year, the evolution of particular surface forcing variables may not be slow. For example, in western Mexico the vegetation type and fractional vegetation coverage change dramatically in just a few weeks during the onset of the summer monsoon. Observations from the Oklahoma Mesonet indicate that soil moisture can change dramatically with one heavy rainfall event. This highlights one of the fundamental modeling challenges, which is to properly simulate the entire frequency range of precipitation intensities. Clearly, the rainfall produced by a short but intense rainfall event, and the same mean rainfall produced by a steady but light rainfall event, will have very different consequences for land-atmosphere interactions.

As indicated above, the surface hydrology of western North America plays a fundamental but inadequately understood role in the warm season precipitation regime. The complex terrain and semi-arid conditions of this region stand in stark contrast to the Mississippi Valley that was the focus of GCIP. For example, in southwestern North America lush natural vegetation exists primarily in narrow strips along the banks of rivers in the middle of arid deserts. A proper characterization of large-scale evapotranspiration must somehow resolve these one-dimensional ribbons of vegetation, which can be much narrower than the typical footprint of an AVHRR-based vegetation scene.

Soil moisture also varies quite differently in the arid NAMS domain compared with the more mesic GCIP region. Soil type and vegetation cover depend strongly on the surface elevation and slope aspect, both of which are tremendously variable over short distances in regions of complex terrain. Runoff is highly channelized. The short duration of most warm season precipitation episodes, combined with intense solar radiation, make for intense but short-lived episodes of surface evaporation following rainstorms. For all of these reasons, the surface hydrology component of GAPP will provide a severe test of land surface models and will continue the progress on these models begun in GCIP.

Recent research suggests that the strength of seasonal land surface-atmosphere interactions is strongly modulated on the decadal time scale. No clear correlations to identified modes of oceanic decadal variability, which are themselves poorly understood and not currently predictable). It seems clear, however, that seasonal-interannual climate variability and predictability in the GAPP study area is intimately intertwined with decadal and longer climate change.

6.2.3 Role of low-level jets

The Great Plains low-level jet (GPLLJ) plays a critical role in the summer precipitation and hydrology of the central US. Though less extensive, the Gulf of California low-level jet (GCLLJ) contributes to the summer precipitation and hydrology in the southwestern US and northwestern Mexico. Developing a better understanding of both of these jets is of critical importance to GAPP.

The GPLLJ transports considerable moisture from the Gulf of Mexico and eastern Mexico into the central US. It is controlled by large-scale dynamics, the strength and size of the energy sources over the Gulf of Mexico and the Intra-Americas Sea and land surface effects, including vertical motion induced by topography, elevated heat sources and dynamic effects over the Rocky Mountains, radiation balances on the land, and temperature contrasts between the land and the Gulf of Mexico. The diabatic effects of land in this regional circulation must be understood and modeled. For example, nocturnal dynamic and thermodynamic factors may be mutually reinforcing, thus contributing to the strength of moisture convergence into the Mississippi River Basin during the night and early morning.

The Gulf of California jet transports low-level moisture from the eastern tropical Pacific towards the southwestern U.S. It is inextricably linked to tropical easterly waves and moisture surge events that play a critical role in the sub-seasonal variability of the monsoon along the west coast of Mexico and in the desert southwest. Most of the moisture in the lower troposphere (below 850-hPa) over the southwestern US (west of the continental divide) arrives with the GCLLJ, while most of the moisture at higher levels arrives from over the Gulf of Mexico. Difficulties in explaining the observed precipitation distribution and its timing reflect, in part, the fact that Baja California and the Gulf of California have not been properly resolved in the past. Recently there has been considerable progress in diagnosing and modeling the regional circulations that contribute moisture to the core region of the North American monsoon, including the diurnal cycle, which must be properly represented to capture the interactions between the circulation and precipitation (see Appendix C, section C.1).

6.2.4 Links to Applications, Assessment, and Human Dimensions Research

There is an active community of researchers who are undertaking studies on the applications of climate and weather information in the American Southwest, on the sensitivity and vulnerability of people in the region to climate variability, and on the usability of climate forecasts in the region. An assessment of the impacts, information needs, and issues for policymaking has been made for the U.S. However, the North American Monsoon crosses national boundaries, so effort to understand the impacts of the monsoon on society must extend beyond the U.S. Southwest.

The research community needs to link to the applications community and interact to improve the potential of GAPP research to address societal needs. This interaction can contribute to improvements in the flow of climate information from producers to users, and produce experimental products and information specific to identified needs of users in the region.

These research and applications efforts have identified a number of specific sectors and user groups for whom information is important on summer precipitation and temperature, and the monsoon in particular. These include reservoir managers, fire managers, dryland farmers, ranchers, small agricultural producers, and urban water users. Water scarcity related to climate variability is also important, especially to the rural poor of the region. Surveys conducted with stakeholders in the region provide valuable information about the needs of certain users for information, and including specific lead times, and variations in information needs across the year.

Several institutions in the American Southwest have a focus on regional studies related to North American Monsoon variability, and are involved in routine or pilot activities to disseminate information to users and evaluate its influence and usability; these institutions include CLIMAS, the Desert Research Institute, the Western Regional Climate Center, and the NOAA Climate Diagnostics Center. In the multinational context, the IAI has emphasized collaborative research in Mexico and Central America focusing on the impacts of monsoon variability on disaster risks in the region. These projects, as well as others of the IAI and the International Research Institute for Climate Prediction, could provide opportunities for international collaboration on applications of monsoon information.

6.3 Objectives

The goal of GAPP studies of the NAMS is to determine the sources and degree of predictability of warm season precipitation and surface air temperature over North America, with emphasis on the role of land surface boundary forcing on time scales ranging up to seasonal and interannual. The studies will address three major objectives:

1) Describe, explain and model the summer climate regime and its associated hydrologic cycle in the context of the evolving land surface-atmosphere-ocean annual cycle.
2) Describe, explain and model warm season precipitation and temperature variability with emphasis on intraseasonal-to-interannual time scales.
3) Describe, explain and model the spatial variability of summertime precipitation on the mesoscale to the continental scale.

Collectively, the major objectives will contribute to the overall objective of GAPP studies of the North American monsoon, which is improved simulation and monthly-to-seasonal prediction of the monsoon and regional water resources.

While the role of the land surface component of boundary forcing is emphasized in GAPP, assessment of the relative roles of land surface and ocean surface forcing (both local and remote) is necessarily a major issue. Thus, much of the work on monsoonal circulations will be advanced through collaboration with the CLIVAR/VAMOS program and the CLIVAR/PACS-GEWEX/GAPP North American Warm Season Precipitation Initiative. During the later stages of GAPP, the efforts of the monsoonal circulation and land memory research will contribute to a GAPP seasonal prediction effort involving high- resolution global models. The North American Monsoon Experiment (NAME) will be a key component of the Monsoon System Initiative (MSI) under the Coordinated Enhanced Observing Period (CEOP), where the focus is the intercomparison and interconnectivity of monsoon systems around the world.

6.4 Scientific Approach

The objectives discussed in Section 6.3 will be addressed by a symbiotic mix of diagnostic, modeling and prediction studies whose integrated thrust can be broadly characterized as "the role of the land surface in warm season precipitation predictability over North America." Diagnostic studies will provide an improved description and understanding of the nature and variability of the NAMS, especially in the vicinity of the GAPP large-scale study areas. This includes the identification of spatially and temporally coherent relationships that have implications for prediction and need to be further explained through subsequent model experiments. Other GAPP related investigations of the land surface will provide initial and boundary conditions and validation for model experiments and guidance as well as hypotheses for the design of these experiments. Conversely, the model experiments will provide a deeper understanding of dynamic and thermodynamic processes and thus allow a broader interpretation of the empirical results. Highly focused field activities of limited temporal / spatial extent will be undertaken in concert with other components of GAPP.

6.4.1 Diagnostic Studies

GAPP diagnostic studies will focus on the description and understanding of the evolutionary aspects of the NAMS, especially as it relates to the land surface. Feedbacks between the land and atmosphere arising from terrain, soil moisture conditions, vegetation, snow cover and groundwater, and their effects on future states of the atmosphere will be emphasized. These studies will constitute a multi-scale approach in both space and time. The temporal resolution will vary, but will usually not exceed one month. In some cases the studies will be "event oriented", i.e. studies "indexed" to the life cycles of specific hydrologic anomaly events. As a consequence, the spatial domain of these studies will necessarily range from regional to planetary. Some studies will require a full latitude perspective over the North American sector, from the ITCZ to at least the middle latitude storm track. These studies will be carried out in tandem with land surface model experiments and land data assimilation experiments, and will benefit from multi-year regional reanalyses and retrospective soil moisture analyses carried out under other components of GAPP.

Three principal scientific questions will be addressed

1) How is the evolution of the warm season (May-October) atmospheric circulation and precipitation regimes over North America related to the seasonal evolution of the land surface boundary conditions? These studies will require an improved characterization or "indexing" of the seasonal evolution of soil moisture and vegetative cover over the entire North American continent, and a higher

resolution climatology over the GAPP large-scale study areas. These studies presume that the general nature of the warm season evolution of the atmospheric circulation and precipitation regimes over North America is reasonably well known from previous studies. However, previous diagnostic studies must be interpreted with care to ensure that decadal and longer variability is properly accounted for.

2) What are the interrelationships between year-to-year variations in warm season continental and oceanic boundary conditions, the atmospheric circulation and the continental hydrologic regime? These are essentially empirical predictability studies that will initially focus on the search for and the better understanding of empirical spatial/temporal linkages between precipitation anomalies, circulation parameters and the boundary forcing parameters. Included is the determination of the role of tropical and extratropical transients in seasonal variability. In addition to simple correlation studies, it will be important to develop methods for characterizing and categorizing extended hydrologic anomaly episodes in terms of their magnitude and space/time evolution, and indexing such episodes to the variability and seasonal evolution of the NAMS and land surface forcing fields. These studies will be structured to identify and quantify feedbacks between land surface boundary forcing and the atmospheric circulation for subsequent modeling and predictability studies.

3) What are the significant features of and interrelationships between the anomaly-sustaining atmospheric circulation and the continental and oceanic boundary conditions that characterize large-scale long lasting continental precipitation and temperature anomaly regimes during the warm season? These studies will be in the nature of case studies of major 20th century hydrologic anomaly regimes over North America, with particular emphasis on the most recent events for which the best data and analyses are available (i.e. the 1988 late spring-early summer drought and subsequent "heat wave", the late 1993 summer flood regime over the upper Midwest, and subsequent large-scale summer anomaly regimes that might develop during the lifetime of GAPP). The emphasis will be on the seasonal-to-interannual time scale, but data limited studies of the more pronounced multi-year anomaly regimes of the past (e.g. the Midwestern drought regime of the 1950s) could be undertaken to better describe and understand the multi-year regimes on which the large-amplitude interannual variations are superimposed. These studies will necessarily rely on data sets produced by other components of the GAPP project, such as the regional reanalysis and retrospective soil moisture analysis.

GAPP is also concerned with dynamical linkages between the NAMS domain and the larger-scale climate system across North America and nearby oceans on seasonal-to-interannual time scales. A central issue encompassing each of the above questions is the relative roles of remote boundary forcing (e.g. Pacific SSTs), local and regional sea and land surface forcing (e.g. soil moisture, vegetation, orography) and internal atmospheric dynamics in the seasonal-to-interannual variability of warm season precipitation over North America.

6.4.2 Modeling

As part of its overall mission, GAPP will pursue the development of improved land surface and hydrologic models as well as improved land-atmosphere coupled models. Modeling studies of the NAMS will build on the model development activities of the other components of GAPP. NAMS-focused diagnostic and predictability studies will emphasize the regional-scale continental perspective of GAPP. Specific recommendations for modeling studies of the North American monsoon will be made in the GAPP Implementation Plan.

Apart from their use in operational prediction, models are essential tools for testing hypotheses of predictability and establishing the sensitivity of predictions to surface boundary conditions. In regions where surface forcing of the atmosphere varies on spatial scales of less than a few hundred kilometers, the current resolution of global models (GCMs) is inadequate to resolve the detailed variability required for application to water resource problems on the catchment scale. On the other hand, higher resolution regional mesoscale models (RMMs) cannot reflect the full planetary forcing, but can more accurately represent the effects of regional gradients associated with features such as coastlines, orography, land use, soil and vegetation type.

With the steady increase in computational power, it seems reasonable to expect the resolution of GCMs to ultimately reach that of current operational RMMs. Until then, both GCMs and RMMs will be needed for process studies of the land surface, ocean and atmosphere. At present, the embedding of RMMs into GCMs provides a method for handling the macroscale-mesoscale mismatch over a limited area of the earth. To date embedded simulations have generally been limited to a one-way procedure (i.e. the RMM is driven by the GCM but there is no feedback to the GCM). Two-way embedding procedures are necessary to allow feedback of the mesoscale variability onto the planetary scale circulation. One approach to this is the so-called “stretched grid” being developed and tested within global models at NASA’s Goddard Laboratory for Atmospheres.

As GAPP began, many state-of-the-art dynamical models had not demonstrated the capability to simulate warm season precipitation in the NAMS domain with sufficient fidelity to support model sensitivity studies. Therefore assessment of model control runs is called for, to identify particular processes, time scales or regional precipitation characteristics that need intensive study or better verification data. These assessment studies could form the basis for GAPP-supported focused model development activities in concert with other model development programs such as the US CLIVAR CPT effort.

Predictability studies will be designed to identify the major physical components of the North American warm season precipitation regime that determine the quality of a prediction. This includes (1) the role of land surface processes in seasonal variability, (2) the relative roles of land and ocean surface processes in seasonal variability, and (3) geographical, regime and variable field dependence of predictability. Since there is a large array of possible sensitivity experiments involving GCMs and RMMs in which different boundary and initial conditions are prescribed, these experiments must be carefully designed and selective in nature.

The multiple-scales challenge inherent in the modeling component of GAPP should extend beyond forcing to consider the various spatial scales associated with precipitation itself. To meet this challenge, GAPP aims to compare the predictive skill of, and understand the differences between:

1) coarse-resolution precipitation fields generated by GCM's versus those generated by spatially averaging RMMs
2) high-resolution fields generated at the native resolution of RMM's versus those produced by statistically downscaling GCM output (e.g. using a PRISM-style approach).

Keeping in mind GAPP's goal of providing socially and economically useful information for water resources management, research on NAMS precipitation prediction will be integrated with local and regional hydrology research.

A comprehensive program of model simulations will be undertaken to demonstrate the level of skill in forecasting warm season precipitation anomalies. These studies will focus on hindcast simulations of carefully selected baseline hydrology anomaly regimes in which various modeling groups can participate. The participants will develop the detailed strategy for each experiment. While initial experiments may use the NCEP/NCAR or ECMWF Reanalyses as the "observed data", multi-year assimilated data sets will become an integral part of the overall experiment design. Therefore, it will be necessary to assemble the best possible suite of data sets for the baseline periods to serve as the standard set of observations for these experiments.

The NCEP Regional Reanalysis project is producting an integrated data product that will be important for assessing the role of large-scale processes, such as the effects of ocean forcing on the prediction of moisture bearing storm systems that affect the interior of North America. The Regional Reanalysis products will be available for use by the GAPP investigators beginning in 2003. Another source of regional information will be the Land Data Assimilation System (LDAS) currently under development by GAPP.

6.4.3 Field Programs

GAPP is currently planning warm season precipitation process field activities in two focus areas:

1) the southwest US (NAME and Land Memory with an emphasis on NAME)
2) the western Mississippi Basin (NAME and Land Memory with an emphasis on Land Memory).

The GAPP Implementation plan discusses those components of the NAME implementation plan that are included in GAPP. NAME is fully integrated into both the GAPP program and the US CLIVAR program. NAME implementation is organized around a multi-scale tiered structure, in which each tier has a specific research focus aimed at improving warm season precipitation prediction. The latest version of the NAME Science and Implementation Plan is found at the URL:

http://www.joss.ucar.edu/name

The NAME enhanced observations will be an important component of CEOP. CEOP will produce multi-disciplinary data sets aimed at detailed water and energy budget studies near reference sites of the GEWEX Continental Scale Experiments (CSEs) tentatively for the period 2001-2003, with a plan to continue the CSE enhanced data sets beyond 2003. An integrated NAME and CSE data set will be extremely important in enabling studies of water and energy cycles associated with warm season precipitation processes over major regions of the continental US. Under the CEOP plans for satellite data integration, satellite data (Level II or above) pertaining to the global hydrologic cycle (e.g. rain, water vapor, clouds, land surface characteristics) from TERRA, AQUA, TRMM, ENVISAT, and ADEOS-II will be exploited and processed into common gridded format for easy access and usage. The integrated data sets will be important in defining the global context of NAME. In addition, the NAME enhanced observations will provide valuable calibration and validation data sets for the satellite data. NAME will also benefit from data exchange and coordination with NASA's Global Energy and Water Cycle (GWEC) Initiative, Land Surface Program and the Global Modeling and Diagnostic Program.

6.4.4 Data Set Development and Data Management

The multi-scale diagnostic and modeling studies of the NAMS will require a variety of basic data sets and data products, which we visualize will be distributed primarily from the established data distribution centers and the data management activities of GAPP. NAMS diagnostic studies will rely heavily on operational analyses and satellite data products, and on global 4DDA operational products, notably the output from the NCEP/NCAR Reanalysis, the ECMWF Reanalysis, the new NASA/DAO Reanalysis, the NCEP Regional Reanalysis, the Eta Model Data Assimilation System (EDAS) and the Land Data Assimilation System (LDAS). However, as previously noted, it will be necessary to assemble comprehensive data sets to be used in the analysis and modeling of "baseline" anomaly regime periods.

Where augmentation is required, it will be accomplished by an expansion of the data management activities of GAPP. For example, selected GAPP observational data sets may be expanded to full continental coverage, or special research efforts may be undertaken (e.g. construction of high resolution satellite data products). Of particular significance in this regard is the use of satellite data to construct an improved, high-resolution description of land surface conditions and the development of high spatial and temporal resolution precipitation data sets over the continent and neighboring ocean regions.

7. COORDINATED ENHANCED OBSERVING PERIOD (CEOP)

7.1 Rationale

The atmospheric circulation and its associated climate patterns and variations result largely from spatial and temporal variations in the atmospheric and surface heat sources and sinks. Land plays a significant role in the development and evolution of these variations through many interactions involving the atmosphere, surface and sub-surface. Seasonally, large surface fluxes occur during the daytime and warm seasons. Interannually, a small amount of water is exchanged between the atmosphere and the land during periods of drought, but a great deal is exchanged during periods of wet conditions. Spatially, monsoons result from fundamental heating differences between land and ocean. Overall, such coupled land-atmosphere interactions impact the fluxes and reservoirs of water and energy in the global system, which in turn impact characteristics of the global circulation.

The complexity of water and energy flux exchange between the land surface and the atmosphere locally and remotely reflects the heterogeneous and time dependent processes that control land-ocean-atmosphere interactions. On a regional scale, there are large differences over land areas in the response to and impact on coupled water and energy processes. The highly variable role of land arises due to many factors including, for example, differences in large scale forcing, surface terrain and vegetation. The variability in local water resources is closely linked with the regional to global water and energy cycle as well as to local to regional processes. Once we establish more accurately the role of coupled land-atmosphere processes on the global water and energy cycle, we will have a better understanding of the causes of local variability on intraseasonal to time scales, and we will be able to better predict these variations for water resources.

Modeling this coupled system relies at present on many parameterizations and empirical relationships and the performance of models varies widely with large systematic and random errors being the norm. The development of fully integrated land-atmosphere models has therefore largely focused on regions having sufficient data to successfully develop parameters tied to landscape characteristics and other variables and empirical relationships for models. However, the development of skillful global models needs an approach that can be successful in data sparse regions as well as demonstrating skill across a spectrum of continental climatic zones and forecast time scales. Individual regional investigations in data-rich areas can help us to move towards our overall global goal of understanding the global circulation's impact on regional scales.

Carrying out a globally focused regional activity under the same climate state as part of a coordinated global activity is a logical next step in our strategy to realize our goal of understanding and modeling the global hydrologic cycle and its impact locally. In particular, the Coordinated Enhanced Observing Period (CEOP; IGPO 2001, also see Bosilovich and Lawford 2002, Roads et al. 2003), a program of the World Climate Research Programme (WCRP) initiated by WCRP's Global Energy and Water-cycle Experiment (GEWEX), is a highly coordinated international activity to understand and model the influence of continental hydroclimate processes on the predictability of global atmospheric circulation and changes in water resources, with a particular focus on the heat source and sink regions that drive and modify the climate system and anomalies. GAPP research can play a key role in this international activity as well as contribute to US Water Cycle activities (Hornberger et al. 2001).

GAPP along with other mid-latitude regions such as BALTEX (Baltic Sea Experiment, see Raschke et al. 2001) MAGS (Mackenzie GEWEX Study, see Stewart et al. 1998) and many areas of GAME (GEWEX Asian Monsoon Experiment, see Yasunari 2001), will choose natural research focal points that are mostly concerned with extra-tropical phenomena including summer features linked with heavy precipitation and the abilities of the region to recycle moisture. These specific scientific issues are linked to the fundamental CEOP question, "How do water and energy cycles over land operate and how do they affect predictability?" In particular:

1) How do land areas respond to the large-scale climate system?
2) How do atmosphere-land surface interactions operate and feed back onto the regional and larger scale climate system?
3) How do these interactions operate over diurnal to the annual cycles, and what are the most critical periods and time scales governing their feedbacks to the overall circulation?
4) Can the representation of land processes in models be substantially improved, especially in regards to climate, seasonal and weather prediction?

7.2 Background

The CEOP observation and data collection phase extends from 1 July 2001 to 31 December 2004 (**Fig. 7.1**).

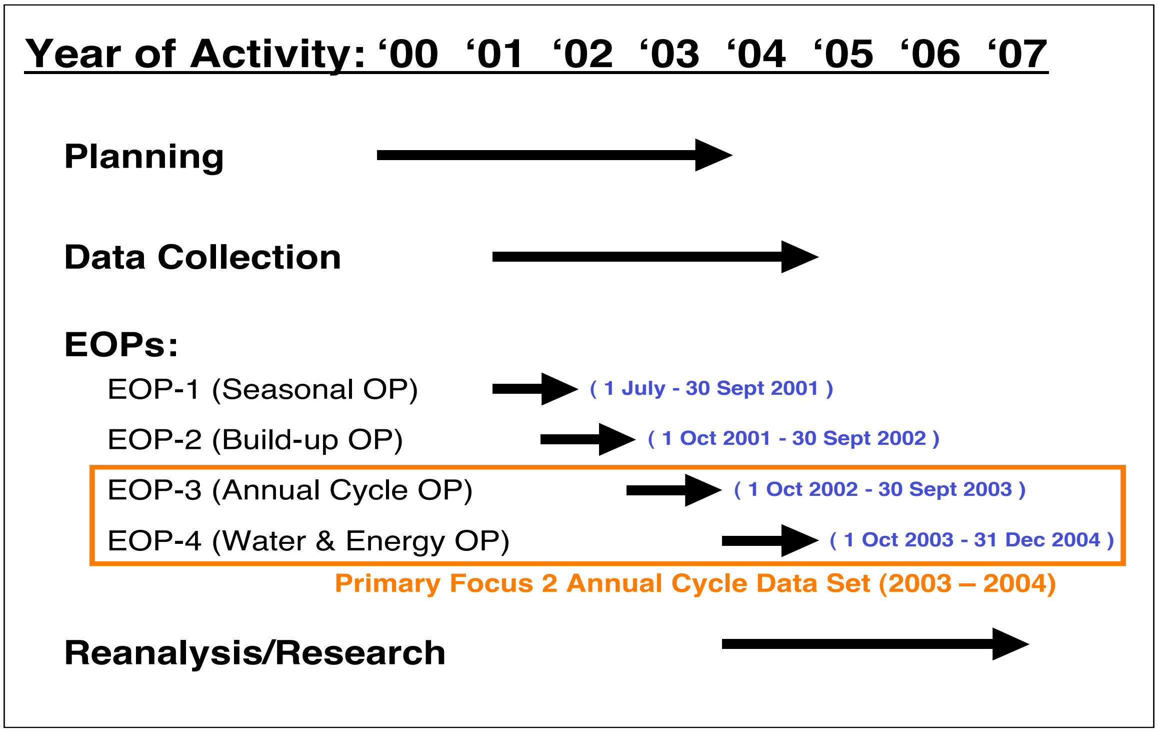

Fig.7.1CEOP Data Collection and Analysis Schedule

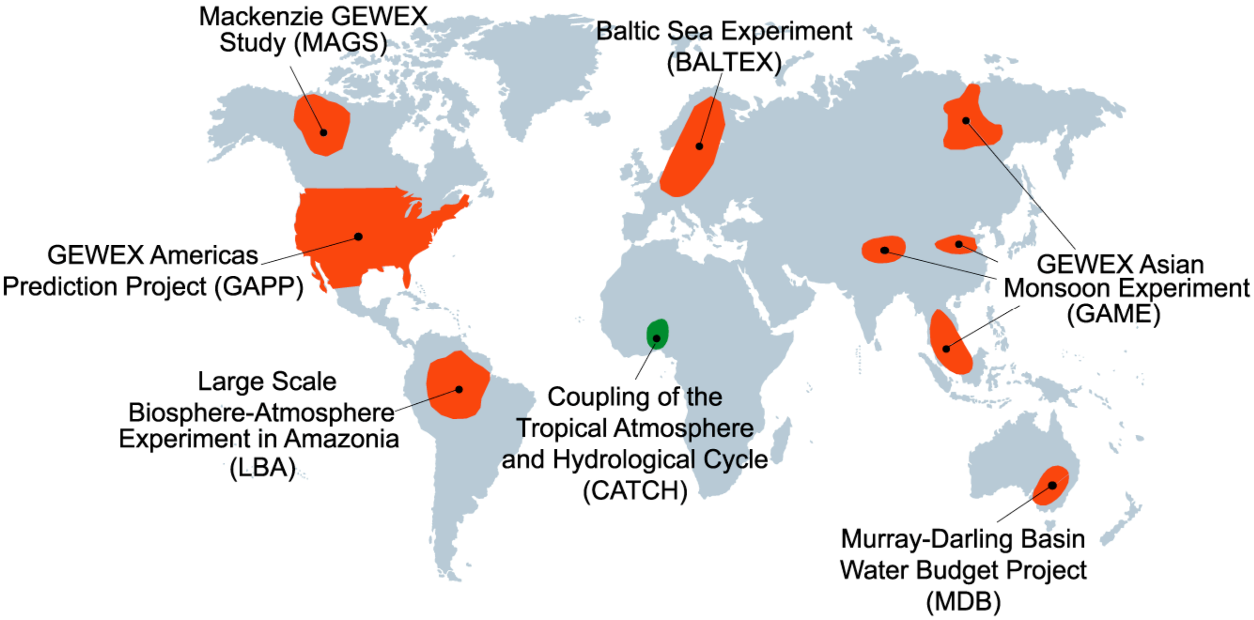

Fig. 7.2 GHP CSEs and AMMA. (La Plata region not shown).

During this time period remote sensing data, in situ measurements, and model output will be transmitted to and saved by several international CEOP archive sites. The implementation of CEOP has been divided into four Enhanced Observing Periods (EOPs). The four periods are designed to start at a relatively low level for EOP-1 as an enhanced seasonal observing period focusing on a selected set of reference sites 1 July to 30 September 2001. EOP-2 from 1 October 2001 to 30 September 2002 will entail a coordinated "Build-up Period" in which CEOP participants begin to make contributions as their capability for model output and satellite data is implemented. The primary focus will be on the collective 2-year data set beginning with EOP-3 (1 October 2002-30 September 2003), which will cover the first of two annual cycles with emphasis on a data set suitable for a synoptic climatology case study. EOP-4 will cover the second annual cycle and beyond (1 October 2003-31 December 2004) with provisions for some intensive water and energy-cycle experiments using coordinated Intensive Observing Periods (IOPs) as part of the major activities. It was decided to extend the second annual cycle observing period to the end of 2004 to allow for analyses within water year as well as prediction and forecasting (e.g. calendar) year frameworks.

The CEOP observation and data collection time period takes advantage of the maturing capabilities of the GEWEX Continental Scale Experiments. Besides GAPP, the mature experiments include: the Baltic Sea Experiment (BALTEX), the GEWEX Asian Monsoon Experiment (GAME), the Large-scale Biosphere Atmosphere Experiment in Amazonia (LBA, see Marengo and Nobre 2001), and the Mackenzie GEWEX Study (MAGS). These Continental Scale Experiment (CSE) areas are outlined in **Fig. 7.2** along with a newer CSE, the Murray Darling Basin (MDB), and two areas that are emerging collaborative experiments with WCRP's Climate Variability (CLIVAR)

Program. The African Monsoon Multidisciplinary Analysis (AMMA) initiative is a regional study being coordinated by France and Benin under the auspices of GEWEX and CLIVAR. The La Plata is recognized as a joint GEWEX/CLIVAR/VAMOS activity and is expected to seek CSE status as the project develops. Each of these CSEs will make major contributions to CEOP under the leadership of the GEWEX Hydrometeorology Panel (GHP; see Lawford et al. 2003). In particular, the CSEs will provide high-quality in situ measurements (many of these are tower sites) at several global locations (**Fig. 7.3**). The international in situ CEOP data is being archived at UCAR as part of GAPP.

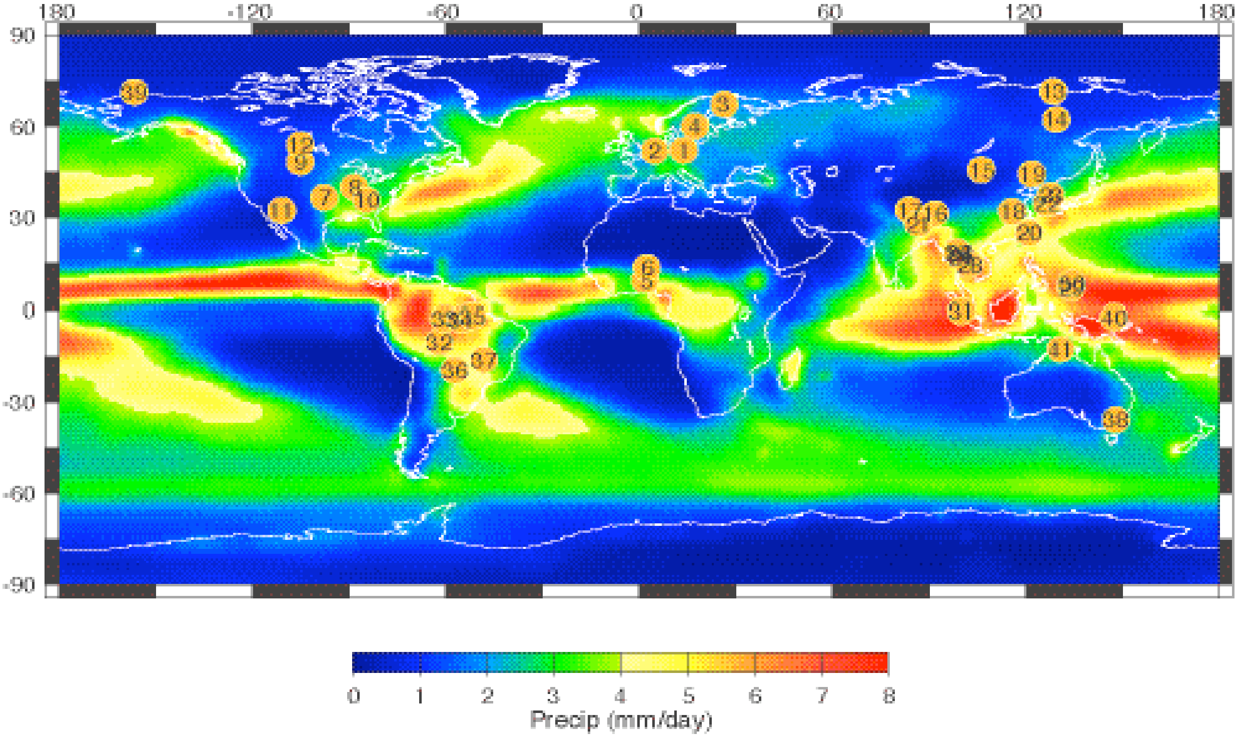

Fig. 7.3 CEOP in situ MOLTS (41) locations associated with the 35 international reference sites. As backround, the 1998-2000 annual mean precipitation is also shown.

The CEOP time period also takes advantage of new generation of remote sensing satellites (including TERRA, AQUA, ENVISAT, ADEOS-II) in addition to TRMM, Landsat-7, NOAA-K series and the other operational satellites, which will provide unprecedented enhancement of observing capabilities to quantify critical atmospheric, surface, hydrological and oceanographic data. Through the involvement of the Committee on Earth Observing Satellites (CEOS) and its members (particularly the Space Agencies), extensive archives of satellite remote sensing data and products will become widely accessible because of CEOP. In particular, 200 km snapshots of the highest resolution raw radiances (with geographic location, i.e. level I) remote sensing data at 41 in situ reference sites will be archived at the CEOP Satellite Data Integration/Archive center at the University of Tokyo, at Tokyo, Japan and the NASA GSFC, Global Land Data Assimilation Project (GLDAS). Geophysical products will be developed for these sites by international research teams as part of individual satellite science teams. The collocated radiance and in situ data over so many regions and climate regimes will provide a unique opportunity for calibration and validation of remote sensing algorithms. At the same time, there are a number of operational products being developed and archived in part because of GEWEX organizational efforts. These are crucial for providing a longer-term perspective as well as for exploiting information from both old and new remote sensing archives.

In conjunction with the in situ and remote sensing observations, international operational numerical weather prediction centers are also archiving both analysis/assimilation and short-term forecast/analysis model products from both global and regional NWP suites. Several model output variables (pertinent to atmospheric and surface water and energy processes) have been requested by CEOP and the two types of requested model output, globally gridded (GRIB) and site-specific model output location time series (MOLTS) at each of the CEOP International Reference Sites are being developed. The Max Planck Institute for Meteorology (MPIM) at Hamburg, Germany has undertaken to serve as the CEOP model output archive center. Corresponding regional model output is being archived locally within each of the CSEs. This will promote the improvement of surface parameterizations in forecast models and data assimilation systems to a level not possible by any one field experiment. GAPP contributions as a CSE are crucial because of the data density in the US, as well as the model development efforts (e.g. NLDAS).

International research activities designed to take advantage of this unprecedented international cooperation are also beginning. There are two major science working groups under CEOP: (1) Water and Energy Simulation and Prediction (WESP), and (2) Monsoon studies.

WESP studies are designed to understand what components of the global water and energy cycles can be measured, simulated, and predicted at regional and global scales? In particular: (1) what are the gaps in our measurements? (2) What are the deficiencies in our models? (3) What is our skill in predicting hydroclimatological water and energy budgets? As part of WESP, it is envisioned that GAPP will develop water and energy budget studies, land data assimilation studies, and transferability experiments, focused on GAPP regions.

Starting from the current efforts to close simplified vertically integrated water and energy budgets with observations and analyses, and beginning efforts to simulate these budgets regionally, WEBs studies will begin the effort to transfer this knowledge to global scales, include more water and energy cycle processes, and begin to examine the vertical structure in the atmosphere and land. WEBs requirements have helped to define the initial CEOP data needs. One WEBs goal is to identify model processes and state variables that can be compared to in situ and satellite measurements as well as each other and to then develop community intercomparison projects that can help to define and quantify measured and modeled hydrometeorological processes.

Traditional coupled land-atmosphere 4-D data assimilation systems (4DDA) often yield significant errors and drift in a) soil moisture and temperature and b) surface energy and water fluxes owing to substantial biases in the surface forcing fields from the parent atmospheric model, especially biases in precipitation and surface solar insolation. Hence, as an uncoupled land-surface alternative to coupled 4DDA, there are a number of regional as well as global Land Data Assimilation System (LDAS; see Houser et al. 2001) projects utilizing common forcings and multiple land surface models are beginning to generate increasingly accurate land surface states and processes. LDAS will take advantage of the in situ and remote sensing data to develop comprehensive continental-scale surface water and energy simulations. In turn, WEBs will utilize continental-scale LDAS estimates of the surface hydrometeorological properties.

Within the GEWEX Hydrometeorology Panel (GHP), there has been much discussion about the transferability of coupled atmosphere/soil regional models to different regions on the globe. CEOP has a special interest in those transferability experiments that will take advantage of the in situ and satellite data and global analyses being collected. Transferability will not only focus on regional model but also global model intercomparisons of hydrometeorological processes for global and CSE regions. Again, WEBs will utilize continental-scale atmospheric model estimates of processes by the regional and global atmospheric analysis/forecast systems.

Monsoon processes involve strong interactions of atmosphere, the land, the biosphere and the oceans, and constitute the basic building blocks of climate models. CEOP Monsoon studies are being developed to assess, validate and improve the particular capabilities of climate models in simulating physical processes in monsoon regions around the world. In particular, monsoon studies are targeted toward improving weather and climate predictions in the global tropics and extratropics. Model errors in these processes need to be identified, and then corrected to improve overall performance of climate models. To begin this study, CEOP Monsoon studies are developing the CEOP Inter-Monsoon Model Study (CIMS). CIMS is different from previous model inter-comparison studies in that it is aimed at model physics improvement, via simulations, and cross-validation of model outputs with detailed observations of the monsoon system. In this regard, the synergistic use of global data, in conjunction with high-resolution space and time observations from field sites is critical. For CIMS, validation data will be derived from CEOP reference sites, which include GEWEX continental scale experiments (CSE) and planned CLIVAR field campaign sites. Numerical experiments will be designed and targeted towards simulation of fundamental physical processes that will likely lead to identification of basic errors and bias in model physics. For this purpose, a hierarchy of models including general circulation models (GCM), regional climate models (RCMs) and cloud resolving models (CRMs) will be used. CIMS should be considered not only as a research project for CEOP but also a pilot research effort aimed at the broader WCRP goal of improving model physics parameterization for climate predictions and global change projections. As such, the collaboration of CIMS with ongoing model intercomparison projects and GEWEX and CLIVAR modeling initiatives are critically important for CEOP Monsoon Studies.

There are other developing international CEOP initiatives focused on surface hydrologic features and cold season processes. These studies are being developed in collaboration with the International Association of Hydrology Society (IAHS) and the

WCRP Climate and Cryosphere (CLIC) Project.

7.3 Objectives

The overall goal of CEOP is to understand and model the influence of continental hydroclimate processes on the predictability of global atmospheric circulation and changes in water resources, with a particular focus on the heat source and sink regions that drive and modify the climate system and anomalies. To achieve this goal CEOP has undertaken an internationally coordinated effort to develop in situ data, remote sensing data, and remote sensing data. CEOP has also developed an international research effort focused on Water and Energy Simulation and Prediction (WESP) and Monsoon Studies. The WESP objective is to better document and simulate water and energy fluxes and reservoirs over land on diurnal to annual temporal scales and to better predict these on temporal scales up to seasonal for water resources application. The Monsoon Studies objective is to document the seasonal march of the monsoon systems, assess their driving mechanisms, and investigate their possible physical connections. These international objectives are in line with GAPP CEOP objectives. In particular, GAPP will:

1) Provide in situ, remote sensing and global and regional land and coupled assimilation products for GAPP and CEOP global regions.
2) Demonstrate the utility of operational and next generation experimental satellites over land areas and in hydrometeorological research aimed at improving NWP and climate predictions
3) Evaluate the performance of regional coupled and uncoupled land-hydrology models across a spectrum of continental climatic zones and forecast time scales
4) Improve the representation of land surface processes in models, including snow and soil freezing processes.
5) Achieve a better understanding of continental to global scale land atmosphere hydrometeorological interactions.

In addition, GAPP will conduct coordinated regional experiments in the American monsoon regions by:

1) Improving the simulation of the North American monsoon and to a lesser extent the South American monsoon
2) Evaluating the model-simulated and predicted snow cover/soil moisture/monsoon relationships in terms of their ability to represent the observations.

GAPP remote sensing research activities contributing to CEOP are described in Sec. 10. GAPP North American Monsoon Experiment activities are described in Sec. 6. Coupled land atmosphere predictability studies are described in Sec. 4. Development and evaluation of seasonal prediction systems are described in Sec. 8. Orographic studies are described in Sec. 5. In short, there are numerous GAPP activities that will make a major contribution to CEOP. In addition, as part of CEOP, GAPP will undertake research activities directed at:

1) Assessing and comparing the regional performance of global and regional model water and energy budgets. Despite the important advances achieved in coupled modeling, deficiencies in water and energy budgets have been detected in diagnostic studies and through careful comparisons with observations. Timely

evaluations can contribute to closing regional water and energy budgets and improving the quality of CEOP data archives over the GAPP region.

2) Conducting model and diagnostic case studies at small and intermediate scales for a number of anomalous periods. This study will include analysis of the physical processes and extreme events using extensive data collected at the GAPP CEOP Reference Sites.

3) Comparing new satellite remote-sensing data products and other more conventional data to in situ and model output. To effectively participate in CEOP, GAPP will need access to new satellite products from say LANDSAT-7 detailed land cover, vegetation mapping and derived products, and the suite of surface and atmospheric observations provided by the Earth Observing System (EOS), ADEOS II and other orbiting platforms.

4) Developing a better understanding of cold season precipitation and hydrology processes including snow and frozen-ground physics in complex terrain. The central issue is to improve the coupled model precipitation forecast skill so that it gives an accurate prediction of the temporal and spatial distribution of snowfall, accumulation and ablation.

7.4 Approach

Again, GAPP will contribute to CEOP monsoon studies in collaboration with the PACS North American Monsoon Experiment (NAME; see Sec. 6), GAPP remote sensing algorithm development and application (Sec. 10), as well as model development in complex orographic regions (sec. 5), and coupled model predictability (sec. 4), leading to integrated seasonal prediction systems (sec. 8).

In addition, CEOP will increase the value of GAPP (and GEWEX) to the academic and operational communities in the US by providing opportunities for global and regional climate modelers to have access to detailed information on land surface conditions for not only the GAPP region but also other similar and diverse climate regions around the world. In particular, besides the above-mentioned activities, GAPP will foster US-Wide Water and Energy Budget Studies (WEBS), Land Data Assimilation System (LDAS) studies, and transferability research. Further details about these particular studies are described below.

7.4.1 WEBS

Roads et al. (2003) previously described water and energy budgets for the Mississippi River Basin as part of the GEWEX Continental International Project (GCIP). Given the regional extension of GAPP to the entire US, it is reasonable to ask what the corresponding water and energy budgets are for the entire US from the “best available” observations and models. CEOP will provide new in situ and remote sensing measurements that can be utilized to better define US water and energy processes and reservoirs. CEOP will provide a number of global analyses/forecasts and it will be useful to also use these model-based estimates to understand better the uncertainty in the GAPP water and energy cycles. Besides the global CEOP data set, GAPP WEBS will take advantage of the pending regional reanalysis (Mesinger et al. 2003), which may provide a needed atmospheric and surface benchmark for water and energy budget processes and reservoirs.

It is important to not only develop these water and energy budget studies for the CEOP time frame but to also extend these studies to previous time periods in order to better understand their interannual variations. Previous comparisons have shown wide discrepancies in descriptions of the interannual variability, suggesting that despite the great progress in describing gross seasonal means, we still do not have a handle on describing, much less predicting, interannual variations. In fact, some of the discrepancies can be traced to how individual models and even observations depict diurnal variations in water and energy processes. In short, characterizing and understanding regional water and energy budgets is still largely unknown not only for GAPP but also for other global regions (e.g. Masuda et al. 2001, Marengo 2003, Jacob et al. 2001, Rouse et al. 2003).

7.4.2 LDAS

As was previously mentioned, traditional coupled land-atmosphere 4-D data assimilation systems (4DDA) often yield significant errors and drift in a) soil moisture and temperature and b) surface energy and water fluxes. Therefore, NCEP/EMC, NCEP/CPC, NASA/GSFC, NWS/OHD, NESDIS/ORA, Princeton University, University of Washington, Rutgers University, University of Maryland, and University of Oklahoma) have undertaken for GAPP the development and demonstration of a National (N-LDAS) -- a real-time, hourly, distributed, uncoupled, land-surface simulation and assimilation system executing on a horizontal grid spanning the U.S. CONUS domain at 0.125 degree resolution (Mitchell et al. 2003). Additional land surface models and collaborators are being encouraged to participate as part of GAPP. The N-LDAS project thus represents a major component of the GAPP continental-scale experiment contribution to CEOP.

Four central scientific questions are being addressed by N-LDAS: (1) What is the relative impact of land-surface boundary conditions versus sea-surface boundary conditions on seasonal-to-annual predictability of the continental water cycle in coupled regional land/atmosphere climate models? Is the land-surface impact increased by utilizing initial land states from an uncoupled versus coupled LDAS (such as the NCEP Regional Reanalysis)? Is the land-surface impact increased by employing the same LSM in both the coupled climate prediction model and the LDAS that generates the initial conditions for the climate model? (2) How can calibration methods for LSMs be extended or relaxed from local point-wise or small-catchment measurements to widespread satellite measurements over large spatial domains? (3) Does the assimilation of satellite data improve the simulated states and fluxes of an LDAS? What satellite data types and assimilation methods are most effective and operationally feasible? (4) Can distributed LSMs running at grid resolutions feasible over a national domain simulate streamflow with accuracies on par with catchment-specific, calibrated lumped models?

To summarize, the N-LDAS project will contribute to CEOP by providing both validation fields and the initial conditions for the land states for regional climate model predictions. N-LDAS evaluates the utility of the new generation of experimental satellites in land area and hydrological research to improve NWP and climate predictions and prepares land data assimilation products. The real-time execution of the N-LDAS began before the start of CEOP and will continue at least through the CEOP period (2004) and beyond.

7.4.3 Transferability

GAPP and the broader GHP coupled modeling activities to date have demonstrated considerable success in simulating and predicting water and energy cycles, and the results have been subsequently implemented in the Numerical Weather Prediction (NWP) models run operationally at the NWP Centers. These modeling results have been developed and evaluated largely from the data obtained within the CSE region. The extension of these regional models to other geographic and climate regions is an important prerequisite to transferring the land/hydrology components to global NWP and climate models. A critical aspect of hydrometeorological modeling success is to develop quantitative relationships between small and large scales. Adapting scientific results achieved at one scale to applications on another scale is also a critical aspect of hydrometeorological modeling. Participation by the operational centers in providing regional model output has led to a mutually beneficial relationship. The principal benefit to GAPP is the ability to document the inter-model variability of outputs from the different regional models that can also be related to the global model output from the operational centers. GAPP is thus providing benefit to the operational centers by enabling them to make use of the enhanced data sets and research results to calibrate and validate the model data assimilation and forecast systems.

Research priorities for transferability studies are:

- Evaluate and improve the representations of the effects of seasonally varying land-use, soil moisture, vegetation cover, and other soil characteristics forcing and their spatial heterogeneity in regional coupled models.
- Determine and model the multiscale responses of complex terrain on the regional hydroclimates at seasonal and diurnal time scales.
- Examine the model's surface energy budgets to evaluate the performance of the parameterizations in physical terms.
- Characterize and model the temporal and spatial distribution of different land surface conditions, such as snow cover including its accumulation/melt and the impact of frozen ground, on atmosphere/hydrology interactions.

GAPP will pay special attention to the Americas as part of its CEOP contributions. To date, results from the GCIP, LBA and MAGS modeling activities have demonstrated significant improvements that have been implemented in the NWP models run operationally at the NWP Centers. The extension of these regional models to other geographic regions on the North and South American continents will provide some excellent opportunities to conduct model transferability studies. Some specific cooperative activities are planned during the CEOP period within the context of Americas' Model Transferability Experiments (AMTEX). The overall objective of AMTEX is to complete, to the extent possible, an evaluation of the performance of coupled land/atmospheric models over the different geographic and climatic regimes of the Americas' continental regions.

7.4.3.1 PIRCS

The Project to Intercompare Regional Climate Simulations (PIRCS) is a community-based project hosted by Iowa State University whose mission is "to provide a common framework for evaluating strengths and weaknesses of regional climate models and their component procedures through systematic comparative simulations." Validation data are provided by the PIRCS program office so that individual modeling groups have opportunity to compare their simulations against observed data for discovery of model deficiencies. Participation in the intercomparison exposes deficiencies and successes common to all models or sub-classes of models (e.g., spectral models, models originating from the Penn State/NCAR MMx lineage), thereby offering priorities for model-improvement efforts.

PIRCS began in 1994 with a meeting of a small group of active regional climate modeling teams who collectively defined two initial intercomparison projects to address goals outlined in the mission statement. Simulation regions and periods chosen for these two experiments were designed to test, in succession, the energy budget component and water cycle components of participating models. Initial and lateral boundary conditions were supplied from reanalysis datasets. Participants submit datasets consisting of specific variables at designated time intervals to the PIRCS archive at Iowa State University. These data are made available to the scientific community for analysis and interpretation.

The initial intercomparison, PIRCS Experiment 1a, focused on the continental US, with emphasis on the GCIP region of the US Midwest, for a 60-day period in the summer of 1988 (Takle et al. 1999). Drought conditions during this period allowed analysis of surface energy processes under conditions of a weak hydrological cycle. PIRCS Experiment 1b used the same domain for the 60-day period of summer 1993, a period of record-breaking floods in this region (Anderson et al. 2003). The simulation periods were constrained by computational power available at the time. Although these periods are quite limited in comparison to current climate modeling capabilities, they proved to be long enough to draw significant conclusions and yet within the capacity of participating modeling groups to complete without outside support. Eight groups submitted results for analysis in PIRCS 1a, and 16 groups participated in PIRCS 1b. Results have been reported in numerous conference proceedings and a few journal papers.

PIRCS Experiment 1c has been opened as of October 2002, and modeling groups are encouraged to participate. This experiment, also guided by the mission statement, is centered on the continental US with domain enlarged from PIRCS 1a and 1b to encompass critical elements of the hydrological cycle originating to the south and west of the US borders. The simulation period starts at the beginning of 1986 and extends to the present, with boundary conditions supplied beginning in fall 1985 to enable spin up before the data-reporting period. Models will employ a common resolution except during enhanced periods (including but not limited to summer of 1988 and summer of 1993) when higher spatial resolution for at least a limited evaluation region will be employed. NCAR/NCEP Reanalysis II datasets will provide initial and lateral boundary conditions.

Science issues for PIRCS 1c include the following:

1) North American Monsoon System (NAMS): initiation and development, role of ocean boundary-layer humidity and coastal terrain under onshore convective flow, mesoscale linkage to the central US.
2) Hydrological processes: role of soil moisture on seasonal and interannual scales, processes regulating diurnal precipitation patterns, mesoscale convective systems, snowfall and snowmelt in relation to elevation and resolution, sensitivity of convective parameterization to terrain, seasonal trends in temperature and precipitation for hydrological applications, extreme precipitation events.
3) Model development: relationship of model resolution to precipitation intensity and spatial patterns, physical parameterizations (land process and convective schemes, the largest source of model differences) and their relation to model skill, optimal construction of ensembles and their added value.

PIRCS experiments contribute to transferability studies by allowing side-by-side comparison of "local" models against models from Europe (currently 5), Canada, and Australia. PIRCS 1a and 1b exposed previously undetected features of models transplanted from their home domains for the first time. PIRCS 1c will overlap with the at least part of the CEOP observation and data collection phase 1 July 2001 to 31 December 2004

7.4.3.2 La Plata

The La Plata Basin is second in size only to the Amazon basin in South America, and plays a critical role in the economies of the region. It is a primary factor in energy production, water resources, transportation, agriculture and livestock. For comparison, the annual mean river discharge of the La Plata River is about 25% larger than that of the Mississippi River, and has a distinctly different annual cycle (Berbery and Collini, 1999). The amplitude of the annual cycle of La Plata River discharge is small: it is slightly larger during late summer, but continues with large volumes even during winter. However, further analysis of the main rivers contributing to La Plata reveals that each contributing river basin has a well defined annual cycle, but with different phases that can be traced primarily to different precipitation regimes. The more important ones are: (a) a summer monsoon regime affecting the northern area, (b) precipitation originated in Mesoscale Convective Complexes (MCCs) toward the central area of the basin, and (c) winter synoptic activity, producing mostly liquid precipitation. The Low-level Jet east of the Andes that supplies moisture from tropical South America to La Plata Basin is present throughout the year (Berbery and Collini, 1999). This is an uncommon feature not observed in other regions like the Great Plains of the United States, where the Low-level Jet develops only during the warm season. Thus, the La Plata Basin has a steady supply of moisture and heat from warmer regions at all times of the year, favoring precipitation during both the warm and cold seasons.

The goal of this transferability experiment is to evaluate the annual cycle of the hydrologic cycle components in various regional models, and when relevant, compare them to those of other basins. Regional models will be evaluated systematically using a special data set of daily-observed precipitation. The low-level jet east of the Andes is strongest over Bolivia, a region where data are sparse. This might pose a problem in assessing how realistic the circulation is at low levels, but the field program to be conducted with PACS support by M. Douglas (NSSL) should be critical for further evaluation of the models. A network of pilot balloons has been deployed and measurements, already under way, will expand during CEOP. CEOP could play a critical role by ensuring that this data are distributed to the community in a timely manner. The transferability experiment will include evaluations of regional models': (a) performance in terms of precipitation and winds in the La Plata basin, (b) potential to reproduce the low-level jet east of the Andes, and, lastly, (c) functioning over complex mountainous terrain. Initial results with the Eta model have been encouraging for all seasons, even in subtropical regions.

8. TOWARD AN INTEGRATED SEASONAL AND LONGER TERM CLIMATE PREDICTION SYSTEM

8.1. Rationale

Section 1 emphasized that GAPP's ultimate mission is to develop a capability to predict variations in water resources of soil moisture, snowpack, and streamflow on time scales up to seasonal and interannual as an integral part of a climate prediction system. This involves modeling both 1) the response of these land-surface states to predicted anomalies of atmospheric precipitation, temperature, wind, humidity, clouds and radiation and 2) the feed-back or reverse response, both locally and remotely, of these atmospheric states to the anomalies of the land states, especially in the warm season when land-atmosphere coupling is strong. As part of this process GAPP will contirbute to the development of an improved land surface module for a longer-term climate prediction system.

It is now widely acknowledged that the intrinsic nature of internal atmospheric dynamics and thermodynamics is so intensely nonlinear (i.e. the chaotic atmospheric circulation) that there exists a limit of about two weeks on deterministic prediction of atmospheric weather (Lorenz, 1982). However, in the prediction range of 1-12 months, pathfinder efforts at extended-range dynamical model prediction over the last 15 years have shown that the combination of ensemble prediction methods, time and space averaging, and coupling of ocean-atmosphere-land models (Shukla, 1993) can yield extended-range predictability of time-mean regional anomalies of temperature and precipitation, especially in the N.H. cool season. This extended range cool-season predictability arises from the quasi-persistent, low frequency, atmospheric variability that is forced by the quasi-persistent lower boundary anomalies in sea-surface temperature (e.g., quasi-persistent for several months or more).

Achieving useful warm-season predictability with dynamical models has proved to be notably more elusive, but research in the last few years is beginning to show promise. As indicated in the preceeding chapters, GAPP will play a leading role in determining the predictability of warm season anomalies in precipitation and temperature. GAPP will focus land-state initialization, process studies and land-atmosphere coupling and feedbacks, to complement the ocean-atmosphere coupling focus of CLIVAR. As emphasized by Pielke et al. (1999), the feedback and nonlinear interaction between land and atmosphere may actually render the seasonal prediction problem as an initial value problem, rather than the more traditional earlier view of seasonal prediction as a boundary value problem at the earth surface. The traditional view fails if regional land-surface anomalies of significant amplitude and spatial extent emerge and fade over roughly the same time scales as the atmospheric anomalies in the seasonal prediction model. There is a growing body of research literature (e.g. references in Pielke et al., 1999) showing that the latter is the case. Hence both the initial specification of land states and the physical two-way coupling of land and atmosphere in the subsequent prediction model can exert strong controls on the modeled seasonal atmospheric circulation. Given this initial value problem, if the feedbacks between the atmosphere and land surfaces are sufficiently nonlinear, then there are necessarily shorter limits on the seasonal predictability of the coupled land-atmosphere system.

This chapter lays out a comprehensive modeling and data assimilation paradigm that can provide the means to investigate simultaneously 1) seasonal to interannual (SI) predictability, and the relative role of land anomalies and land/atmosphere coupling therein, 2) physical processes of the land/atmosphere coupled system, 3) viable means of initializing land, atmosphere, and ocean states over continental and global domains, 4) interannual variability of the coupled land/atmosphere system, 5) model transferability, 6) actual seasonal prediction, and 7) downscaling for water resource applications. These areas fairly well embrace all the components of Figure 3.1. The chapter also indicates how GAPP will contribute to longer term prediction.

The seasonal prediction/predictability infrastructure will be composed of free-running prediction models and 4-D data assimilation systems (4DDA) ingesting in-situ and satellite-observations into assimilating "background" models. The prediction and 4DDA backround models are frequently and ideally the same model. For both the models and data assimilation capabi.lity, this comprehensive infrastructure includes:

1) land, atmosphere, ocean,
2) global and regional,
3) coupled and uncoupled,
4) retrospective and realtime.

An integrated seasonal prediction system that can further advance both cool season and warm season prediction skill at the smaller regional scales needed for meaningful water resource management will require 1) coupled modeling of the entire earth system (land, ocean, atmosphere), 2) companion data assimilation systems for land, ocean, atmosphere, and 3) spatial downscaling via imbedded land-atmosphere regional climate models and distributed macroscale land/hydrology models.

8.2 Objective

One of the two objectives of GAPP is to develop and demonstrate a reliable monthly to seasonal prediction system for precipitation and land surface hydrologic variables and to provide and demonstrate the land modeling contribtuion to the skill of this seasonal prediction system. This is to be accomplished through improved initialization and physical modeling of land states, land and boundary layer processes and related hydrometeorological processes.

The pathfinder research already accomplished by the GEWEX program, and its sub-programs such as GCIP, ISLSCP, and GLASS (which now includes GSWP and PILPS) in the area of land modeling, land atmosphere coupling, land data assimilation, and regional climate modeling, together with the companion ocean modeling and ocean 4DDA initiatives and pathfinder successes arising from the TOGA and CLIVAR programs, have provided all the pilot components to construct and demonstrate an integrated, end-to-end, multi-scale, land-ocean-atmosphere seasonal prediction system. GAPP commits to develop, demonstrate, and deliver the land components (including land data assimilation) of the end-to-end system depicted in the schematic of Figure 8.1. This figure is an extension of the widely cited ‘Shukla Staircase’ presented by Shukla at the Joint PACS/GCIP Workshop in (September, 1997), and also employed in the U.S. Water Cycle Science Plan (Hornberger et al., 2001).

The key extension added to the ‘Shukla staircase’ in Figure 8.1 is the companion suite of land, atmosphere, and ocean data assimilation components to initialize each of the forecast model components. The Figure begins in the upper left and the chain of downscaling models proceeds counterclockwise. Circles represent data assimilation systems. The layers of boxes represent a set of ensemble predictions. The diamonds represent ensembles of model output fields. The ensemble forecast members may be from the same model (via perturbed initial conditions or model physics) or from multiple models. The first model is a coupled global ocean/atmosphere/land climate model. The second model is a higher resolution coupled global atmosphere/land climate model, with no coupled ocean component and time-dependent SST anomalies provided by the first model. The third model is a high resolution imbedded regional coupled atmosphere/land model, using the same SST anomalies. The fourth and last model is a very high resolution uncoupled land-only macroscale hydrology model (MHM), such as those discussed in Section 9.

Within the paradigm of Figure 8.1, GAPP will support studies to demonstrate the following for each of the four modeling scales:

1) the relative value to seasonal predictability and prediction of improvements to the physical modeling and initialization of land processes and land-atmosphere coupling,
2) the relative value to seasonal predictability and prediction of the respective increase in model resolutions, and
3) the relative value to water resource applications of each successive downscaling.

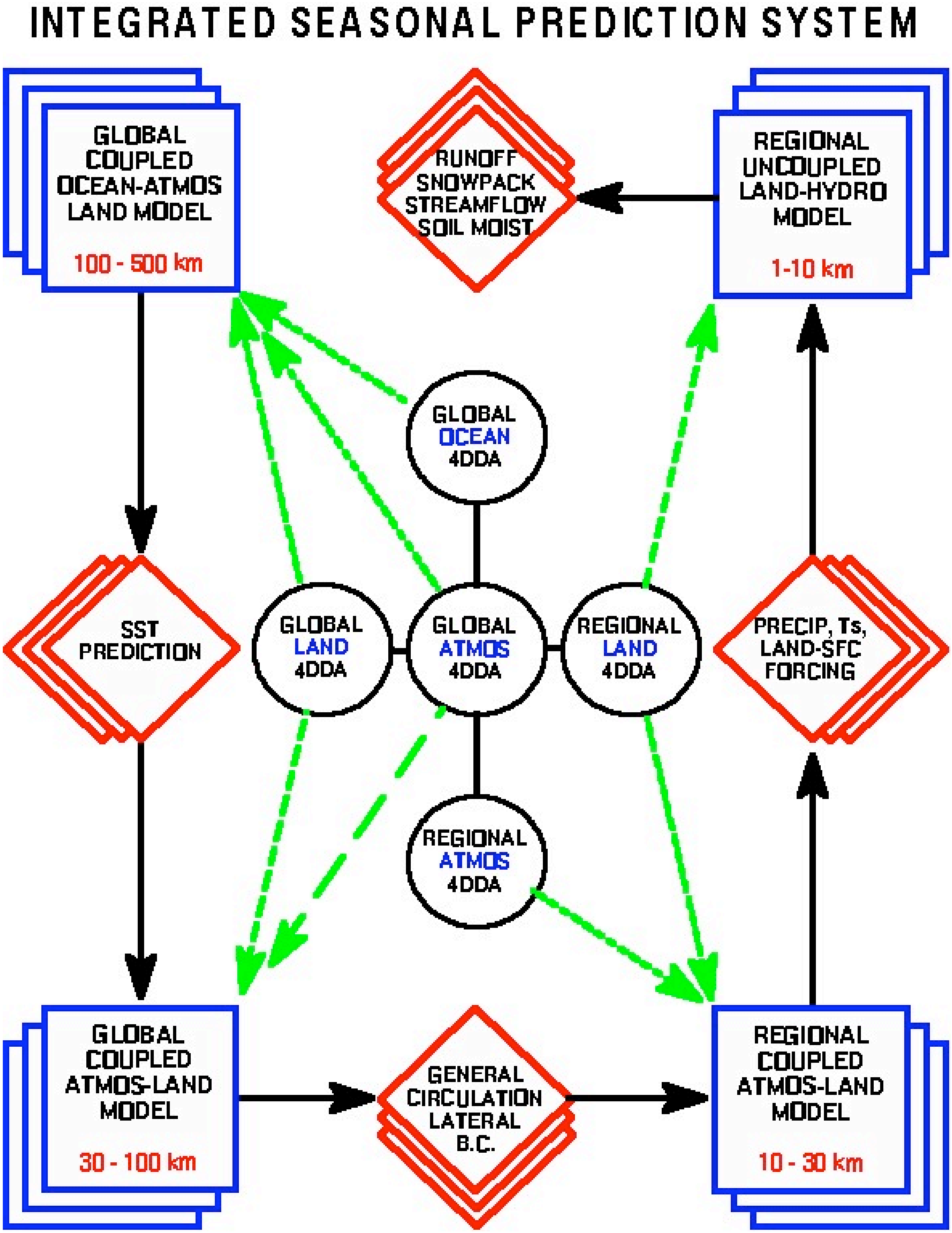

Figure 8.1. Integrated Multi-Scale Seasonal and Interannual Prediction System

8.3 Approach

8.3.1 Land Surface Modeling

With the exception of the ocean data assimilation component in Figure 8.1, every other modeling component of the figure includes a land-surface component. One goal of GAPP is to promote and demonstrate the use of a single, unified land surface model (LSM) in all components of Figure 8.1, hence a land-surface model that is transferable to any climate regime globally and is able to perform robustly at multiple scales in models ranging from 500 km to 5 km resolution. This may be accomplished by such approaches as the tiling method to represent sub-grid variability thereby allowing several different LSMs to demonstrate their multi-scale utility. As part of this process GAPP will contribute to the development of improved land surface modules

GAPP will carry forward the legacy of GCIP, PILPS, and GSWP and continue to sponsor the intercomparison of leading land surface models, with a focus on spearheading initiatives that yield increased convergence in the behavior of leading LSMs under conditions of identical surface forcing and land-surface characteristics. As Figure 8.1 shows, these land surface models must be tested and applied in three modes as follows:

1) as uncoupled quasi-distributed macroscale hydrology models,
2) as the land component in global and regional climate and NWP models, and
3) as the land component in global and regional land data assimilation systems.

8.3.2 Land Data Assimilation Systems

GAPP will lead the development and demonstration of both global and regional land data assimilation systems (LDAS), both coupled and uncoupled. An LDAS is the crucial component that will provide the initial conditions of soil moisture, soil temperature, and snowpack for the integrated seasonal prediction system. The heart of each LDAS will be the land surface model (LSM) that generates the physical background states into which land-surface observations and forcing will be assimilated.

A key thrust of some LDAS initiatives will be to demonstrate whether the imminent state-of-the-art in the assimilation of gage-, radar-, and satellite-derived precipitation estimates in coupled data assimilation systems is sufficient to overcome the typically severe precipitation biases that characterize such present-day coupled 4DDA systems. Until such a coupled assimilation system with realistic precipitation patterns is achieved, the LDAS for the integrated seasonal prediction system will likely be uncoupled in the early phases of GAPP, directly using the gage, radar, and satellite precipitation estimates as surface forcing.

A second key thrust of GAPP LDAS initiatives will be the development of algorithms for the assimilation of satellite-derived land-state information (soil moisture, vegetation, snowpack, skin temperature) (Houser et al., 1998; Reichle, 2000). This effirt will include the development of so-called adjoint models and tangent-linear models needed by modern-era variational assimilation methods. In this context of variational assimilation, new forward radiative surface emissivity models must be developed to transform LDAS land states and surface characteristics into the satellite radiance channels (e.g. microwave) sensed by the growing number of satellite instruments in the EOS era. Chapter 10 discusses the various current and near-future satellite platforms that will provide remotely sensed observations relevant to land state assimilation.

8.3.3 Coupled ocean-atmosphere-land GCMs

The TOGA research program, and the follow-on CLIVAR program, have provided a progression of initial successes and follow-on improvements to coupled ocean-atmosphere GCMs, ocean state initialization and data assimilation (Cane et al., 1986; Zebiak and Cane, 1987; Ji et al., 1994; Chen et al., 1995; Behringer et al., 1998; Ji et al., 1998). GAPP will utilize the coupled ocean-atmosphere GCMs and ocean data assimilation systems emerging from these programs. The GAPP focus on the GCM scale will be to provide the land surface model component and the global land data assimilation system (GDAS) for the coupled ocean-land-atmosphere GCMs.

8.3.4 Imbedded Regional Climate Models

An increasing body of literature shows that high resolution regional climate models driven by time-dependent atmospheric lateral boundary conditions (LBC) from a coupled GCM can be used to successfully downscale climate simulations generated from relatively coarse resolution global models (Giorgi and Mearns, 1999; Fennessey and Shukla, 1999; Hong and Leetmaa, 1998; Kim et al., 2000; Leung and Ghan., 1999).

The success of imbedded regional climate models comes from the ability of the higher resolution imbedded models to better resolve: 1) the influence of orography, especially the role of regional elevated heat sources as central forcing mechanisms for monsoon circulations; 2) the diurnal cycle, especially the summer season low-level nocturnal jets prominent, for example, in south central U.S. and central South America (Berbery et al., 1996; Berbery and Collini., 2000); 3) summer season nocturnal precipitation maxima associated with these nocturnal jets; 4) SST gradients in nearby coastal ocean areas, and 5) mesoscale convective complexes, which play a dominant role in summer season precipitation anomalies.

The full potential of this approach still requires substantial research and development to address the issues and problems of model spin-up, incompatibility between regional model and global model physics, trade-off of model domain size and resolution, discontinuities introduced by the lateral boundary conditions, one-way versus two-way nesting, and solution splitting between the regional model and parent global model. However, Fennesey and Shukla (1999) have already shown seasonal skill for precipitatioin and temperature anomalies, providing striking examples of warm season precipitation predictability improvement via an imbedded regional model compared to the parent global model and other global models.

8.3.5 Generation of ensemble predictions

All the forecast components of Figure 8.1 will utilize ensemble predictions. Following the tradition of medium range predictions (1-2 weeks), ensemble forecasts invariably are produced from an ensemble of modestly varying initial conditions for the atmospheric state, created by adding perturbations to a mainline operational atmospheric initial analysis (Toth and Kalnay, 1997; Molteni et al., 1996). This philosophy of generating ensemble forecasts merely from an ensemble of initial atmospheric states is rooted in the medium-range perspective, wherein the implicit assumption is that the forecast model is "perfect" (i.e. no model uncertainties) and the resulting spread of forecast evolution results from the internal nonlinear dynamic response to only initial condition uncertainties. This assumption of perfect model clearly breaks down at seasonal and longer time scales. Even at the medium range, recent results (Harrison et al., 1999; Krishnamurti et al., 1999, 2003) indicate that model uncertainties have substantial impacts on ensemble forecast spread, as evidenced by superior capture of forecast spread and realizations by using multiple models, multiple physical parameterizations in a given model (convection, radiation, gravity wave drag, horizontal diffusion, land-surface, etc), and stochastic perturbations to a given model's diabatic heating tendencies (Buizza et al., 1999). At seasonal forecast time scales, such approaches to model uncertainty will have to be utilized in addition to using techniaues to deal with lower boundary condition uncertainty (i.e. extending initial state uncertainty to the land states of soil moisture, snowpack, etc, and ocean states of SST, salinity, etc).

8.3.6 Empirical prediction backdrops

As discussed by Kumar and Hoerling (2000), empirical methods to seasonal prediction provide a fundamental backdrop to the dynamical model approaches of Figure 8.1, and such empirical methods should be further explored, extended, and utilized, as applied forecast tools and as a baseline to compare to GCM-based skill. Indeed, the advantage of GCM-based seasonal predictions versus empirical methods, they argue, depends solely on the extent of nonlinearity of the observed atmosphere to SST forcings. Yet there is strong observational evidence that, at least in the case of El Nino episodes, there is a quasi-linear relation between the strength of the SST anomaly and the strength of the atmospheric perturbation. This raises the prospect of only marginally increased seasonal prediction skill from GCM methods versus empirical methods. These relationships will be explored in collaboration with the CLIVAR/ PACS program.

Similar empirical backdrops are needed in the context of downscaling. Noteworthy success has been achieved using empirical methods to downscale GCM seasonal predictions to smaller scales, and such methods have been notably competitive in some studies with the more expensive and demanding downscaling approach of using imbedded regional models. Such empirical downscaling success is again most likely in cases where the downscaling response is fairly linear (e.g. straightforward orography signature in a winter season precipitation anomaly in the Pacific Northwest). Empirical downscaling will likely show minimal success in warm season situations where nonlinear feedback processes play a more dominant role.

Finally, despite the extensions to ensemble prediction methods outlined in the previous section, present and future ensemble forecasts suites will invariably underforecast the spread of observed realizations and skew the observed frequency of the spectrum of precipitation amount categories. Here again, empirical methods should be extended and expanded to better correct these ensemble suite biases.

8.4 Role of Land Surface Modules in Longer-term Climate Prediction

The role of land surface processes in the persistence and variability of seasonal climate anomalies over the land is crucial to understanding the limits of seasonal and interannual predictability over continental regions. Local land-atmosphere interactions strongly influence the remote effects of tropical SST anomalies over land. The "correct" initial values of land surface conditions are a key to seasonal prediction of the hydrological cycle over the land (SIMAP, 2000).

The persistence of soil moisture anomalies is an important contribution to seasonal predictability. In particular, the magnitude of the present anomaly is needed to estimate the magnitude of the future anomaly, which can then have a predictable impact on concurrent precipitation. In order to attain the increase in forecast skill, the following conditions must be met: (1) actual soil moisture anomalies in the particular region must exhibit significant persistence or "memory", (2) the overlying atmosphere must exhibit a predictable response to an imposed soil moisture anomaly, and (3) the modeling system employed must represent both this memory and this atmospheric response. While land surface modeling studies have mostly focused on their reproduction of observed surface fluxes, modeling issues related to seasonal predictability (the third condition above) have largely been ignored (SIMAP, 2000).

One set of proposed experiments to test the role of soil moisture is to first quantify the impact of realistic soil moisture contents on precipitation and then to establish directly the impact of a realistic land surface moisture initialization on precipitation forecasts. In the first phase, a coupled land-atmosphere model is forced to maintain realistic soil moistures at all times, so that the focus is mainly on atmospheric response to land conditions -- the modeling of persistence in the coupled system is not so much an issue. In the second "initialization" phase, the issue of persistence is addressed specifically. Another set of experiments can be designed to separate the precipitation variability associated with the land boundary condition from that stemming from atmospheric chaos acting alone (SIMAP, 2000).

GAPP research can make a unique contribution to the development and testing of land surface models (LSMs) coupled to GCMs. The current generation of Soil-Vegetation-Atmosphere Transfer Schemes (SVATS) includes complex vegetation interactions in addition to soil moisture and other land surface processes. These models include both biogeochemistry and biogeography models. Biogeochemistry models simulate change in basic ecosystem processes such as the cycling of carbon, nutrients, and water (ecosystem function). Biogeography models simulate shifts in the geographic distribution of major plant species and communities (ecosystem structure) (US National Assessment). The additional elements of carbon cycling and vegetation dynamics allow for a more realistic description of the land surface and ultimately, the hydrological cycle.

Existing or new SVATS models coupled to GCMs can be tested within a predictability framework by using them within current forecasting systems. For example, the NOAH LSM used with NCEP's Eta model and the Land Data Assimilation System (LDAS), is currently being used in an end-to-end prediction system over the US domain. New CEOP-based remote sensing measurements, as well as other observations such as those from NASA's Cold Land Processes Field Experiment, can be used to validate the forecast land surface characteristics. Several new instruments on the TERRA mission, for example, are designed to measure land surface variables such as vegetation and photosynthetic activity. These vegetation measurements will be crucial to validating the next generation of SVATS. GAPP efforts should concentrate on using SVATS within data assimilation systems, GCMs, or RCMs to improve the characterization of the land surface and the predictability and predictions of the hydrological cycle.

9. HYDROLOGY AND WATER RESOURCES

9.1. Rationale

One of the two primary objectives of GAPP is "to interpret and facilitate the transfer of the results of improved seasonal predictions to users for the optimal management of water resources." To accomplish this objective, it is necessary to understand: (i) what kinds of forecast products are most useful to water resources agencies; (ii) how this information could be used in water management decisions; and (iii) how this information can best be produced and transferred to water managers. Addressing these issues will, in turn, help focus related science needs (e.g., development of improved hydrologic prediction capability).

The linkage between the science (hydrology) and applications (water resources) activities within GAPP is particularly important. GAPP, like GEWEX, is a science program that also has a set of applications objectives. In this case, the scientific requirements involve the better understanding of large scale hydrologic processes over the GAPP domain, how they influence hydrologic predictability, and the development of hydrologic prediction tools. With respect to time scale, the focus is on relatively long lead times (e.g., climate time scales of months to years). The applications objective is to improve operation of water resource systems using GAPP science. In this chapter, we identify the primary science questions driving the GAPP hydrology and water resources initiative, and describe research activities that address the scientific requirements and the applications objective.

9.2. Science Background and Questions

The GAPP Hydrology and Water Resources activity will be guided by six science questions that will serve to focus the activity at the intersection between the scientific contributions of GAPP (and more broadly, GEWEX) and the water management community. These science questions are elaborated below.

9.2.1. Hydrologic Predictability

Science Question: What are the key factors governing hydrologic predictability, and in particular, the ability to predict streamflow, evapotranspiration, and soil moisture? To what extent can improved process understanding, and its incorporation into hydrologic models, result in more accurate hydrologic predictions?

As defined by the NAS Committee on Hydrological Sciences (COHS), "Predictability is the extent to which the future state of a system can be estimated based upon the (theoretical) availability of a comprehensive set of observations characterizing the system's initial condition" (NRC, 1999a). The predictability of land surface hydrologic processes is thought to be attributable primarily to two mechanisms. As described in Chapter 4, the first mechanism is persistence due to the storage of moisture, as groundwater, snow and/or ice, soil moisture, and (manmade or natural) surface impoundments. The second is recycling of moisture stored on or near the land surface and the influence of the recycling process on moisture fluxes to and from the atmosphere. Therefore, the ability to make hydrologically useful predictions requires understanding of the storage of water as well as the factors controlling moisture fluxes, their variability, and the dynamics of the coupled land-atmosphere system.

In the western U.S., the mechanisms controlling hydrologic predictability are substantially different than in the GCIP study area (Mississippi River basin). In particular, the precipitation regimes in the West are dominant in the winter, and the role of orography in controlling the spatial distribution of precipitation and runoff production is key. Evaporative processes as they affect precipitation (both directly and indirectly) are arguably less important. Understanding the role of snow, its interaction with topography, and the factors controlling its ablation, are crucial. On the other hand, evapotranspiration does control soil moisture antecedent conditions, which in turn controls runoff production. Likewise, the direct role of vegetation is somewhat different in the West than in the Mississippi River Basin. Runoff source areas are largely forested with nonforested areas generally contributing in only a minor way to streamflow. Exceptions are monsoonal conditions in the Southwest and flash floods on relatively small watersheds. Quantifying the effects of forests and deforestation on the hydrologic cycle also are important research issues for the western USA.

9.2.2. Distributed Hydrologic Model Development

Science Question: What is the best strategy for implementing distributed and semi-distributed hydrology models over a range of spatial scales, and how can their performance be evaluated? What are the relevant spatial scales, and how transferable are model parameters? How do we develop a pathway for model improvements.

A major contribution of GCIP has been the development of a new generation of land-atmosphere transfer schemes, which represent both the energy and water balances of the land surfaces, at resolutions down to about 1/8 degree and domains up to the continental scale. Implementation of these new land surface schemes into the NCEP family of coupled land-atmosphere models has greatly improved their ability to partition energy at the land surface, among other things. The ongoing Land Data Assimilation System (LDAS) project (Mitchell et al., 1999) is using several of these models to create better initial conditions for numerical weather forecasts. LDAS and other GCIP activities have shown that land surface schemes that properly represent runoff production (as a subgrid process) can also be used to predict streamflow over large continental river basins and their major tributaries. Less progress has been made in adaptation of these models in the operational hydrology community.

Distributed and semi-distributed hydrologic models, which are generally pixel-based (i.e., represent a watershed as a collection of rectangular elements) are distinguished from more conventional hydrologic models through their explicit use of land surface characteristics, including topography, soils, and vegetation. However, like more conventional models, they inevitably require some calibration, especially for parameters that are related to soil characteristics, which cannot be represented directly due to the large spatial scales involved (Koren et al., 1999). Furthermore, there is a concern that the parameters of these models depend on model spatial scale. Among the strategies for model implementation are regionalizing parameters through use of a representative set of Intermediate Scale study Areas (ISAs – typically catchments with drainage areas $10^2 - 10^3$ km^2) over the region, and direct transfer from nearby, calibrated catchments (see e.g., Abdulla and Lettenmaier, 1997). More generally, the evolving field of macroscale hydrological modeling (MHMs) creates an opportunity for a well-defined pathway for incorporation of improved physical understanding into hydrologic prediction. Such a pathway has proved quite successful in numerical weather prediction and has resulted in a documented history of continuously improving skill scores (NRC, 1999b). Such a history is largely lacking in surface hydrology.

A parallel applications question is how better models and supporting data can make the process of model implementation and testing more efficient. At present, implementation of hydrologic models involves a fairly time-consuming process of calibration and verification and is largely site specific. The hope in using more physically based models is that the number of free parameters will be reduced, and the calibration will be simplified. To date, no rigorous studies have been performed to determine whether, and to what extent, this approach is feasible, although anecdotal evidence suggests that it is.

9.2.3. Integration of Hydrologic Models and Coupled Land-Atmosphere Models

Science Question: What is the role of hydrologic prediction in coupled land-atmosphere modeling? Is one-way (or two-way) coupling in land-atmosphere models a viable hydrological forecasting strategy?

With the evolution of coupled land-atmosphere models, particularly MHMs that predict runoff and streamflow, as well as surface energy fluxes, the distinction between land surface models and hydrologic simulation models has become blurred (Maurer et al., 2001). MHMs arose from the need to partition net radiation into turbulent and ground heat fluxes within coupled land-atmosphere models. This partitioning is coupled, however, with the surface water budget (because evapotranspiration is a common term in the energy and water balances). Therefore, MHMs predict not only energy partitioning, but also streamflow. As noted earlier, the advantages of MHMs over more conventional hydrologic simulation models include more direct incorporation of physical process understanding, which should reduce the need for parameter estimation (see Section 9.2.2) and make greater use of modern high resolution land cover data, including soils, topographic, and vegetation information. However, there remain open questions as to how MHMs are best implemented in so-called “off-line” mode – that is, with surface forcings prescribed. Whether and how parameters vary depends on whether an MHM is implemented in “water balance” mode (basically meaning that no iteration is performed on the effective skin temperature, or in effect assuming the skin temperature is equal to air temperature), or an "energy budget" mode where skin temperature values are iterated by closing the surface energy budget. The assessment of the best approach is still an open question. More generally, there also is a question as to the role of MHM predictions within a fully coupled model, and how, whether and under what circumstances it is more consistent to use a fully coupled implementation.

9.2.4 The Source and Consequences of Model Biases

Science Question: What are the causes of biases in hydrologic model forcings and outputs? What are their effects on the potential use of hydrological model output in hydrologic prediction, and in turn in water resources system operation? How can these biases best be removed?

Interpreting seasonal climate impacts on water resources requires coupling of climate and hydrologic models. Usually, outputs from a climate forecast model are used as surface forcing for the hydrologic model, and then the hydrologic forecasts become input to a water resources decision model. Yet all dynamic models contain some bias (as compared to statistical models, which can be designed to be unbiased). This fact is certainly true of atmospheric models, especially when evaluated with respect to their ability to reproduce observed precipitation. Hydrological models, even when forced with historical meteorology, are inherently biased; seasonal biases in the statistical properties (e.g., means and variances) are common, as are systematic errors for low flow conditions (Koren et al., 1999).

Attention needs to be given to the role of biases in both climate forecasts (forcings to hydrologic forecast models) and in the hydrologic model forecasts. Some method of correcting for these biases is essential for use of the forecasts in water resource applications. Methods for removal of atmospheric model biases are evolving, and are accomplished through post processing of model outputs. These methods are of two general types. The first requires a retrospective climatology for both the model and observations, usually for a period of at least a decade. The second, "on the fly" method uses a shorter period, with additional assumptions that allow the information needed to remove the bias from multiple storm events over a shorter period. In concept, similar approaches can be applied to hydrological model output.

Although these methods can eliminate hydrological model input and output bias, a question remains regarding how the bias (and its removal) affects the information content of both the atmospheric and hydrologic forecasts. Experiments are needed to demonstrate that the climatology of these hydrologic forecasts agrees with the climatology of historical streamflow events. In addition, useful methods to measure the skill in these forecasts need to be developed and demonstrated so that water resource managers can have the appropriate level of confidence in the forecasts.

9.2.5 Infusion of New Technologies into Hydrologic Prediction Systems

Science Question: How can improved modeling strategies, such as land data assimilation and ensemble forecasting, best be implemented in a hydrologic prediction framework? Where is the greatest potential, in both the short-term and long-term, for improving hydrologic predictions and forecasts? What is the interaction between the need and potential for improved observations and modeling in terms of operational forecasting?

The development of a Land Data Assimilation System (LDAS) has been a major undertaking of GCIP, which is expected to continue and broaden in scope under GAPP. LDAS was motivated by the problem of providing proper initialization for the land surface state variables (primarily soil moisture and snow) in NCEP's suite of operational forecast models. In most current weather and climate forecast systems, errors in the atmospheric model forcings accumulate in the surface and energy stores, leading to incorrect surface water and energy partitioning and related processes. The problem is especially acute for precipitation, as precipitation errors lead to errors in soil moisture, which in turn affect surface energy partitioning during subsequent forecast cycles (Mitchell et al., 1999). LDAS consists of uncoupled models forced with observations, which therefore are not affected by atmospheric model forcing biases. The observations include a merged precipitation gage and radar product, satellite data (primarily for solar radiation), and at present, some forecast model analysis fields. Land surface model parameters are derived from high-resolution vegetation and soil data. LDAS has both a real-time pathway, which operates in parallel with the operational Eta model at NCEP, and a retrospective pathway through which quality-controlled retrospective data can be used for parameter estimation and other purposes.

In addition to its immediate goal of providing better initial conditions for weather and climate forecasts, LDAS has implications for water resources management, as it provides a hydrologic prediction capability for large river basins. At present, this capability has been demonstrated primarily within the GCIP Mississippi River basin and the Columbia River basin (Wood et al., 1999; Hamlet and Lettenmaier, 1999). Among the major issues to be addressed by LDAS under GAPP are: 1) what are the most important external forcings, and how can they best be derived independently of model analysis, 2) what improvements in climate forecasts result from the use of LDAS in comparison with more conventional methods, and what are the space-time characteristics of these improvements, 3) how can remote sensing data be used more effectively in LDAS, and to what extent can remote sensing data either extend or replace surface observations, and 4) how can LDAS be expanded to have a comprehensive data assimilation capability, e.g., through assimilation of remotely sensed soil moisture, surface temperature, snow, and/or other variables?

Ensemble climate forecasting is a second area in which advances under GAPP have the potential to improve hydrologic forecasts, and through them, water management. On seasonal to interannual time scales, hydrologic predictions are necessarily probabilistic forecasts. Ensemble forecasting provides a direct pathway for linking climate and hydrologic prediction, and generating probabilistic forecasts needed for water resources decision-making. For instance, ensemble prediction systems allow uncertainty in future precipitation patterns throughout a river basin to be analyzed in a way that is statistically consistent for all forecast points in the basin. Also, a water resources decision model, designed to process an ensemble of streamflow sequences, can be used to evaluate the implications of alternative operational decisions (e.g., future reservoir releases). Still, hydrologically relevant verification methods are needed to assess the quality of ensemble forecasts from climate and hydrologic models. For instance, analysis of space-time precipitation climatologies should be undertaken to support verification and testing of precipitation forecasts; climate model assessments are needed to assure that the climatology of precipitation forecasts (including ensemble forecasts) matches climatology (i.e. the forecasts are statistically unbiased). Verification approaches are also needed to measure the skill in these forecasts over a range of space time scales.

9.2.6. Linkages between GAPP and the Water Resources Sector

Science Question: How can the scientific contributions of GCIP/GAPP, in areas such as coupled land-atmosphere modeling, land data assimilation, and ensemble forecasting, best be transferred to the operational hydrology and water resources community? What are the implications for operational prediction services of science issues to be addressed by GAPP, like possible tradeoffs between observations and model complexity as they affect forecast skill, and between the ability to characterize forecast uncertainty and forecast space-time resolution?

As noted above, GCIP made considerable progress in the development of models and modeling strategies. Its contributions have important implications, not only for understanding water and energy budgets over the central U.S., but also for the predictive capability of land-atmosphere models used by the operational weather and climate communities (Roads et al., 2002). GCIP has placed less emphasis on transferring those scientific advances to the operational hydrology and water management communities. Slow progress in this area can perhaps be attributed to two factors. First, the operational community is utility driven, rather than hypothesis driven. That is, better understanding of the science ("why") isn't necessarily of immediate interest unless it helps in some measureable way in achieving an objective (e.g., making a more accurate forecast). Second, the operational community has a large investment in modeling structures that aren't necessarily compatible with the new generation of land-atmosphere models, and there has been an understandable "show me" attitude. It is incumbent on GAPP to develop an effective technology transfer strategy that can show the benefits (or lack thereof) in adaptation of new technology. In Section 9.3, a strategy is outlined which addresses the general problem of interaction with the operational community, as well as specifics of how scientific advances can be incorporated into operations.

The hydrologic community can look to GCIP and GAPP's interactions with the weather and climate forecasting communites to understand how the lead-time between advances in science and research and their inclusion in operational systems can be reduced. One strategy that has been used successfully in involves parallel research and operational pathways, wherein improved process understanding is translated to better parameterizations and algorithms that are tested in parallel with operational models. If and when the research path improvements are shown to result in forecasting improvements, they are adopted in a new "cycle" of the operational model. This approach has resulted in an ability to "fast track" scientific advances, which hasn't been the case in the operational hydrology community, probably because there is no apparent model upgrade pathway in operational hydrology, analogous to those that have been adopted for NCEP's suite of coupled land-atmosphere models.

The potential for a strategy utilizing parallel operational and research pathways addresses only the hydrologic prediction aspects of the GAPP technology transfer problem, however. The second part of the problem has to do with transfer of scientific improvements, as represented by GCIP and GAPP models, to the water management community. This problem is somewhat more complicated conceptually than the hydrologic prediction problem, because the decision process is much more distributed.

There is a question as to how involved a program like GAPP (or more generally GEWEX) should become in water management decision processes. GAPP will make its greatest impact by facilitating some “joint ventures” with water managers to serve as templates for translating advances in hydrologic forecasting over intraseasonal to interannual time scales to water resources decision-making. This process may well involve demonstration projects or similar mechanisms (see Georgakakos et al., 1998; Hamlet and Lettenmaier, 1999). Such projects would have to deal not only with the modeling and prediction issues, but also with the use of improved predictions in a decision framework. This is a new perspective for a science-driven program like GAPP, and will require interactions with the OGP Human Dimensions and Regional Integrated Scientific Assessment activities. In the following section, we suggest some possible implementation pathways.

9.3. Research and Applications Activities

The overarching GAPP strategy for hydrologic prediction, and its incorporation into water resources decision making, follows the so-called “Shukla Staircase” outlined at the 1998 GCIP/ PACS Warm Season Precipitation Workshop (Silver Spring, MD). A slight variation of the Shukla scheme is shown in Figure 8.1. It exploits global climate teleconnections; consequently its first step involves forecasting sea surface temperature anomalies globally. This element of the staircase relies on the considerable thermal inertia, hence persistence, in sea surface temperature anomalies. The SST forecasts are then used as boundary conditions for global coupled land-atmosphere models, which subsequently, through nesting to the continental or finer scale, provide forcings for a macroscale hydrology model. As noted in Section 9.2.3, there is an open research question regarding the need for two-way or one-way coupling with the land surface hydrology model at this step. In this case, the macroscale hydrology model then provides forecasts (in practice, multiple ensembles) to a water management model, which in turn supports the management decision process. This entire procedure, sometimes termed end-to-end prediction, is conceptually straightforward, but has yet to be demonstrated in practice.

A major thrust of GAPP, and the hydrology/water resources activities in particular, is to develop and implement the end-to-end prediction approach and to demonstrate its utility for “real” water resource systems. The steps involved in so doing are:

1) Re-scale and downscale seasonal to interannual forecasts of precipitation and surface meteorology (from the continental or regional scale climate prediction models, as shown in Figure 8.1) to the time and space scales required by macroscale hydrologic forecast models.
2) Assimilate observations (e.g. precipitation, surface meteorology, snow cover and water equivalent, streamflow and surface skin temperature) into the hydrologic forecast model(s) to estimate initial conditions.
3) Implement hydrologic models in an ensemble mode using forecasts and initial conditions.
4) Operate a hydrologic uncertainty post processor to adjust the hydrologic forecasts to account for effects of hydrologic biases and assure validity of probabilistic forecast information to be used by water resources decision-makers.

The following GAPP activities are oriented toward developing the models, implementation tools, and practical understanding required to make end-to-end prediction a reality in the water management field. The activities will be organized around individual GAPP supported research projects, related non-GAPP research projects, operational activities of the NWS hydrology program, and other activities of NASA, NOAA and other agencies. These activities will be structured within parallel research and operational pathways, following the successful GCIP structure for coupled model development.

9.3.1. Coupled Model Ensemble Products Analyses

This activity would provide analyses of global and regional model ensembles from a hydrologic forecasting perspective. One important activity will involve developing quantitative measures of forecast quality to assess the space-time evolution in forecast skill and the validity of probabilistic forecasts from climate ensembles. Another step will be to develop methods for evaluating and correcting for biases in the model forecasts. Because these ensemble products are provided at coarser space and time scales than the data input requirements of hydrologic forecast models, techniques to re-scale and down-scale the ensemble information will need to be developed and tested. This activity will be carried out in cooperation with the NWS Advanced Hydrologic Prediction System (AHPS), parts of which may be treated as an NWS contribution to the operational pathway (Connelly et al., 1999).

9.3.2. Hydrologic Model Intercomparison Studies

Improving the operational models used for hydrologic forecasting is a potential outcome of the extensive land surface model development accomplished during GCIP. For example, existing hydrologic forecast models do not have well developed representations of vegetation, they do not explicitly account for energy flux and storage, and they were not designed to make use of satellite remote sensing data. On the other hand, they are explicitly designed to make good estimates of runoff and streamflow. An important next step is to compare the performance of current operational and alternative research models in terms of hydrologic forecasting.

One central element of this activity is the Distributed Model Intercomparison Project (DMIP), which is comparing alternative approaches to modeling the area upstream from several forecast points (NWS/HRL, 2000). The alternative hydrologic modeling approaches represent spatially distributed precipitation and basin characteristics at different levels of detail. The goal of this study is to evaluate alternative models relative to the existing operational NWS River Forecasting System models (operated in both lumped and distributed modes). The results will help guide future distributed modeling research and would be used to improve the application of spatially distributed models used by operational forecast offices.

Other model intercomparison studies would be conducted as part of the verification activity of the LDAS project. Currently, LDAS represents all of the land surface processes on a 1/8th degree grid covering the continental U.S. as well as parts of Mexico and Canada. Runoff from the grid elements is routed to downstream gage or psuedo-gage locations. A number of such locations (between 100 and 200) are being identified based on the criterion that they have enough precipitation gages in their upstream catchement areas to assure high quality basin average precipitation estimates for use as streamflow validation sites. Intercomparisons of different models participating in LDAS will be made both retrospectively and in real time. The evaluation sites cover a range of basin sizes, generally 1000 to 10,000 km^2. They will also include some composite areas such as the ARM/CART site (where surface flux and soil moisture measurements are made) as well as networks in Illinois (where a long record of soil moisture measurements is available) and the Oklahoma mesonet, which has also installed soil moisture network.

9.3.3. Parameter Estimation Experiments

All land surface and hydrologic forecast models require estimation of model parameters for any practical implementation. Some model parameters can be assumed to be related to physical properties such as soil hydraulic properties or vegetation rooting depths. However, the scales at which the models are applied and the scales at which basin characteristics can be observed are vastly different. Moreover, many basin characteristics vary spatially, and detailed local values are unknown. Therefore the relationships between model parameters and basin characteristics are not necessarily the same as those assumed by the land surface modeling community. Experience has shown that substantial improvements in runoff simulation can be obtained by calibrating model parameters as opposed to using existing techniques for *a priori* estimation. The objective of this activity is to improve our understanding of the relationships between model parameters and basin characteristics and what can be learned about model parameters through calibration. Results of the activity will guide future research and will be used in operational meteorological and hydrological prediction systems.

9.3.4. Hydrologic Model Data Assimilation Experiments

One opportunity for improving hydrologic prediction skill over climate time scales is to develop better initial values of soil moisture, temperature and snow cover state variables. Although some work has been done in this area over the last two decades, the results are not widely used in operational hydrologic forecast systems. Typically, operational hydrologic forecast models use observed precipitation (and surface temperature) forcings, together with some estimate of potential evaporation to predict initial conditions at the time of the forecast. Effects of errors in the forcing values on the predicted state variables (hence streamflow) are usually dealt with manually. Methods are needed to use observed river stages, soil moisture, snow water content and snow cover, and remotely sensed surface temperatures to modify the initial values of these state variables. Such methods must account for the effects of uncertainty in the observations, model parameters and model structure.

GAPP hydrologic model data assimilation experiments are intended to be collaborative studies between academic researchers and operational hydrologists and will incorporate elements of the LDAS project as well. These activities are intended to develop improved data assimilation techniques, which would be implemented in a test environment and would serve to guide future research.

9.3.5. Water Resources Applications of Hydrologic Predictions

Application of hydrologic predictions in water resources decision analysis requires evidence of forecast skill and its quantification. Because all hydrologic models have biases, adjustments must be made to model output variables to compensate for these biases and to assure that the probabilistic estimates are reliable. GCIP has initiated work (in the Ohio River basin, and elsewhere) to develop methods for quantifying and accounting for bias in climate forecasts and for describing its effects on hydrologic predictions. A cooperative effort between NWS and NCEP is also addressing this issue, but much more needs to be done.

GAPP activities in this area will evaluate the accuracy of probabilistic hydrologic predictions made using ensemble (climate and hydrologic) forecasts, with particular focus on selected water resource systems within the GAPP area. Through a parallel evaluation pathway in cooperation with selected water management agencies, these projects will evaluate uncertainties in hydrologic forecasts generated using long-lead climate forecasts and their implications for water resources decisions. The primary strategy will involve retrospective analyses and evaluations of how past decisions might have been influenced by long-lead forecast information. Subsequently, long-lead and advanced hydrologic prediction capabilities will be implemented within a parallel real-time evaluation framework.

9.4. Linkages with Other Hydrology and Water Resources Programs

The GAPP hydrology and water resources activities will be coordinated with activities of other national and international programs, as well as programs within other U.S. agencies. The most important of these linkages are outlined briefly below, while others are included in Chapter 12.

9.4.1. NWS Advanced Hydrologic Prediction Services (AHPS)

Advanced Hydrologic Prediction Services (AHPS) is a National Weather Service Hydrology Laboratory activity that is designed to provide its users with improved hydrologic forecast information. A particular emphasis is on extending forecast lead times, producing long range forecasts (up to seasonal) and devising forecast products with formats that assist decision makers with the assessment of risk. In part, the motivation for AHPS comes from the increase in flood losses (which exceeds $4 billion annually within the U.S. and approached $10 billion in 1997). Under pre-AHPS pilot projects, NWS has begun to implement advanced hydrologic and hydraulic models, new forecast procedures and displays, and to develop inter-agency commitments for broader implementation of its forecast system. AHPS first received formal funding in FY 2000, and the project team is now actively evaluating the potential for such advanced forecast methods as ensemble weather and climate forecasts. Although the focus of AHPS is primarily flood forecasting, there is a convergence of interests with GAPP in the intermediate (roughly 2-week to seasonal) forecast range, where some of the problems and issues surrounding use of advanced hydrologic forecast tools are common. NWS has expressed an interest in possible collaboration with GAPP, which could involve using an appropriate part of the AHPS activities as a parallel implementation and testing pathway (as outlined in Section 9.3).

9.4.2. OGP Regional Integrated Sciences and Assessment Program

The NOAA Regional Integrated Scientific Assessments Program (RISA) was formed to facilitate better interactions between three elements of OGP research: 1) climate and environmental monitoring; 2) economic and human dimensions, especially trends and factors influencing climate-sensitive human activities, and 3) applications, specifically the transformation and communication of relevant research results to meet specific needs. RISA is based on the premise that "Regions" (typically defined as subcontinental areas of which there might be about 10 within the continental U.S.A.) exist at the nexus of the local to global continuum. It is argued that the regional scale is an appropriate organizational unit at which to coordinate climate research and to provide socially relevant information that reflects geographical (e.g., river basin) and jurisdictional boundaries. RISA is made up of a set of regional assessments activities. These activities are intended to (1) characterize the current state of knowledge of climate variability, and its social and environmental impacts within a region; (2) assess vulnerability to climate on the seasonal and decadal to centennial time scales; (3) improve decision support dialogues; and (4) develop awareness of climate impacts on regional socioeconomic systems. RISA relies on the results and data from ongoing NOAA disciplinary process research in the physical sciences and economic and human dimensions research, and performs primarily an integrative function in this respect. Integration is accomplished by means of RISA projects, five of which are currently active (in the Pacific Northwest, the Southwest, Interior Mountain West, California, and the Southeast). Consistent with the theme of integration, all case studies include activities in multiple sectors (e.g., water resources, agriculture, fisheries, forestry, and others depending on the specific region). The Pacific Northwest (PNW) study is the most mature of the RISAs, and has a strong focus on hydrology and water resources. Through informal collaborations, the PNW activities have made extensive use of macroscale hydrology modeling research supported by GCIP. Water resources are also important aspect of the Southwest, Interior Mountain West, and California RISA as well.

There are important synergies between hydrologic research in GAPP and in the RISAs. For instance, forecasting changes in climate, hydrology, and water resources over seasonal to interannual time scales is a common focus of the two projects. One possible protocol for GAPP-RISA interaction is for GAPP to take the lead on development and testing of forecast products and RISA to lead in assessment of management and policy implications. Informally, this process has been the mechanism for interaction between GCIP and RAP (Regional Applications Project) in the PNW. RISA, on the other hand, could play a key role in facilitating the parallel "applications pathway" outlined in Section 9.3.

9.4.3 Hydrology for Environment, Life and Policy (HELP)

The WMO/UNESCO HELP program offers GAPP a unique opportunity to work within an international framework as it structures a dialogue between water resource managers and GAPP scientists who have experimental products to be tested in an operational environment. This catchment-based project focuses on "down-to-earth" problems that affect the lives of people in individual basins. It presents an opportunity to test new approaches such as Integrated Water Resources Management (IWRM) in different areas of the world. To the extent that HELP will provide a testbed for GAPP products GAPP will actively engage in the program and support basin studies. To this end GAPP supports work in the two HELP basins described below.

1) The San Pedro Basin is a transboundary basin covering 5,810 km^2 in Arizona and 1,800 km^2 in Mexico. The San Pedro River drains the northern Sonora in Mexico and flows north through Arizona, joining the Gila River and then flows into the Colorado River which then flows back into Mexico and the Gulf of California. Water in the basin is used for mining, municipal and domestic uses and irrigation. There is extensive riparian vegetation in the basin that is dependent on the rainfall. Better scientific information on the water cycle and seasonal to interannual precipitation forecasts could be helpful in resolving issues related to the loss of riparian zones, the pressures on groundwater arising from population increases, and the consequences of changing evaporative water losses and vegetation.

2) The Red Arkansas Basin builds on work that was carried out in GCIP and supports a number of the operational interests of the Bureau of Reclamation. Together, the Red and Arkansas rivers drain an area of more than 550,000 km^2 as they flow from their headwaters in the Rocky Mountains to the main channel of the Mississippi River. Water is used for irrigation, municipal and industrial purposes, hydropower, recreation and habitat for fish and wildlife. Water management decisions are influenced by the needs for irrigation water, water quality considerations arising from issues related to animal management, and environmental problems arising from oil seepage into groundwater. Part of the GAPP activities in this basin will involve the identification and education of a group of potential users for experimental GAPP forecasts and products.

10. REMOTE SENSING RESEARCH AND APPLICATIONS

10.1. Rationale

Satellite data sets provide a valuable extension to conventional in-situ ground-based observations. Traditional in-situ ground observations have limitations for input, validation and assimilation in models. GAPP satellite efforts will be directed at GAPP objectives and will support the researh development needs of the US Water Cycle program and the planned IGOS-P water cycle theme. Point data are difficult to interpret for the resolution over spatial domain of models which range from $1/8^{o}$ X $1/8^{o}$ for the high resolution Land Surface Data Assimilation Schemes (LDAS) to 2^{o} X 2.5^{o} for Global Climate Models. Satellite data provide continuous spatial coverage and repeat temporal coverage. The frequency of coverage is dependent on the orbit and swath of the satellite and resolution of the sensor. EOS satellites that provide data sets for a large number of atmospheric and land surface variables could be especially valuable for GAPP land-atmosphere modeling activities. These new data sources are the EOS Terra satellite launched in December 1999 and the EOS Aqua satellite that will be launched in 2001 or 2002. There are also a variety of satellites being launched by Japan (ADEOS II), Europe (ENVISAT), India (INSAT) that will provide global coverage using different sensors but measuring similar variables at different overpass times. These satellites carry new and enhanced sensors that will provide high resolution data sets and will be made available to the scientific community through the Goddard Data Active Archival Center (DAAC).

10.2. Objectives

Within GAPP, remotely sensed satellite data will be used to:

1) Provide forcing and other variables to offline land surface hydrological models. These input variables include, vegetation cover, air temperature, precipitation, total atmospheric precipitable water content, atmospheric temperature and water vapor profile, cloud fraction and height to cloud base.
2) Validate model outputs such as surface temperature and soil moisture content,
3) Provide more comprehensive data inputs to land surface models in data assimilation and prediction systems. Products that could be assimilated include surface temperature and soil moisture.
4) Compare satellite derived land surface products with observations made during field experiments and CEOP data sets.

It should be noted that although the same data sets have been mentioned in the validation and the assimilation modes, these data sets are designed to be unique and complementary. The data used in the assimilation will not be used in validation and vice-versa.

10.3. Remote Sensed Data Sets

This section outlines the various variables that can be retrieved from satellite data. It is proposed that GAPP utilize single variables that may be derived from sensors with different spatial and temporal resolutions, coverages and times of overpass.

10.3.1 Variables and Parameters in Land Surface Models

Land surface models require various input data sets in order to characterize the properties of the land surface as well as provide meteorological forcings. The input data sets include:

1) Leaf area index (LAI) derived from the Normalized Difference Vegetation Index (NDVI) from AVHRR and/or MODIS,
2) Surface roughness parameters – roughness length and zero plane displacement from the Vegetation Canopy Lidar (VCL),
3) Precipitation from SSM/I and TRMM,
4) Surface air temperature derived from AVHRR data or from the AIRS/AMSU and TOVS data,
5) Surface specific humidity from AIRS/AMSU and TOVS,
6) Cloud cover fraction and height to cloud base derived from AIRS/AMSU, TOVS and CERES, and
7) Atmospheric temperature and moisture profile from AIRS/AMSU and TOVS.

10.3.2 Validation Data Sets

Validation will be carried out using the following data sets:

1) Soil moisture derived using AMSR,
2) Surface temperature using AVHRR, ASTER, AIRS/AMSU, MODIS, TOVS and GOES.

10.3.3 Assimilation

The following data sets will be used in GAPP data assimilation activities:

1) Soil moisture derived using AMSR,
2) Surface temperature using AVHRR, ASTER, AIRS/AMSU, MODIS, TOVS and GOES,
3) Air temperature and specific humidity profile of the atmosphere using AIRS/AMSU.

10.4. Prediction

GAPP will deal with numerous prediction issues on seasonal, annual and inter-annual time scales. The use of satellite data in prediction models will have a major positive impact on the accuracy of the definition of the initial state. Assimilation of satellite data in real-time for soil moisture, surface temperature and precipitation will help improve the specification of initial conditions thereby reducing forecast errors. These predictions and assimilations will be carried out on regional and meso scales depending on the particular application. In the case of detailed mesoscale applications, GOES-derived surface temperatures that have a high spatial (1km) and temporal (15 minutes) resolution will be utilized for validation and assimilation purposes. In the case of seasonal predictions, coarser data sets should be sufficient.

The key objectives of an integrated seasonal prediction system can be realized by a better representation of the land surface system. This land surface system model will require inputs that have to be specified using satellite data. Data assimilation for the land surface will be carried out using remotely sensed data. In addition, prediction of land surface variables such as soil moisture and surface temperature can be validated using the satellite data over continental regions and extended time periods. Land surface states need to be initialized properly for accurate predictability. The initialization of land surface soil moisture and temperature can be carried out by the use of satellite data.

Multi-scale downscaling of prediction components can be carried out using satellite data at appropriate resolution. For example, a forecast of land surface evapotranspiration at 1^{o} X 1^{o} resolution can be disaggregated using the 1km GOES surface temperatures and 250m MODIS vegetation indices. The potential for the use of satellite data in disaggregating model forecasts onto higher spatial resolutions will be of prime importance in the future as satellite sensor resolutions increase.

10.5. Scaling and Process Inter-Relationships

The reliance on different sensors with different spatial resolution and overpass times for specific variables leads to a challenge in merging these data sets when they are derived from different satellites. For example, surface temperature can be derived from GOES, AVHRR, MODIS, TOVS and AIRS/AMSU and ASTER. Each of these sensors has a different spatial resolution. The spatial resolution for GOES is 1km, AVHRR is either 1km (raw data) or 4km; MODIS has thermal bands around 1km, TOVS resolution is 60km, AIRS/AMSU is at 12.5km, and ASTER is around 90m. In addition, the overpass times are different for each satellite. As a result, it will be possible to piece together the data from various satellite sensors to obtain a diurnal cycle. Therefore, it is important to merge data sets for the same variable from different satellites in time and space to create a consistent and comprehensive data set. Such a merged data set will have to ensure spatial continuity between data from different sensors and temporal continuity between data from different platforms. The goal of producing integrated satellite data products is featured in the IGOS-P (Integrated Global Observing Strategy – Partners) water cycle theme.

Process inter-relationships can be studied using data for different variables that are related to each other. For example the relationships between precipitation, soil moisture, surface temperature and vegetation could be studied. Changes in precipitation patterns in time and space will affect vegetation, soil moisture and surface temperature. However, land-atmosphere feedback effects could result in these affected variables (vegetation, soil moisture and surface temperature) changing the precipitation patterns. Such feedbacks could be positive, i.e. changes in precipitation results in changes in the land surface variables that, in turn, could further change the precipitation. A negative feedback would result in a damping effect rather than amplification as described above. All of these variables can be estimated from satellite data. Precipitation can be derived from TRMM, SSM/I, TOVS and AIRS/AMSU; soil moisture from AMSR; surface temperatures from many sources as noted above and vegetation from AVHRR and MODIS. Regional scale process studies would focus on understanding the spatial distribution of these variables and the diurnal, seasonal and inter-annual variations. These studies will provide useful comparisons with models for process interrelationships and will lead to better model parameterizations at a variety of space and time scales.

10.6. Support to the Coordinated Enhanced Observing Period (CEOP)

As discussed in Chapter 8, GAPP along with the other GEWEX CSEs will carry out enhanced measurements with in-situ systems as part of CEOP. Remote sensing will be combined with these data sets in studies to validate satellite algorithms used for retrieval of land surface variables. To advance these studies, scientists will need access to satellite data in user-friendly formats. In addition, the availability of spatially distributed satellite data will be used in the interpolation of these point-based measurements. Satellite data are available at specific times of the day but spatially continuous. Field measurements are at a point in space but temporally continuous. Therefore, analysis schemes and data assimilation systems need to be developed that use the spatial continuity of satellite data and the temporal continuity of the field measurements to create data sets that can be used for various process studies. Variables that will be the focal points of these studies include (but should not be limited to) soil moisture, surface temperature, precipitation, air temperature, and specific humidity near the surface. These variables will come from a variety of satellite sensors including AMSR, AIRS/AMSU, MODIS, GOES, TOVS, AVHRR, SSM/I, TMI, and ASTER.

11. GAPP DATA MANAGEMENT

To accomplish GAPP goals and science objectives a comprehensive and accessible observational database for new areas being addressed in the Continental-scale GAPP study area will be developed, and an evolving program of model development will be established. GAPP will enable observations and analyses to be extended spatially within the coterminous USA or applied globally. These data sets will consist primarily of relevant data from existing in situ, remote sensing, and model output sources and will also include special (surface, upper air, and satellite) meteorological and hydrological observations with increased spatial and temporal resolution as provided through GAPP and GAPP-related field campaigns. Some retrospective data sets may be necessary for development of hypotheses, parameterizations and models, and for determining the stability of inmterannual variability relationships across multi-decadal time scales.

While GAPP researchers will produce individual unique data sets for hydrological and atmospheric studies during the course of the project, most of the data of interest will be collected routinely from operational sources or accessed through established data centers. However, GAPP will make arrangements to ensure that relevant “orphan” data sets (i.e. smaller regional and local networks) will be archived and made available through the GAPP database. GAPP will take advantage of the infrastructure and information base produced by GCIP, which relied upon and enhanced existing operational/research meteorological and hydrological networks that have been upgraded with facilities such as doppler radars, wind profilers, automatic weather stations, and soil moisture measurements. GAPP will support the development of specialized data sets.

The GAPP data management strategic plan will take advantage of the work accomplished by GCIP. In particular, Volume I of the GCIP Implementation Plan (IGPO, 1993) contains information that (1) identified the sources of observations from existing and planned networks; (2) suggested further enhancements of those networks where necessary; and (3) assisted in developing data sets accumulated from existing observational systems and derived from operational model outputs, such as the NOAA/NCEP Eta operational model. In addition, the strategic portion of the data management planning (IGPO, 1994) outlines some implementation strategies that could help GAPP data collection and management objectives.

The cost for data management and services, including data reproduction costs, will be kept to a minimum, primarily through use of distributed data archives and existing data centers. The initial compilation of metadata will be carried out by the Project. Priorities for data sets needed for general use by investigators will be negotiated with program management. For purposes of priorities and costing, there are three types of compiled data sets, referred to as standard, custom, and as requested.

A standard data set is one whose specifications are agreed to before the data collection period starts so that standing orders can be provided to the data centers. The specifications will be determined and negotiated at the project level on a year-by-year basis. The primary purpose of the standard data sets is to give wide distribution, both nationally and internationally, to specific GAPP data so as to encourage GAPP relevant analysis, research, and modeling studies.

A custom data set is one that is either distributed from or compiled at a central location and will be made easily accessible for a group research effort. Applications of custom data sets include validation or intercomparison of algorithms, energy and water budget studies, and model evaluation studies. The primary purpose of the custom data sets is to facilitate "group" research efforts on GAPP relevant topics. The specifications for custom data sets will be agreed to by the group requesting the data set and the Project.

The primary purpose of “as requested” data sets is to enable GAPP PIs to order a data set with individual specifications from any of the data sets listed in the GAPP master catalog or data set guides. The GAPP data and information service will assist the user in the compilation of information on data availability to facilitate ordering data sets to specification. The incremental costs for compiling and distributing an “as requested” data set will be borne by the PI making the request.

GAPP will take advantage of the capabilities at several existing data centers to implement a prototype data management system similar to the one developed for GCIP. This system will provide single-point access for search and order of GAPP data from data centers operated by different agencies with capability to transfer small data sets electronically from the data center to the user. Initially the GAPP data system will begin collecting information on the data and add the data services (access) capability as the project matures. The system will have the capability to implement “one-stop shopping” for data services using the World Wide Web (WWW) as a method of data access.

GAPP has established a Data Management Committee (DMC) to address a number of data related issues and activities. The DMC will report to the GAPP Scienece Advisory Group. The terms of reference of the DMC are as follows:

- Coordinate with the GAPP scientific community through the SAG and other GAPP working groups to define the needs for GAPP data and for other data to be used by GAPP PIs,
- Design a distributed data management system to provide access to existing data sets,
- Prepare a data management plan describing the GAPP data strategy and implementation,
- Review and recommend augmentation of existing GCIP data sets to include the continental-scale region required of GAPP.
- Recommend assembly and oversee the production of new data sets as needed to achieve the GAPP objectives,
- Oversee the collection of data to ensure a permanent archive upon completion of the program, and
- Coordinate and collaborate with other field projects/programs.

The Data Management Committee will also play an important role in defining and developing strategies for meeting the needs of GAPP for data and data services.

12. LINKS WITH INTERNATIONAL AND NATIONAL PROGRAMS:

12.1. International Linkages

12.1.1. World Climate Research Programme (WCRP)

The World Climate Research Program (WCRP) fosters better understanding of global climate variability and change by pursuing its objective "to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of man's influence on climate." It sponsors three "major projects" that are important for GAPP, including GEWEX (the Global Energy and Water Cycle Experiment), ACSYS/CLiC, the Arctic Climate System Study, and CLIVAR (Climate Variability and Predictability).

12.1.1.1 GEWEX

GEWEX studies "atmospheric and thermodynamic processes that determine the global hydrological cycle and regional water budgets and their adjustment to global changes such as the increase in greenhouse gases." GEWEX coordinates research designed to understand, model and predict radiative processes involving cloud, aerosol, and water vapor and their impact on radiation transfer and radiation flux divergence in the atmospheric column. GEWEX also has a major focus on hydrometeorological processes involving the transport and release heat in the atmosphere, precipitation, evapotranspiration and land surface energy and mass exchanges, such as water storage on and near the surface and run-off. Within WCRP, GEWEX is the sole program with a major focus on land surface processes, and for this reason a major focus of GEWEX activities involves understanding and modeling land surface hydrology at continental and regional scales.

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. GEWEX initially encouraged a suite of exploratory studies over relatively small experimental sites, involving intensive field observations and theoretical process modeling, like FIFE (First ISLSCP Field Experiment, conducted at a Kansas grassland site in the mid 1980s), a study organized by the GEWEX International Satellite Land Surface Climatology Project (ISLSCP).

Just as GCIP was a central program in GEWEX, GAPP will continue strong ties to GEWEX, particulary through the GEWEX Hydrometeorology Panel. GAPP will provide leadership for GHP predictability studies. It will address many of the issues of concern to GEWEX and will become the GEWEX flagship activity for linking its global products and understanding to regional users and applications. GAPP will take a leadership role in meeting the objectives of the GHP Global Applications and Transferability Strategy, using its links with US Agencies to the mutual benefit of WCRP/GEWEX and those agencies. Within GHP, GAPP will also develop strong ties with LBA for predictability and model transferability studies, MAGS and BALTEX for model transferability studies, and GAME for remote sensing and model transferability initiatives. Scientific initiatives under discussion/implementation include a transferability study in the SAGE area and the Lake Winnipeg drainage basin (including the Red River of the North) and the la Plata Basin. GAPP will also contribute to GHP and GEWEX through contributions to the Water Resources Applications Project (WRAP) and through individual projects such as MOPEX and data set development.

Within the World Climate Research Programme, GEWEX is the "parent" of GCIP and GAPP. GCIP was initially formulated as the sole Continental Scale Experiment, and has been, in some respects, the model for the other CSEs. GEWEX has always had the goal of transferring improved process understanding, as embodied in models, data products, and predictive tools, to the water resources community. At the Honolulu SSG meeting (February, 2000) GEWEX renewed its commitment to activities in the water resources area, especially the evaluation and implementation of long-lead climate forecasts. As the "flagship" CSE, GCIP/GAPP will leadGEWEX in this area. The GAPP hydrology and water resources activities are designed in part to fill this need.

GAPP will also maintain strong ties to the CLIVAR program through VAMOS. CLIVAR tends to look to GEWEX to provide the land components for monsoonal studies. GAPP will be an important component of VAMOS in the same way that GCIP has been. In addition, a joint CLIVAR/PACS/GAPP modeling panel will be established in order to develop a joint modeling strategy that includes both land and ocean-atmosphere feedbacks. GAPP will also assist in assessing and interpreting CLIVAR and GEWEX prediction products for water resource management applications.

12.1.1.2. CLIVAR

The overall scientific objectives of CLIVAR are to (1) describe and understand the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal and centennial time scales, through the collection and analysis of observations and the development and application of models of the coupled climate system, in co-operation with other relevant climate research and observing programs; (2) extend the record of climate variability over the time scales of interest through the assembly of quality-controlled paleoclimatic and instrumental data sets; (3) extend the range and accuracy of seasonal-to-interannual climate prediction through the development of global coupled predictive models; (4) understand and predict the response of the climate system to increases of radiatively active gases and aerosols, and (5) compare these predictions to the observed climate record in order to detect the anthropogenic modification of the natural climate signal.

In the Pacific Sector, the Pan American Climate Study (PACS) and the Variability of the American Monsoon System (VAMOS) programs are under active development, and will be included within U.S. CLIVAR. The overall goal of PACS is to advance the understanding of seasonal and longer time scale phenomena needed to extend the scope and skill of climate prediction over the Americas, with emphasis on warm season precipitation. PACS is concentrating on the North American monsoon, including the structure and variability of the continental scale mode and the mechanisms that generate warm season precipitation anomalies. PACS is specifically concerned with explaining climatological characteristics of the atmospheric hydrologic cycle, including the relationship of the eastern Pacific coastal stratus and continental precipitation, as well as the influence of ocean and land surfaces on seasonal predictability.

12.1.1.3. ACSYS/CLiC

At present, ACSYS is transitioning from a regional (Arctic drainage basin) activity to a global focus. The new WCRP programme that is replacing ACSYS, is known as Climate and Cryosphere (CLiC). CLiC will incorporate ACSYS sea ice and oceanographic activities in the Arctic, which will be expanded to include Antarctic research in these areas, as well as glaciers and ice sheets. Beyond shifting from a Boreal to a bipolar focus, CLiC will also include relevant cold season and regions processes elsewhere, such as glaciers in temperate regions, permafrost, and ephemeral snow cover over the GAPP region. At its annual meeting in March, 2000, the WCRP Joint Scientific Committee approved the draft CLiC Science and Coordination Plan.

12.1.2. International Geosphere-Biosphere Program

The objective of the International Geosphere Biosphere Programme (IGBP) is "… to describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human activities." GAPP linkages wth IGBP are primarily through Biological Aspects of the Hydrological Cycle (BAHC).

The BAHC core project addresses the nature of the interaction between vegetation and the hydrologic cycle. BAHC is an interdisciplinary project combining and integrating expertise from many disciplines, in particular ecophysiology, pedology, hydrology, and meteorology. In this respect BAHC cuts across disciplines as well as across spatial scales. At smaller scales, BAHC is involved in developing techniques and algorithms to provide climatic data needed at the scales used to study changes of land surface conditions. At larger scales, BAHC provides soil-vegetation-atmosphere transfer models, in particular, the areal pattern of heat and moisture fluxes according to land-surface heterogeneity. BAHC is involved in these activities in a number of selected areas in the world, representing major ecosystems.

12.1.3. UNESCO

As indicated in Section 9.4.3, GAPP will also contribute to the UNESCO/WMO Hydrology for Environment Life and Policy (HELP) initiative by contributing to a modeling framework for HELP, using their data sets in model development and providing a link between the international water research community and climate modelers. HELP is a joint project developed under the guidance of UNESCO and endorsed by a number of agencies including WMO and the IGBP. HELP has been established to deliver social, economic and environmental benefits to stakeholders through sustainable and appropriate use of water by directing hydrological science towards improved integrated catchement management. HELP is a proactive program aimed at preparing appropriate strategies to capture climate variability and thereby provide better advice for the development of water policy. It will also address issues related to global change at the watershed scale. The agenda for research under this program is being developed through a working partnership between water policy and management and the research community. Two GAPP basins have been accepted by the HELP program, namely the San Pedro basin in the Southwest and the Red Arkansas Basin. It is believed that the dialogue that will be needed to implement these HELP basins will advance the goals of GAPP in the area of water resource applications.

In order to be an effective HELP project each of these catchments must provide an opportunity to study a water policy or water management issue for which hydrological process studies are needed; relevant national and local agencies must agree to cooperate in the execution of HELP; there must be adequate local capacity to participate in the program as a full partner; a minimum range of key variables and parameters must be monitored; data, information and technological expertise must be shared openly; and HELP data standards, quality assurance and quality control must be adhered to.

Recently UNESCO and the World Water Council established a new program known as the World Water Assessment Programme to undertake assessments on a routine basis. This initiative relies on good scientific inputs and techniques to effectively carry out its assessments. GAPP will contribute the scientific basis for the work done in the USA and through transferability studies to scientific efforts undertaken on a world wide basis in the assessment of water resources.

12.2 National Programs:

12.2.1. United States Weather Research Program (USWRP)

The U.S. Weather Research Program (USWRP) provides a research focus for the ongoing modernization of the National Weather Service. USWRP is attempting to improve the specificity, accuracy, and reliability of weather forecasts using the best possible mix of modern observations, data assimilation, and forecast models. In particular, USWRP's goal is to improve forecasts of high impact weather for agriculture, construction, defense, energy, transportation, public safety (emergency management), and water resource management, including floods. USWRP is especially concerned with studies related to quantitative precipitation forecasting. These studies include the measurement, estimation and depiction of water vapor, representation of convection in forecast models, and estimation of precipitation amount and type by radar and satellite. USWRP has also begun to consider the control on extreme events by surface effects, including soil and vegetation canopy effects. These weather prediction research efforts complement GAPP's regional climate activities. In addition, USWRP's studies related to quantitative precipitation forecasting will help GAPP understand how to make better use of NEXRAD products. The USWRP is also beginning to coordinate its activities with the World Weather Research Programme, which is currently exploring a formal linkage with GEWEX through WMO/WCRP.

12.2.2. EOS

The Earth Observing System (EOS), in planning since the 1980s, is a NASA program (with national and international collaborators) that has entered a new stage with the launch of Terra (formerly known as EOS-AM) in December 1999 and AQUA in May 2002. A significant part of the EOS program is focused on observation of atmospheric and land surface phenomena, with the goal of better understanding the dynamics of the Earth's physical climate. NASA has been a major supporter of field projects, modeling, and data assimilation activities aimed at better representing the coupled land-ocean-atmosphere system. These studies have included, for instance, intensive field campaigns like FIFE, the BOReal Ecoysystem-Atmosphere Study, and LBA, which integrated in situ observations with aircraft and satellite remote sensing. The International Satellite Land Surface Climatology Project (ISLSCP) has had major support from NASA. NASA also provides data products and analyzed fields essential to the success of GAPP, notably diagnostics of cloud amount and properties through the International Satellite Cloud Climatology Project (ISCCP), surface radiation flux estimates (Langley Research Center), and soil/hydrology/vegetation data (Huntsville Global Hydrology and Climate Center). Conversely, it is expected that GAPP multi-disciplinary studies and data products will provide a high quality benchmark for the validation of EOS observations for Terra, Aqua, and other missions like the Tropical Rainfall Monitoring Mission (TRMM).

12.2.3. Regional Integrated Sciences and Assessments:

NOAA, through its Office of Global Programs, supports integrated scientific assessments of the effects of climate variability and change on the natural and managed environment. These continuing projects are designed to characterize the state of knowledge of climate variations and changes at regional scales, to identify knowledge gaps and linkages in selected climate-environment-society interactions, and to provide an informed basis for responding to climate-related risks. At present, there are five regional integrated science assessments funded by NOAA-OGP. These assessments are focused on the Pacific Northwest, the Southwest, California, the Inter-Mountain West, and the Southeast regions of the United States. In addition, other agencies are funding assessment studies in other parts of the United States.

12.2.4. Advanced Hydrologic Prediction Systems

Within the National Weather Service Office of Hydrology (NWS/OH), the Advanced Hydrological Prediction System (AHPS) is seeking to improve the state of the art of hydrologic prediction as applied primarily to flood forecasting. Although NWS/OH does not formally suppport extramural research, it is cooperating with the academic community in the development of AHPS, in particular through an evolving partnership with GAPP. Details of this partnership are provided in Chapter 9.

12.2.5. Atmospheric Radiation Program (ARM)

The Department of Energy funds the Atmospheric Radiation Measurement (ARM) program, which is intended to improve understanding of the transfer of radiation through the atmosphere. A central ARM component is the Cloud and Radiation Testbed (CART) concept, which is currently underway at sites in the Southern Great Plains (SGP) of south central Kansas and central Oklahoma, the North Slope of Alaska, and at a Tropical Western Pacific site. The CART sites provide surface radiation flux data and boundary layer soundings at multiple observing locations. Enhanced observations are collected during Intensive Observation Periods (IOP) of a few weeks, several times during each year. At the SGP CART site, observations are coordinated with GAPP studies of summer rainfall and re-evaporation.

12.2.6. NASA Seasonal-to-Interannual Prediction Project (NSIPP)

NSIPP is a project of NASA's Goddard Space Flight Center (GSFC). It has the goal of developing an experimental short-term climate prediction capability, and focuses on demonstrating the utility of satellite data, especially altimeter, air-sea flux and soil moisture observations, in a coupled land-atmosphere-ocean modeling framework. A major thrust of NSIPP is the assimilation of satellite data into the GSFC coupled atmosphere-ocean-land-ice modeling system, for the purpose of predicting not only the short term climate variations associated with SST variations in the tropical Pacific, but also those processes and teleconnections that have socio-economic impacts on the United States. There are significant opportunities for GAPP interactions with NSIPP, particularly through exploitation of opportunities for climate forecast improvements using satellite data. Furthermore, NASA, through its Land Surface Hydrology Program, has been a major source of funding for GCIP in recent years, and will play a role in coordinating relevant GAPP activities with NSIPP. However, the NSIPP interest is in global and regional climate prediction; consequently it does not have a significant activity in the macroscale hydrologic modeling or water resources. In is also expected that GAPP will play a similar role in US climate modeling activities emerging at GFDL.

13. PROGRAM IMPLEMENTATION

GAPP is being phased in as GCIP is being phased out. This transition must be smooth to ensure that the GCIP community and the principal funding agencies, NOAA and NASA, derive the full benefits of the investment they have made in GCIP. The management of GAPP will be built on the successful aspects of the GCIP management structure. In particular GAPP will have:

- Scientific Steering Committee (SSC) (whose members will be chosen from the scientists currently working with GCIP/ GAPP and other scientists specializing in related subject areas such as predictability) as well as a data committee and a number of working groups, including one dealing with warm season precipitation, that would report possibly to both the GAPP SSC and the PACS SSC.

- A link with the US Global Water Cycle (GWC) Initiative and the infrastructure developed to support that program (e.g. GWC Scientific Steering Group, GWC program office, GWC Interagency Working Group). The GWC program office will provide liaison with funding agencies, the scientific committee, and where appropriate, international bodies. It will also organize planning and science meetings, coordinate the preparation of program plans, develop syntheses of the scientific results, provide information to PIs through newsletters, information bulletins and a home page, coordinate evaluations, and provide scientific and programmatic advice to federal funding agencies.

The time line for GAPP implementation is shown in Figure 13.1.

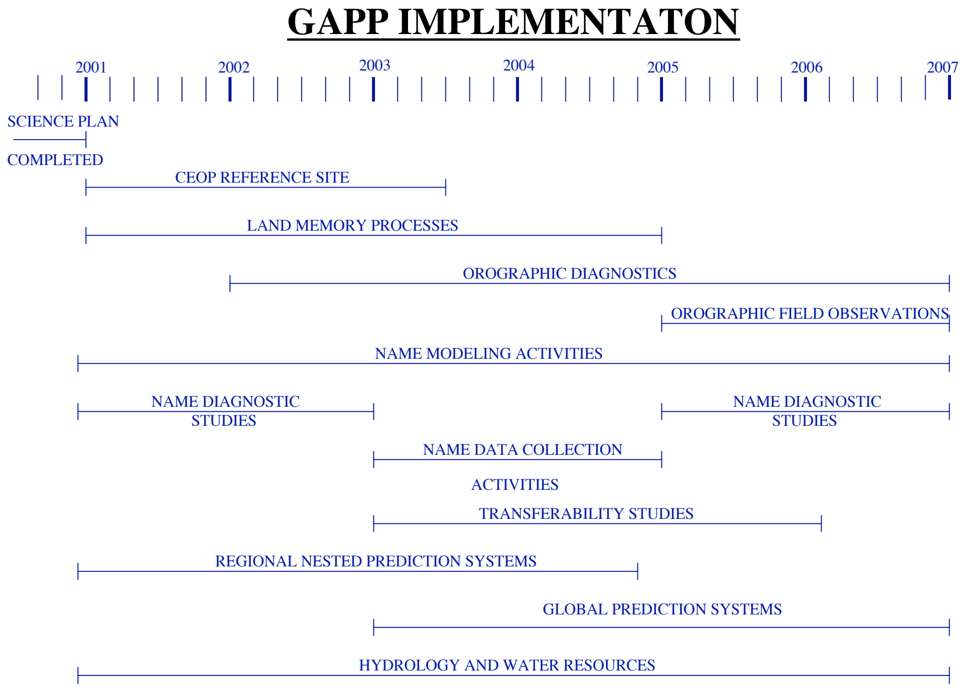

Figure 13.1. The time line for GAPP implementation.

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APPENDIX A: PROPOSED GAPP MILESTONES

2002: Products from a land data assimilation system available for climate research.

2002: Completion of the GAPP Implementation Plan.

2003: An assessment of the best approach for working with water resource agencies and organizations based on demonstration projects linking climate predictions and water resource management in the Mississippi River Basin

2004: Modified land surface and hydrologic models based on data and process studies in arid regions.

2004: Initial data sets available from CEOP for the GAPP community.

2004: An understanding of the role of land processes in the North American Monsoon.

2005: Initial results from model transferability studies based on data from the WCRP/ GEWEX Coordinated Enhanced Observing Program.

2005: Modified land surface and hydrologic models based on data and process studies in the western Cordillera.

2005: Data sets from NAMS available for the scientific community.

2006: Development of an integrated land surface model that accounts for the different processes found in the GEWEX Continental-scale Experiments and the utilization of these models together with global models in a nested mode.

2006: An integrated approach for modeling surface and subsurface hydrology in climate models.

2006: An understanding of the role of land in the dynamics and thermodynamics of the Low Level Jet in the central USA and its contribution to the climate of the USA on time scales up to annual.

2007: Assessment of the integrated effects of land-atmosphere processes for North America and the world.

2007: Through collaboration with CLIVAR, successful testing of a global climate prediction system that properly accounts for land-atmosphere coupling.

2007: Delivery of meaningful hydrologic prediction products through participation in the WMO/UNESCO Hydrology for Environment, Life and Policy (HELP)

APPENDIX B: ACRONYMS

4DDA	Four Dimensional Data Assimilation
ACSYS/CLIC	Arctic Climate System Study/ Climate and Cryosphere
ADEOS	Advanced Earth Observation Satellite
AHPS	Advanced Hydrologic Prediction Service
AIRS	Advanced Infrared Sounder
ALLS	American Low-Level Jets
AMERIFLUX	American Flux (Network)
AMSR	Advancd Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AMTEX	America's Model Transferability Experiments
ARM	Atmospheric Radiation Measurement
ASCOT	DOE's Atmospheric Studies in Complex Terrain
ASTER	Advanced Spaceborne Thermal and Reflection Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AZNM	Arizona/ New Mexico
BAHC	Biological Aspects of the Hydrological Cycle
BALTEX	Baltic Sea Experiment
BATS	Biosphere-Atmosphere Transfer Scheme
BoR	Bureau of Reclamation
BOREAS	Boreal Ecosystem-Atmosphere Study
CART	Clouds and Radiation Testbed
CASES	Cooperative Atmosphere-Surface Exchange Study
CATCH	Coupling of the Tropical Atmosphere and Hydrological Cycle
CCN	Cloud Condensation Nuclei
CEOP	Coordinated Enhanced Observing Period

CERES	Clouds and the Earth's Radiant Energy System
CLIVAR	Climate Variations
CLL-JET	California Low Level Jet
CLM	Common Land Model
CMC	Canadian Meteorological Centre
COARE	Coupled Ocean-Atmosphere Response Experiment
COHS	Committee on Hydrological Sciences
COLA	Center for Ocean, Land Atmosphere
CPC	Climate Prediction Center
CPTEC	Center for Weather Prediction and Climate Studies
CSE	Continental Scale Experiment
CSU	Colorado State University
DAAC	Distributed Active Archive Center
DAO	Data Assimilation Office
DMIP	Distrubuted Model Intercomparison Project
DOE	Department of Energy
ECMWF	European Center for Medium Range Weather Forecasts
EDAS	Eta Model Data Assimilation System
ENSO	El Niño Southern Oscillation
ENVISAT	Environmental Satellite, European Space Agency
EOS	Earth Observing System
FIFE	First ISLSCP Field Experiment
FSL	Forecast Systems Laboratory
GAME	GEWEX American Monsoon Experiment
GAPP	GEWEX Americas Prediction Project
GCIP	GEWEX Continental-scale International Project

GCLLJ	Gulf of California Low Level Jet
GCM	General Circulation Model
GDAS	Global Data Assimilation System
GEM	Global Environmental Multi-scale Model
GEWEX	Global Energy and Water Cycle Experiment
GHP	GEWEX Hydrometeorology Panel
GLASS	GEWEX Land Atmosphere Simulation System
GLSM	Global Land Surface Model
GOC	Gulf of California
GOES	Geostationary Operational Environmental Satellite
GPLLJ	Great Plains Low Level Jet
GSFC	Goddard Space Flight Center
GSWP	Global Soil Wetness Project
GWEC	Global Water and Energy Cycle
HELP	Hydrology for Environment, Life and Policy
IBIS	Integrated Biosphere Simulator
IGBP	International Geobiosphere Program
IGOS	Integrated Global Observing Strategy
IGPO	International GEWEX Project Office
IMPROVE	Improvement of Microphysical Parameterization through Observational Verification Experiment
INSAT	Indian Satellite, India
IOP	Intensive Observational Period
IPCC	Intergovernmental Panel on Climate Change
IPEX	Intermountain Precipitation Experiment
IRI	International Research Institute

ISA	Intermediate Scale Study Area
ISLSCP	International Land Surface Satellite Climatology Project
ITCZ	Intertropical Convergence Zone
LAI	Leaf Area Index
LBA	Large Scale Biosphere-Atmosphere Experiment in Amazonia
LBC	Lateral Boundary Condition
LDAS	Land Data Assimilation System
LLJ	Low-Level Jet
LLNL	Lawrence Livermore National Laboratory
LSA	Large Scale Area
LSM	Land Surface Model
JMC	Japanese Meteorological Center
MAGS	Mackenzie GEWEX Study
MAP	Mesoscale Alpine Program
MAPS	Meterological Analysis and Prediction System
MSC	Meteorological Services of Canada
MHM	Macroscale Hydrologic Model
MJO	Madden Julian Oscillation
MODIS	Moderate Resolution Imaging Spectroradiometer
MOPEX	Model Parameter Estimation Experiment
NAME	North American Monsoon Experiment
NAMS	North American Monsoon System
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction

NDVI	Normalized Difference Vegetation Index
NEXRAD	Next Generation Radar
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NSIPP	NASA Seasonal-to-Interannual Prediction Project
NWP	Numerical Weather Prediction
NWS	National Weather Service
NWSRFS	National Weather Service River Forecast System
ODAE	Ocean Data Assimilation Experiment
OGP	Office of Global Programs
OH	Office of Hydrology
PACS	Pan American Climate Studies
PDO	Pacific Decadal Oscillation
PI	Principal Investigator
PILPS	Project for the Intercomparison of Land Surface Parameterization Schemes
PNA	Pacific North American (Teleconnection)
PNW	Pacific Northwest
PRISM	Parameter Elevation Regressions on Independent Slopes Model
QPF	Quantitative Precipitation Forecasts
RAMS	Regional Atmospheric Modeling System
RAP	Regional Applications Project
RISA	Regional Integrated Science and Assessment
RMM	Regional Mesoscale Model
SALSA	Semi-Arid Land Surface Atmosphere Program

SAGE	Saskatchewan and surrounding Area GEWEX Experiment
SGP	Southern Great Plains
SIMAP	Seasonal to Interannual Modeling and Prediction (SIMAP) Panel Of US CLIVAR
SSC	Scientific Steering Committee
SSiB	Simple Biosphere Model
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
SSTA	Sea Surface Temperature Anomaly
SVATS	Soil-Vegetation-Atmosphere Transfer Scheme
TEW	Tropospheric Easterly Wave
TMI	TRMM Microwave Imager
TOGA	Tropical Ocean Global Atmosphere
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Monitoring Mission
URL	Unified Resource Locator
UNESCO	United Nations Education Science and Culture Organization
USA	United States of America
USACE	US Army Corps of Engineers
USDA	United States Department of Agriculture
USGCRP	United State Global Change Research Program
USGS	United States Geological Survey
USWRP	United States Weather Research Program
VAMOS	Variability of the American Monsoon System
VCL	Vegetation Canopy Lidar
VEPIC	VAMOS Eastern Pacific Investigation of Climate Processes and

	the Coupled Ocean-Atmosphere System
VTMX	Vertical Transport and Mixing Experiment
WCRP	World Climate Research Programme
WMO	World Meteorological Association
WWW	World Wide Web

Appendix C: The North American Monsoon System

C.1 Life Cycle

The life-cycle and large-scale features of the NAMS can be described using terms typically reserved for the much larger Asian Monsoon system; that is, we can characterize the life-cycle in terms of development, mature and decay phases. The development (May-June) phase is characterized by a period of transition from the cold season circulation regime to the warm season regime. This is accompanied by a decrease in mid-latitude synoptic-scale transient activity over the conterminous United States and northern Mexico as the extratropical storm track weakens and migrates poleward to a position near the Canadian border by late June (e.g. Whittaker and Horn 1981; Parker et al. 1989). During this time there are increases in the amplitude of the diurnal cycle of precipitation (e.g. Wallace 1975; Higgins et al. 1996) and in the frequency of occurrence of the Great Plains low-level jet (e.g. Bonner 1968; Bonner and Paegle 1970; Augustine and Caracena 1994; Mitchell et al. 1995; Helfand and Schubert 1995; Higgins et al. 1997). The onset of the Mexican Monsoon (Douglas et al. 1993; Stensrud et al. 1995) is characterized by heavy rainfall over southern Mexico, which quickly spreads northward along the western slopes of the Sierra Madre Occidental into Arizona and New Mexico by early July. Precipitation increases over northwestern Mexico coincide with increased vertical transport of moisture by convection (Douglas et al. 1993) and southerly winds flowing up the Gulf of California (Badan-Dagan et al. 1991). Increases in precipitation over the southwestern United States coincide with the development of a pronounced anticyclone at the jet stream level (e.g. Okabe 1995), the development of thermally induced trough in the desert Southwest (Tang and Reiter 1984; Rowson and Colucci 1992), northward displacements of the Pacific and Bermuda highs (Carleton 1986; 1987), the formation of southerly low-level jets over the Gulf of California (Carleton 1986; Douglas 1995), the formation of the Arizona monsoon boundary, and increases in eastern Pacific sea surface temperature gradients (Carleton et al. 1990). From June to July there is also an increase in sea-level pressure over the southwestern United States (Okabe 1995) and a general increase in pressure level heights in mid-latitudes associated with the seasonal heating of the troposphere. The largest increases in height occur over the western and southern United States and are likely related to enhanced atmospheric heating over the elevated terrain of the western United States and Mexico and increased latent heating associated with the development of the Mexican Monsoon. The resulting middle and upper tropospheric "monsoon high" is analogous to the Tibetan High over Asia (e.g. Tang and Reiter 1984) and the warm season Bolivian High over South America (e.g. Johnson 1976).

During the mature (July-August) phase, the NAMS is fully developed and can be related to the seasonal evolution of the continental precipitation regime. The monsoon high is associated with enhanced upper tropospheric divergence in its vicinity and to the south, and with enhanced easterlies (or weaker westerlies) and enhanced Mexican Monsoon rainfall (Douglas et al. 1993). To the north and east of the monsoon high, the atmospheric flow is more convergent at upper levels and rainfall diminishes from June to July in the increasingly anticyclonic westerly flow (e.g. Harman 1991). Surges of maritime tropical air northward over the Gulf of California are linked to active and break periods of the monsoon rains over the deserts of Arizona and California (Hales 1972). The mature phase has also been linked with increased upper-level tropospheric divergence and precipitation in the vicinity of an "induced" trough over the eastern United States.

The decay (September-October) phase of the NAMS can be characterized as the reverse of the onset phase, although the changes tend to proceed at a slower rate. During this phase the ridge over the western United States weakens as the monsoon high retreats southward and Mexican Monsoon precipitation diminishes. The decay phase is also accompanied by an increase in rainfall over much of the surrounding region (Okabe 1995).

Numerous authors have attempted to identify the primary source of moisture for the summer rains over the southwestern United States. Bryson and Lowery (1955) suggested that horizontal advection of moist air at middle levels from the east or southeast around a westward extension of the Bermuda high might explain the onset of summer rainfall over the southwest; this was later corroborated by Sellers and Hill (1974). Several authors (Hales 1972, 1974; Brenner 1974; Douglas et al. 1993) expressed skepticism for this type of explanation, because moisture from the Gulf of Mexico would first have to traverse the Mexican Plateau and Sierra Madre Occidental before contributing to Arizona rainfall. Rasmusson (1966; 1967) was among the first to show a clear separation between water vapor east of the continental divide, which clearly originates from the Gulf of Mexico/Caribbean Sea, and moisture over the Sonoran Desert that appears to originate from the Gulf of California. Schmitz and Mullen (1996) examined the relative importance of the Gulf of Mexico, the Gulf of California, and the eastern tropical Pacific as moisture sources for the Sonoran Desert using ECMWF analyses. They found that most of the moisture at upper levels over the Sonoran desert arrives from over the Gulf of Mexico, while most of the moisture at lower levels comes from the northern Gulf of California.

Berbery (2000) used the Eta model Data Assimilation System (EDAS) to show that the diurnal cycle in moisture flux divergence over the core monsoon region is related to the diurnal cycle in the sea breeze/land breeze circulation. In particular, the afternoon seabreeze is associated with strong moisture flux divergence over the Gulf of California and strong moisture flux convergence over the west slopes of the Sierra Madre Occidental leading to intense afternoon and evening precipitation (Fig. C.1). At night the land breeze develops, leading to moisture flux convergence near the coastline and over the Gulf of California where morning precipitation often develops.

C.2 Continental-scale Precipitation Pattern

The onset of the summer monsoon rains over southwestern North America has been linked to a decrease of rainfall over the Great Plains of the U.S. (e.g., Tang and Reiter 1984; Douglas et al. 1993; Mock 1996; Higgins et al. 1997) and to an increase of rainfall along the East Coast (e.g., Tang and Reiter 1984; Higgins et al. 1997). Okabe (1995) has shown that phase reversals in this continental-scale precipitation pattern are related to the development and decay of the monsoon. Changes in the upper-tropospheric wind and divergence fields (mean vertical motion) are broadly consistent with the evolution of this precipitation pattern (Higgins et al. 1997).

Recently, Higgins et al. (1998) demonstrated that interannual variability of the continental-scale precipitation pattern closely mimics the seasonal changes associated with the development of the NAMS, suggesting that summer drought (flood) episodes in the central U.S. are linked to an amplification (weakening) of the NAMS and, in particular, to the intensity of the monsoon anticyclone over the southwestern U.S. It is important to determine to what extent this pattern is captured in global and regional models.

C.3 Interannual Variability

There is a growing body of modeling and observational evidence that slowly varying oceanic boundary conditions (i.e., SST, sea ice) and land boundary conditions (e.g. snow cover, vegetation, soil moisture and ground water) influence the variability of the atmospheric circulation on time scales up to seasonal and annual (e.g. Yasunari 1990; Yasunari et al. 1991; Yasunari and Seki 1992). Within the context of the NAMS, Higgins et al. (1998) showed that wet (dry) summer monsoons in the southwestern U.S. tend to follow winters characterized by dry (wet) conditions in the southwestern U.S. and wet (dry) conditions in the northwestern U.S. (Fig. C.2). This association was attributed, at least in part, to the wintertime pattern of Pacific SST anomalies (SSTA) which provide an ocean-based source of memory of antecedent climate fluctuations.

A number of studies have considered the simultaneous relationship between SST in the tropical Pacific and NAMS rainfall. Harrington et al. (1992) found significant correlations between the phase of the southern oscillation and AZNM precipitation. Hereford and Webb (1992) suggested a relationship between increased summer precipitation in the Colorado plateau region and the warm phase of ENSO. During the summer season other studies have argued that more localized SSTA are important. Carleton et al. (1990) showed that the Southwest Monsoon is negatively correlated with SSTA along the northern Baja coast, while Huang and Lai (1998) found positive correlations with SSTA over the Gulf of Mexico. Ting and Wang (1997) found that SSTA in the North Pacific may also influence precipitation over the central United States.

Another possibility is that both winter and summer precipitation regimes are influenced by coherent patterns of SSTA that persist from winter to summer. Namias et al. (1988) emphasized that persistent SSTA patterns in the North Pacific are often associated with persistent atmospheric teleconnection patterns. They identified the region in the midlatitudes of the central North Pacific (near 40^o N) as being an important area where SSTA have an effect on circulation anomalies downstream over the U.S. Of particular relevance for the NAMS is the work of Carleton et al. (1990) who demonstrated that anomalously wet (dry) summers in Arizona tend to follow winters characterized by the positive (negative) phase of the Pacific-North America teleconnection pattern.

Monsoonal rains are also influenced by changes in land-based conditions that provide memory of antecedent hydrologic anomalies. Observational and modeling evidence indicates that the springtime snowpack across Eurasia modulates the amplitude of the

Asian monsoon rains in the following summer, such that heavy snowpack leads to a weak monsoon, and light snowpack leads to a strong monsoon (e.g., Barnett et al. 1989; Vernekar et al. 1995; Yang et. al 1996). Gutzler and Preston (1997) found an analogous relationship in North America such that excessive snow in the west-central U.S. leads to deficient summer rain in the Southwest and deficient snow leads to abundant summer rain.

Seasonal weather prediction has also been shown to be dependent, at least in portions of the land, on the soil moisture at the beginning of the growing season (Pielke et al. 1999) and the feedback between vegetation growth and rainfall (Eastman et al. 2000, Lu et al. 2000). This feedback may explain why correlations between ocean sea surface temperatures and rainfall over the Great Plains and southwest United States deteriorate during the warm season (Castro et al. 2000). The inclusion of models of the vegetation response to weather, and the subsequent feedback to rainfall and other weather variables, therefore, may improve seasonal weather prediction. To achieve this improvement, however, soil physics and vegetation dynamics must be included as seasonal weather variables in the same context as rainfall, temperature, and other atmospheric variables.

C.4 Decadal Variability

Latif and Barnett (1996) discussed two types of decadal variability in the North Pacific that may be relevant for the NAMS. The first is associated with the recent climate shift in the North Pacific in the mid-1970s (e.g. Trenberth and Hurrell 1994; Miller et al. 1994; Graham et al. 1994), which many authors agree is a manifestation of atmospheric forcing driving ocean variations. The second type is more oscillatory and involves unstable ocean-atmosphere interactions over the North Pacific as originally hypothesized by Namias (1959). Namias argued that SSTA in the North Pacific influence the atmospheric transients, hence the mean westerly flow, in such a way as to reinforce the original SSTA. Recent coupled GCM and observational studies (e.g. Latif and Barnett 1994; 1996) have implicated Namias' hypothesis in the decadal variability of the North Pacific-North American sector.

In a recent study Higgins and Shi (2000) argued that the summer monsoon in the southwest U.S. is modulated by longer term (decade-scale) fluctuations in the North Pacific SSTs associated with the Pacific Decadal Oscillation. They found that the mechanism relating the North Pacific wintertime SST pattern to the summer monsoon appears to be via the impact of variations in the Pacific jet on west coast precipitation regimes during the preceding winter . This mechanism affects local land-based sources of memory in the southwestern U.S., which in turn influence the subsequent timing and intensity of the summer monsoon.

Occasionally long-term (decade-scale) periods of persistent drought or rainy conditions occur in the southwestern U.S. The reasons for such climate anomalies are poorly understood, and the modulation of interannual variability by longer term climate fluctuations also needs to be examined as part of the broader effort to develop useful short-term climate prediction capabilities. At the present time it is unclear whether any of the links between the monsoon in the southwestern U.S. and antecedent conditions are robust enough to have a positive impact on the predictability of warm season precipitation. Nevertheless, these relationships need to be described and sorted out.

C.5 Intraseasonal Variability

The intensity of the seasonal mean monsoon is influenced by the nature of the variability within the monsoon season. Previous attempts to relate rainfall anomalies for the monsoon season to the date of onset of the Indian monsoon (e.g. Dhar et al. 1980) have generally shown little relationship, indicating that the intraseasonal variability of monsoon rainfall is quite large. In other words, a season with deficient monsoon rainfall does not imply an absence of rainfall for the whole season, but rather prolonged periods of reduced rainfall often referred to as "break" monsoons; prolonged periods of enhanced rainfall are referred to as "active" monsoons. Douglas and Englehart (1996) demonstrated that a dominant mode of variability of summer rainfall in Southwest Mexico was a tendency for an alternating wet-dry-wet period in the July-August-September time frame. The NAMS exhibits a pronounced double peak structure in precipitation and diurnal temperature range between the equator and the Tropic of Cancer (Fig. C.3) but the physical setting responsible for this intraseasonal variability remains elusive.

Stensrud et al. (1995) showed that a mesoscale model can simulate the observed features of the NAMS, including southerly low-level flow over the Gulf of California, the durnal cycle of convection, and a low-level jet that develops over the northern end of the Gulf of California. One particularly important mesoscale feature that the model reproduces is a gulf surge, a low-level, northward surge of moist tropical air that often travels the entire length of the Gulf of California. Common characteristics of these disturbances (Hales 1972 and Brenner 1974) include changes in surface weather (a rise in dewpoint temperature, a decrease in the diurnal temperature range, a windshift with an increased southerly wind component, and increased cloudiness and precipitation). Gulf surges appear to promote increased convective activity in Arizona and are related to the passage of Tropical Easterly Waves (TEWs) across western Mexico (Fig. C.4); (Stensrud et al. 1997; Fuller and Stensrud 2000).

Mesoscale low-pressure systems at the southern end of the Gulf of California may also be important in triggering gulf surges. In many cases, these lows result from northward excursions of the ITCZ in the east Pacific. Zehnder et al. (1999) hypothesize that easterly waves approach from the Caribbean and perturb the ITCZ from it's climatological mean position at 10°N. They also describe the case of an eastern Pacific tropical cyclone that formed on the eastern edge of the perturbed ITCZ.

The response of the ITCZ to the easterly wave forcing may depend on the phase of the Madden-Julian Oscillation (MJO). In particular, the westerly phase of the MJO may result in a larger vorticity of the ITCZ, consistent with Zehnder et al. (1999).

One aspect of the connection between gulf surges and TEWs that has not been explored systematically is the extent to which it may influence the interannual variability in the onset and intensity of the monsoon. Because TEWs and Gulf surges are most active during the summer months, they are most likely to play a role in the onset of the monsoon in the southwestern US, which typically begins in early July. In addition, the extent to which TEWs might help explain the midsummer transitions over southern Mexico and central America also needs to be explored.

In a recent study Higgins and Shi (2001) separated the dominant modes of intraseasonal and interannual variability of the North American monsoon system (NAMS) in order to examine MJO-related and ENSO-related influences on U.S. weather during the summer months. They found a strong relationship between the leading mode of intraseasonal variability of the NAMS, MJO, and the points of origin of tropical cyclones in the Pacific and Atlantic basins (Fig. C.5) which should be examined further.

C.6 Modeling

a. Limited-area models

In addition to the mesoscale modeling work of Stensrud et al. (1997) and Fuller and Stensrud (2000) discussed in the previous subsection, Small (2000) used the MM5 model linked to the OSU land surface scheme in season-long experiments designed to investigate the effects of soil moisture anomalies on the NAMS. Results showed that monsoon response to soil moisture anomalies depends strongly on the location of the surface forcing. Positive (negative) soil moisture anomalies within the NAMS region enhance (inhibit) summertime precipitation in that region, consistent with previous studies (e.g. Betts and Ball 1998). In contrast, positive (negative) soil moisture anomalies in the southern Rocky Mountains inhibit (enhance) monsoon precipitation, consistent with the findings of Gutzler and Preston (1997) regarding snow cover (hence soil moisture) effects on the NAMS.

b. Global models

Boyle (1998) analyzed the annual cycle of precipitation over the southwestern U.S. in output from 30 GCMs participating in the Atmospheric Model Intercomparison Project (AMIP) (Gates 1992). Results tended to improve with finer resolution, although fine resolution was neither necessary nor sufficient to produce a precipitation trend consistent with observations. Arritt et al. (2000) examined the NAMS in ten-year records for control climate and enhanced greenhouse-gas scenarios from the Hadley Centre coupled ocean-atmosphere GCM. They found that precipitation trends and dynamical response to the NAMS were reasonably well represented for current climate and that the NAMS signal was stronger in the greenhouse-gas scenario.

Yang et al. (2000) found that summertime precipitation associated with the NAMS was largely under represented in simulations using the NCAR Community Climate Model version 3 (CCM3) forced with prescribed sea surface temperatures. Diagnostic analyses suggest that excessive convection over the eastern Pacific and the Caribbean produces excess subsidence over much of northern Mexico and the southwestern United States, and prohibits the northward transport of atmospheric moisture into the NAMS region. Using an experimental semi-Lagrangian version of CCM3, Hahmann et al. (1999) carried out climate simulations at high (T63L and T127L) and ultra-high (T191L) resolutions. Over the Southwest United States, while the simulation of wintertime precipitation appears to improve with increased resolution, the southwest summer monsoon is consistently under represented.

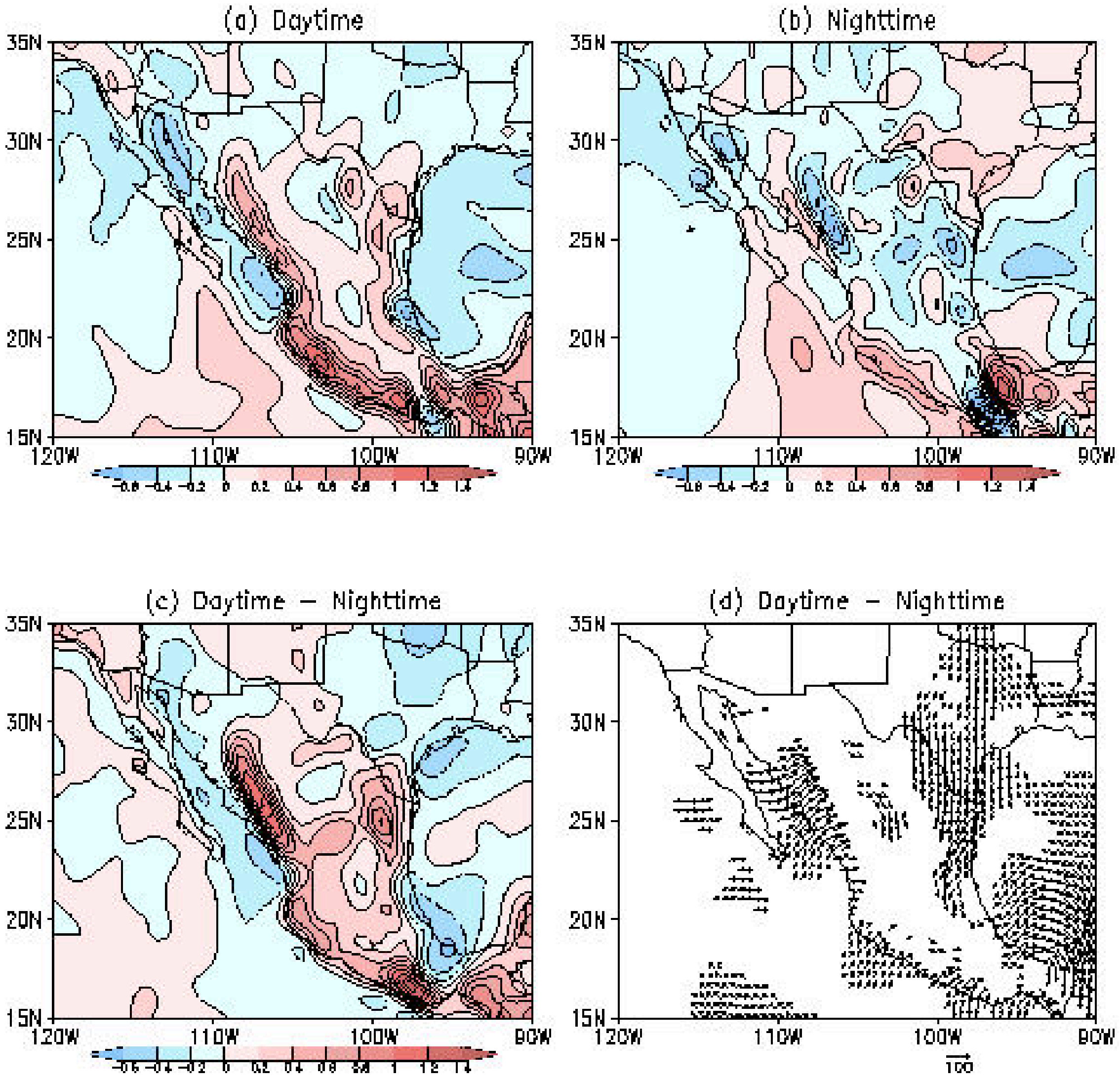

Figure C.1. Moisture flux convergence during (a) daytime, (b) nighttime , (c) their difference and (d) daytime minus nighttime difference in moisture flux. Daytime is defined as 18-24 UTC (11 a.m.-5 p.m. local time). Nighttime is defined as 6-12 UTC (11 p.m.-5 a.m. local time). Contour intervals in (a)-(c) are 0.2 mm hour^{-1} and positive values are shaded. The standard vector length is 100 kg (m s)$^{-1}$ and values smaller than 30 kg (m s)$^{-1}$ are masked. (From Berbery 2000)

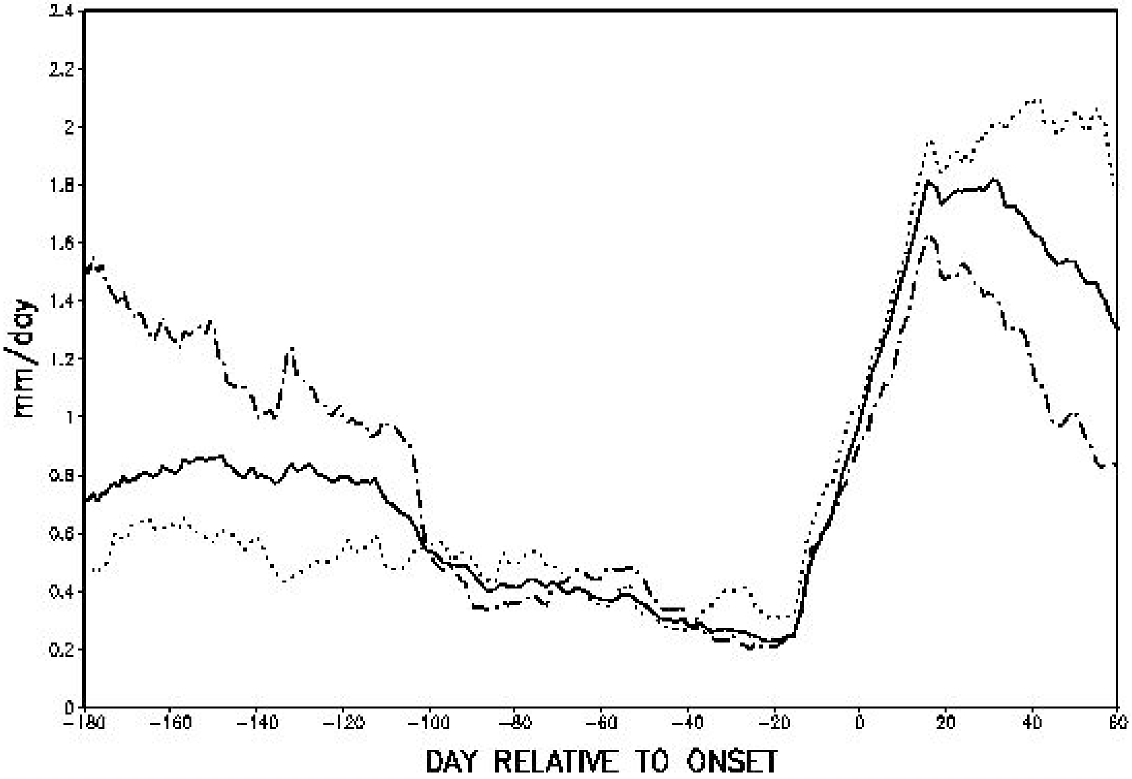

Figure C.2. Composite evolution of the 30-day running mean area average precipitation (units: mm/day) over Arizona and New Mexico for wet monsoons (dotted line), dry monsoons (dot-dashed line) and all (1963-94) monsoons (solid line). The average date of monsoon onset is July 1 for wet monsoons, July 11 for dry monsoons and July 7 for all monsoons (defined as day 0 in each case).

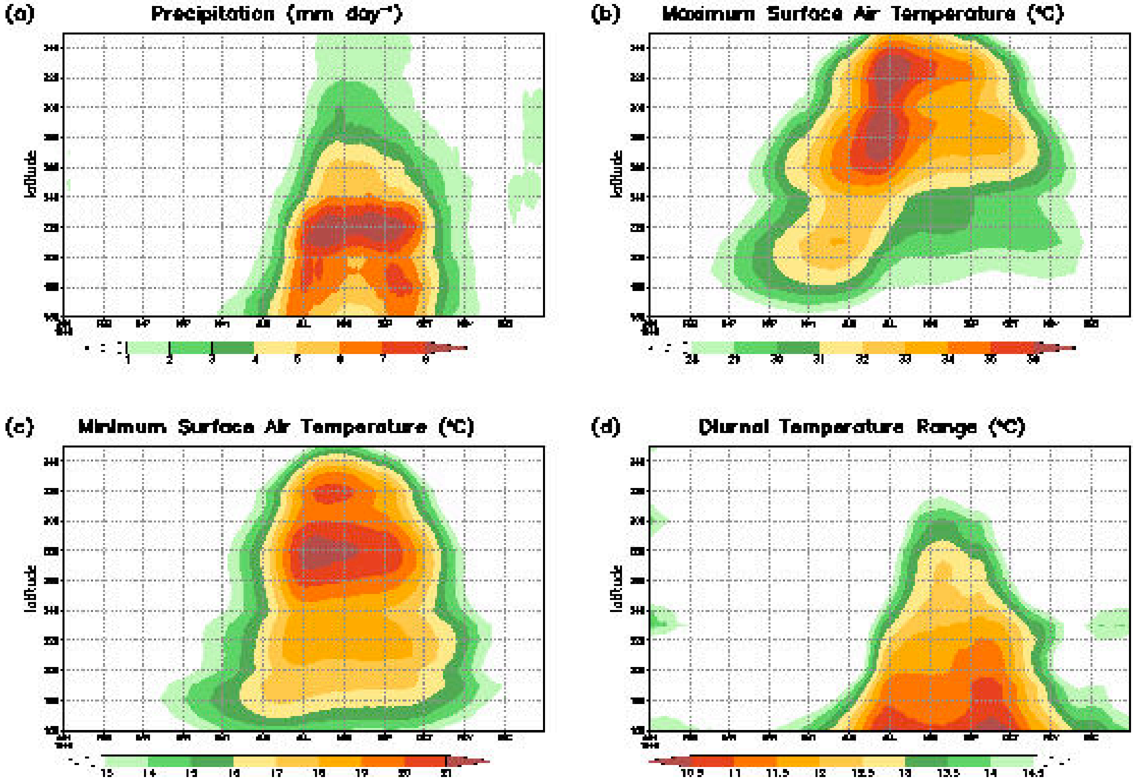

Figure C.3. Time-latitude sections of the mean (1961-1990) annual cycle of (a) precipitation, (b) maximum surface temperature, (c) minimum surface temperature, and (d) diurnal temperature range (i.e. the difference between (b) and (c)). Data are averaged zonally over west coast land points at each latitude.

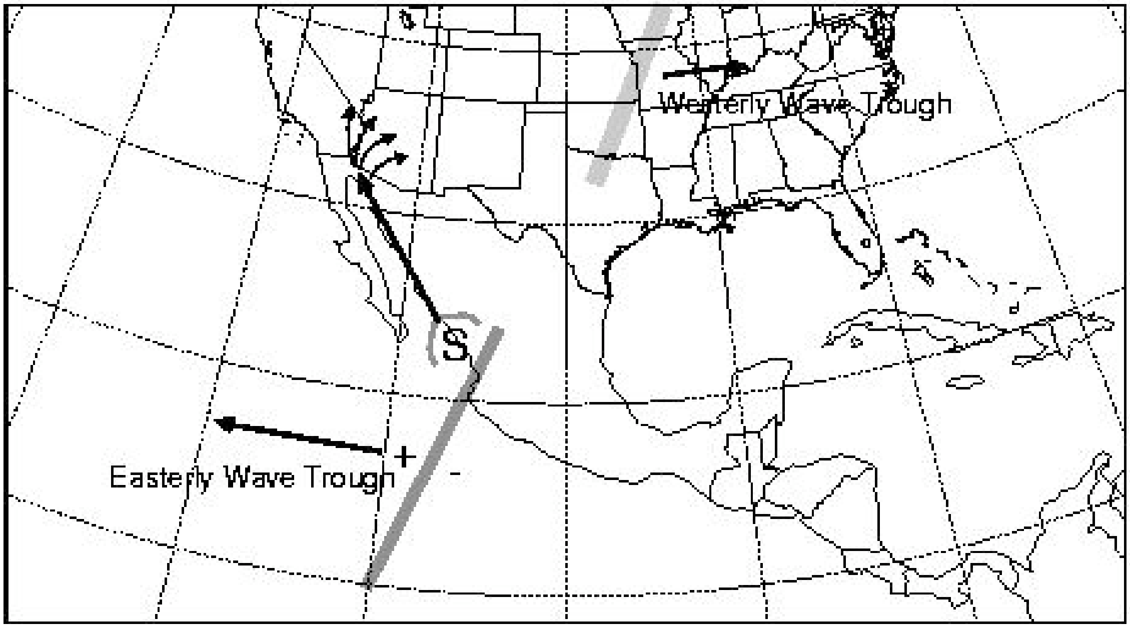

Figure C.4. Conceptual model of the initiation and propagation of gulf surge events as suggested by Stensrud et al. (1997). Letter S denotes the area of surge initiation, with the diagonal arrow indicating the direction of surge propagation. The +/- indicate regions of upward / downward motion associated with the easterly wave trough, while the arrow indicates the direction of movement of the trough (from Fuller and Stensrud, 2000).

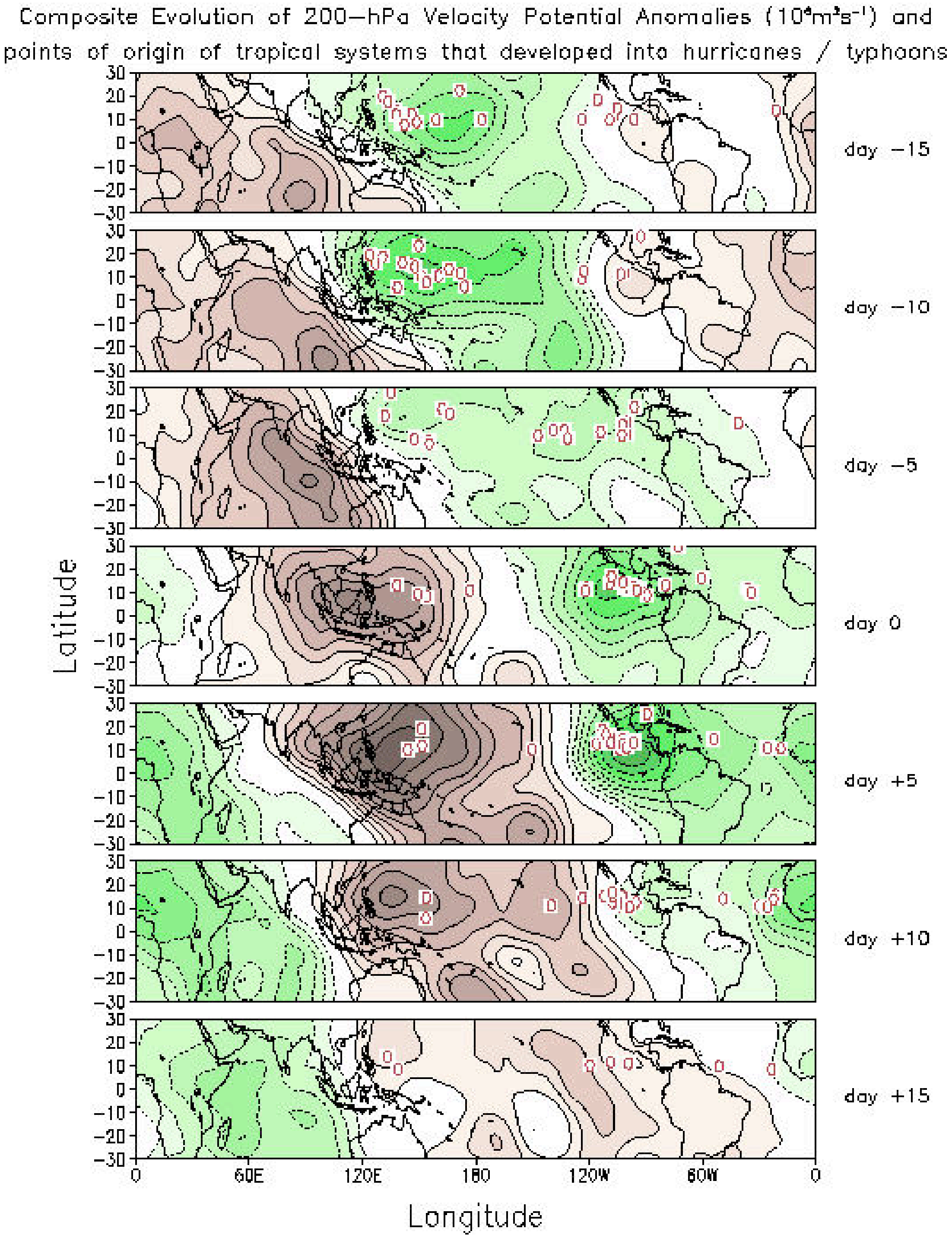
Composite Evolution of 200–hPa Velocity Potential Anomalies ($10^6 m^2 s^{-1}$) and points of origin of tropical systems that developed into hurricanes / typhoons

Figure C.5. Composite evolution of MJO events during the summer months together with points of origin of tropical cyclones that developed into hurricanes / typhoons (open circles). The green (brown) shading roughly corresponds to regions where convection is favored (suppressed) as represented by 200-hPa velocity potential anomalies. Composites are based on 21 events over a 19 summer period. Hurricane track data is for the period JAS 1979-1997. Points of origin in each panel are for different storms. Contour interval is 0.5×10^6 m^2 s^{-1}, negative contours are dashed, and the zero contour is omitted for clarity.

APPENDIX D: North American Monsoon Experiment (NAME)

The North American Monsoon Experiment (NAME) is an internationally coordinated field program designed to (i) monitor, quantify and analyze low-level circulations that modulate monsoon precipitation, (ii) understand the role of the North American monsoon in the global water and energy cycles, and (iii) improve the simulation and monthly-to-seasonal prediction of the monsoon and regional water resources. At the present time, a NAME Implementation Plan is under development.

By design, NAME will link CLIVAR/VAMOS, which has an emphasis on ocean-atmosphere interactions with GEWEX/GAPP, which has an emphasis on land-atmosphere interactions, in order to determine the relative importance of the coupled interactions between the ocean, land and atmosphere as they relate to the monsoon. NAME will benefit from linkages to other ongoing projects within GAPP, including the LDAS and the NCEP Regional Reanalysis, and from linkages to other field programs within CLIVAR/VAMOS, such as the American Low-Level Jets (ALLS) and VEPIC.

Some anticipated benefits from NAME include (i) a better understanding of key components of the NAMS and their variability; (ii) a better understanding of the role of the NAMS in the global water cycle; (iii) improved observational data sets of the regional circulations and moisture cycles that will contribute to more successful weather and climate forecasts (i.e. added skill in predictions up to seasonal); and (iv) improved modeling of key monsoon features and their variability, including the diurnal cycle of convection.

Among the questions relating to warm season precipitation predictability that will be addressed by NAME:

1) How are the Gulf of California (GOC) sea breeze/land breeze circulations related to the diurnal cycle of moisture and convection?

2) What role does the GOC low-level jet play in the summer precipitation and hydrology of southwestern North America?

3) How do interactions between tropical easterly waves and GOC surge events contribute to monsoon precipitation along the GOC?

4) What are the dominant sources of precipitable moisture for monsoon precipitation?

5) To what extent are active/break cycles in the monsoon modulated by intraseasonal fluctuations in the eastern Pacific warm pool?

6) What role do regional variations in land surface parameters (e.g. soil moisture, soil temperature, vegetation biomass) play in modulating monsoon precipitation?

7) How important are relationships between intraseasonal variability of the NAMS, the MJO, and tropical cyclone activity in the Pacific and Atlantic basins?

NAME activities will include planning, preparation, data collection and principal research phases. NAME planning will include the development of a NAME Science and Implementation Plan and a CLIVAR/GEWEX Planning Workshop to consider the plan. NAME preparations will include a build-up phase leading to a two-summer Enhanced Observing Period (EOP). The NAME principal research phase will continue for several years following the data collection phase, culminating in a NAME Research Conference. A timetable for NAME activities is being developed for the NAME Science and Implementation Strategy.

A multiscale approach to the analysis, diagnostic and model development activities of NAME, similar to that used by the GCIP Continental Scale Experiments (CSEs), is recommended. NAME will identify two different spatial scales. Reference sites will consist of well instrumented locations of small to intermediate scale areas (10^4 km or less) distributed around the Gulf of California, Baja and western Mexico. These sites will provide data on the mesoscale (and smaller) for research in land area and hydrology processes and model validation.

Larger Regional Scale Areas (i.e. larger fractions of the NAMS domain) will be chosen as a function of the research objective. A two-year period (possibly 2003-2004) has been identified as providing an excellent opportunity to carry out NAME data collection because (i) a new generation of remote sensing satellites will be available to provide unprecedented enhancement of observing capabilities to quantify critical atmospheric, surface, hydrologic and oceanographic parameters; (ii) several NWP centers (e.g. NCEP, ECMWF) are able to run their coupled modeling system to provide dynamically consistent datasets over the NAMS domain, and (iii) other GEWEX/GAPP and CLIVAR/VAMOS field experiments are planned during this period.

The components and scope of the observational effort will be closely linked to the magnitude of the overall effort. For NAME, the observational approach will focus on short-term observations. For reference sites within the NAMS domain, well-instrumented locations in different climatic regimes can provide the data needed on the mesoscale and/or smaller scale. For regional scales ranging from a subarea of the NAMS domain to the NAMS domain, less extensive instrumentation is required; some augmentation will be required above the standard observational networks.

APPENDIX E: WEB SITES.

INTERNATIONAL PROGRAMS

ACSYS/ CLIC: http://www.npolar.no/acsys/
BAHC: http://www.pik-potsdam.de/~bahc/
CEOP: http://www.joss.ucar.edu/ghp/ceopdm/
CEOS: http://www.ceos.org
CLIVAR: http://www.dkrz.de/clivar/hp_nf.html
GCOS: http://www.wmo.ch/web/gcos/gcoshome.html
GEWEX: http://www.gewex.com
HWRP: http://www.wmo.ch/web/homs/hwrphome.html
HELP: http://www.unesco/science/help
IGBP: http://www.igbp.kva.se/progelem.html
IGOS: http://www.igospartners.org
IHP: http://www.nfr.se/internat/ihp_igbp/IHPindex.html
WCRP: http://www.wmo.ch/web/wcrp/wcrp-home.html
WMO: http://www.wmo.ch/

US NATIONAL PROGRAMS

ARM: http://www.arm.gov/
EOS: http://eospso.gsfc.nasa.gov/
GAPP: http://www.ogp.noaa.gov/pme/gapp.htm
IPEX: http://www.met.utah/jimsteen/IPEX
Snow and Ice data: http://www.nside.colorado.edu
Snow Models: http://www.atmo.arizona.edu/~zly/snow.html
U.S. CLIVAR: http://www.clivar.ucar.edu/hp.html
USDA-ARS: http://www.nps.ars.usda.gov/programs/201s2.htm
USGS-NRP: http://water.usgs.gov/nrp/
USWRP: http://box.mmm.ucar.edu/uswrp/

APPENDIX F: LEAD SECTION AUTHORS FOR THIS SCIENCE PLAN

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