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GEWEX America Prediction Project (GAPP)
Science and Implementation Plan

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supported by

National Oceanic and Atmospheric Administration (NOAA)

and

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1. OVERVIEW OF THE GEWEX AMERICAS PREDICTION PROJECT (GAPP)

The purpose of this Science and Implementation Plan is to describe GAPP science objectives and the activities required to meet these objectives, both specifically for the near-term and more generally for the longer-term. This plan complements the GAPP Science Background (available at http://www.ogp.noaa.gov/mpe/gapp/index.htm) with detailed implementation strategies and latest developments. For detailed scientific discussions, linkages and references, please read the GAPP Science Background.

1.1 What is GAPP?

The GEWEX Americas Prediction Project (GAPP) is part of the Global Energy and Water Cycle Experiment (GEWEX) initiative that is aimed at observing, understanding and modeling the hydrological cycle and energy fluxes at various time and spatial scales. GAPP was approved and initiated in 2001 with funding from NOAA and NASA and is expected to continue until 2007.

The **mission** of GAPP is to demonstrate skill in predicting changes in water resources over intraseasonal-to-interannual time scales, as an integral part of the climate system. To achieve its overall mission, GAPP has the following **two science objectives**:

- <u>Prediction</u>: 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.
- <u>Decision support</u>: To develop application products for resource managers by interpreting and transferring the results of improved climate predictions for the optimal management of water resources.

GAPP is a follow-on project to the GEWEX Continental-Scale International Project (GCIP). GCIP was launched in 1995 in the Mississippi River Basin as one of the GEWEX Continental Scale Projects. While GAPP is proceeding with a focus on land-atmosphere interactions and hydrology similar to GCIP, it has a larger geographical domain (the contiguous USA) and a clearer focus on intraseasonal-to-interannual prediction and applications.

1.2 Scientific rational

While precipitation forecasts on "weather" time scales have improved, current global and regional models demonstrate limited skill in predicting precipitation, soil moisture, and runoff on monthly, seasonal and longer time scales. Water managers indicate this skill level to be inadequate for their needs. Improvements in precipitation prediction, or more generally improved prediction of hydrologic variables that relate to the surface water budget, would have large economic benefits. 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.

Seasonal to interannual predictability comes from local and remote influences involving both ocean and land processes. Enhanced predictability can result from persistence of specific phenomena or slowly varying boundary conditions (soil moisture/groundwater, snow/ice, vegetation/land cover, and ocean surface temperatures) that persist over periods of weeks, months or even years. Understanding the El Niño Southern Oscillation (ENSO) cycle has provided improved predictive skill, particularly with respect to seasonal outlooks in specific geographic locations resulting in improved hydrologic predictions. Over the last few decades, a body of evidence has accumulated on the importance of the land-surface for climate predictions. More accurate initial surface fields produced by recently developed land data assimilation systems for prediction models can provide a basis for reducing prediction errors. However, the land surface processes and how they affect climate variability and predictability are not sufficiently understood. Precise modeling of these influences requires a stronger physically based development. Testing model-calculated energy and water budget terms against all available observations, and against data produced in comprehensive reanalyses, is another area where additional work is required to improve predictions. Thus, 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 as the GAPP contributions to improved climate and hydrologic forecasts on intraseasonal- to-interannual time scales.

While the importance of improved climate prediction in water resources management is well recognized, it remains a challenge to translate these improvements into information on the probability of future streamflow conditions for water management. It is important to recognize the linkage between the hydrologic science and the water resources application activities. It is also a challenge for water managers to understand uncertainty of probabilistic forecasts and adapt management strategies for such information. GAPP will assist in building ownership within the water management community for these predictions, so that conditions will be favourable when a comprehensive national or international climate prediction system is ready for implementation.

1.3 Implementation strategies

The GAPP program consists of **seven research components** to achieve its science objectives (see Fig. 1.1). The GAPP implementation strategies include data development, process studies and modeling studies, and transition to operations. These activities cross cut all the GAPP research components. Different components will emphasize different aspects of these approaches. The detailed scientific priorities and implementation strategies are described in the following sections.

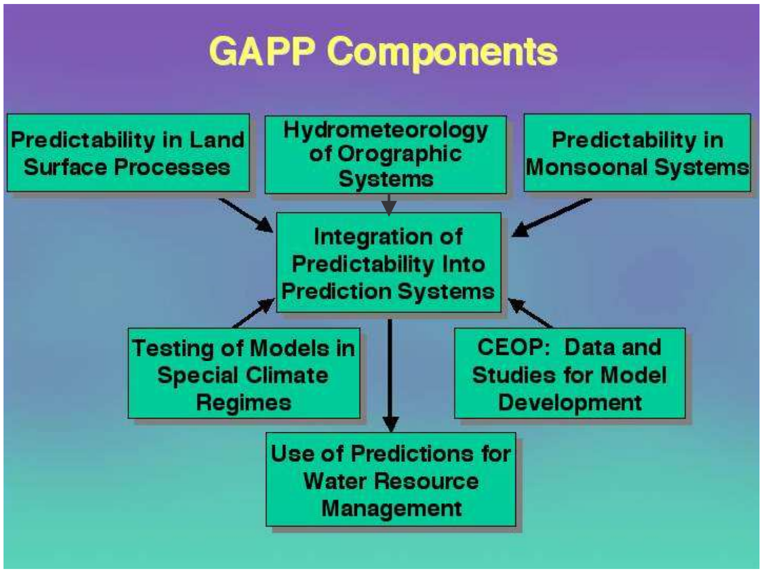

Figure 1.1: Research components of the GAPP program.

Implementation strategies for the **prediction objective** involve data development, process and modeling studies and decision support.

- Data development: GAPP will continue to develop critical hydroclimatic datasets to improve current understanding of land-atmosphere interaction, and to validate, calibrate and improve land surface models, climate models and satellite algorithms. GAPP encourages the analyses of existing GAPP datasets, such as, long-term precipitation datasets, long-term LDAS datasets, Regional Reanalysis, data from CEOP reference sites, and NAME field campaign data. New field observations, if necessary, may be developed in the future.
- Process and modeling studies: GAPP will continue its efforts to improve the understanding and representation of land-surface processes in soil moisture/groundwater, snow/ice, vegetation, and topography. GAPP will also study how land hydrologic states affect climate variability and how the representations of land-surface processes in both global and regional climate models affect the precipitation and hydrologic predictions. Collaborating with CLIVAR, GAPP will expand the current focus to further understand ocean-land-atmosphere interactions.
- Transition to operations: Through the NOAA GAPP Core Project**,** GAPP will facilitate this transition. The GAPP Core Project consists of scientists from NCEP and NWS/Office of Hydrology Development and supports both GAPP science objectives. The primary NCEP activities of the project include climate prediction and predictability studies, land data assimilation products, land surface model improvement/implementation in NOAA operational climate model, and regional climate modeling.

Implementation strategies for the **decision support objective** include research on hydrologic predictability and prediction studies and development of decision support tools for water resources applications.

- Hydrologic predictability and prediction studies: These include downscaling climate model outputs to relevant hydrological applications, bias-corrections of climate forecasts, hydrologic predictability studies, hydrologic model improvement, and ensemble streamflow forecasts.
- Development of decision support tools for water resources applications: GAPP will initiate community efforts to develop and evaluate hydrologic prediction systems for monthly-to-seasonal hydrologic forecasting and their applications for improved water resources management. GAPP will help resource managers to understand and apply probabilistic climate and hydrologic forecasts, assess forecast quality for decision-making, and communicate with water resources managers to get their requirements to the science community.

1.4 Programmatic context and linkages

1.4.1 Contributions to U.S. sponsoring agencies

In 2004, the NOAA/OGP GAPP program will be merged with the NOAA CLIVAR/PACS program into a new **Climate Prediction Program for the Americas (CPPA)** program. The NOAA CPPA program goals are (i) improving the skill of intra-seasonal-to-interannual climate predictions over the Americas and (ii) developing decision support products through the interpretation of climate forecasts for water resources applications. The scientific rational for the integrated CPPA program is knowledge that intraseasonal-to-interannual climate variability is largely determined by both ocean and land processes and their impacts on the atmosphere. The new CPPA program will bring together the PACS expertise in coupled ocean-atmospheric processes and modeling and the GAPP expertise in land-atmospheric interactions and regional modeling to improve understanding and modeling of land-ocean-atmospheric interactions and to provide the scientific basis for an end-to-end prediction system for the Americas' water resources.

GAPP will continue to be an inter-agency program with support from NOAA and NASA. It has a Scientific Advisory Group to provide scientific guidance to both agencies. NOAA support to GAPP is through the CPPA program. **GAPP contributes to the NOAA prediction goal** through incorporating improved understanding and modeling of land-surface processes into its seasonal prediction system and through the infusion of GAPP science into operational hydrologic forecasts. NASA support to GAPP is through the NASA Terrestrial Hydrology Program. **GAPP contributes to NASA** by its multidisciplinary studies and data products that provide a benchmark for the validation of satellite observations and improvement of retrieval algorithms, and by its connections to the stakeholders in water resources applications.

1.4.2 Linkage to international programs

- Global Energy and Water Cycle Experiment (GEWEX) is the sole program with a major focus on land surface processes within WCRP. GAPP will continue to be one of the GEWEX Continental-Scale Experiments (CSEs) and a member of the

GEWEX Hydrometeorology Panel (GHP), and will continue to get scientific guidance from GEWEX SSG and GHP. Other continental scale experiments and GHP members are BALTEX, MAGS, GAME, LBA, MDB and PLATIN. GHP gives guidance to GAPP and others to achieve demonstrable skill in predicting changes in water resources and soil moisture as an integral part of the climate system up to seasonal and annual time scales. GAPP will provide leadership for GHP predictability studies, transferability strategies and contribute to the Water Resources Applications Project (WRAP).

- Climate Variability and Predictability (CLIVAR) main goal is to increase the skill of global climate prediction on seasonal, interannual, decadal and centennial time scales, with an emphasis on climate events such as El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). The CLIVAR study proposes to identify the major aspects of climatic variability and support scientific investigation into these areas. The newly integrated CPPA program from GAPP and PACS within NOAA allows GAPP to interact with the CLIVAR community more efficiently.
- Climate and Cryosphere (CliC) is to assess and quantify the impacts of climatic variability and change on components of the cryosphere and their consequences for the climate system, and determine the stability of the global cryosphere. Beyond the bipolar focus, CliC will also include relevant cold season regions processes elsewhere, such as permafrost and ephemeral snow cover over the GAPP region.
- United Nations Educational Science and Culture Organization/Hydrology for Environment, Life and Policy (UNESCO/HELP) is a joint project developed under the guidance of UNESCO and endorsed by a number of agencies including WMO and the IGBP. 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. 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 resources applications.

1.4.3 Linkage to national programs

- U.S. Climate Change Science Program (CCSP): GAPP is expected to make major contributions to the CCSP mainly through its contributions to the Global Water Cycle component and the Climate Variability and Change component. A number of new GAPP initiatives will directly address water cycle priorities. For example, the mountain hydrometeorology activities being planned for the western Cordillera will help to address issues related to complex terrain and its effects on precipitation and runoff. More generally, GAPP will be a major contributor to addressing questions related to “uncertainties in seasonal and interannual predictions of water cycle variables”, “improvements to global and regional models to reduce these uncertainties” and “making climate knowledge more useful and responsive to the needs of decision makers, policy makers, and the public" in both Water Cycle and Climate Variability and Change components.

- United States Weather Research Program (USWRP) goal is to improve forecasts of high impact weather. 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. The 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.
- Earth Observing System (EOS) is a NASA program (with national and international collaborators). 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. 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 Measuring Mission (TRMM).
- Regional Integrated Sciences and Assessments (RISA) 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. RISA and GAPP work very closely on water resource application issues.
- Advanced Hydrologic Prediction Systems (AHPS) is seeking to improve the state of the art of hydrologic prediction as applied primarily to flood forecasting. Although NWS/OHD does not formally support extramural research, it is cooperating with the academic community in the development of AHPS, in particular through an evolving partnership with GAPP.
- Atmospheric Radiation Program (ARM) 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.

2. LAND-MEMORY AND VARIABILITY STUDIES

Within the GEWEX Americas Prediction Project (GAPP), research into land memory, climate variability and seasonal prediction studies is motivated by the first GAPP objective:
"*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-related hydrometeorological and boundary layer processes in climate prediction models.*"
To fulfill this objective, it is necessary to identify, adequately understand, and capably model those land-surface features, phenomena, and processes that can contribute to improved predictions of precipitation and hydrologic variables at the relevant timescales. The research focus in this element will be developed around the following four areas: (i) quantification of the strength of land memory processes, (ii) understanding the spatial and temporal extent of the land memory signal, (iii) quantifying the role of land-memory in climate variability and prediction, and (iv) understanding land memory and variability across modeling scales. The land memory and variability studies will specifically address these issues as they relate to soil moisture; snow extent, amount and duration; and vegetation and land cover.

2.1 Background

2.1.1 Science

The GAPP Science Plan identifies three aspects of the land surface which possess "memory like" characteristics, in the sense that, at any point in time, the then current land-surface energy and water exchanges that influence the overlying atmosphere are themselves, in part, determined by the history or the climate to which the land-surface has itself been exposed in preceding months. These land-memory mechanisms include: (i) the storage of water near the surface as soil moisture (ii) its storage on the surface as snow and ice, and (iii) nature and seasonal progression of growing vegetation. Both water storages affect the surface interactions with the overlying atmosphere and the amount of water leaving as runoff in streams or to ground water. The nature and seasonal progression of growing vegetation also represents a land memory, because the nature and growth status of plants partly reflect past climate but controls current surface energy, moisture, and momentum exchanges. In addition, topography, although not a land memory in the sense just described, has a well-recognized and persistent (remembered) influence on precipitation and hydrologic flows and, depending on the time of year, can determine whether precipitation falls in liquid or solid form.

Recent research in land-memory processes suggest that seasonal predictions conditioned on land-memory states have lower variability and therefore higher predictability than unconditioned seasonal predictions. Understanding the strength of these relationships for different geographical regions and seasons, and their robustness over time and models remains a challenge that needs to be addressed in the GAPP Implementation activities.

The research activity into land-memory, and how land hydrologic states affect climate variability and prediction, that will be implemented under GAPP will be sufficiently broad to answer scientific questions relating to the previously mentioned land-memory processes and phenomena. However, there is a substantial similarity in the approach that will be used to address these different science questions, including:

1. Quantification of the strength of land memory processes.

Analysis of existing, relevant data, including remote-sensing data, in diagnostic studies will help establish the nature of land-atmosphere interaction, the role of land-memory in climate variability, and connections between predictability time scales and hydrologic processes. The analyses should apply advanced statistical analyses to diagnose interrelationships between observations, and to identify potential sources of predictability. It is necessary as GAPP moves forward to utilize GAPP-supported long-term datasets such as the NCEP 25-year Regional Reanalysis, the University of Washington 50-year NLDAS retrospective data set with the VIC LSM and the NCEP 50-year NLDAS retrospective data set with the Noah LSM to promote such studies. In addition, GAPP will encourage the use of other heritage data sets for understanding the role of the land in climate variability and prediction. To the greatest extent possible in such studies, GAPP intends to establish and adhere to ALMA data-set conventions (www.lmd.jussieu.fr/ALMA) to facilitate the ready transfer of data sets between participating researchers.

2. Understanding the spatial and temporal extent of the land memory signal.

There is a need to understand land memory and its variability over a range of temporal and spatial scales, including the relationship across scales—short temporal and spatial scales to seasonal and regional scales. Consequently, there is a need to acquire and, if necessary, collect new field observations to improve and validate model parameterizations and, if appropriate, calibrate the ability of models to describe the seasonal evolution of state variables associated with predictability, both in one-dimension and spatially over larger domains. Spatial fields of land surface variables estimated from remotely sensed observations, either space-borne from the suite existing and planned earth observation satellites or airborne sensors will also be useful for this implementation element. Studies will be needed to determine whether models adequately describe the horizontal transfer processes that generate hydrological variables such as surface and subsurface runoff and contribute to spatial variability in soil moisture and snow redistribution due to wind. Off-line tests that compare both point-scale and distributed fields of observed and model-calculated variables will be required, and should be conducted in selected well-instrumented catchments; such studies could be linked to the Distributed Model Intercomparison Project (DMIP; www.nws.noaa.gov/oh/hrl/dmip). It is anticipated that coordination with other GEWEX programs, such as the GEWEX Land Atmosphere Scheme Study (GLASS; hydro.iis.u-tokyo.ac.jp/GLASS) and the GEWEX Atmospheric Boundary Layer Study (GABLS; www.gewex.com/gabls.htm) will be helpful when addressing this GAPP program element.

3. Quantifying the role of land-memory in climate variability and prediction.

This quantification is needed to address the first GAPP science goal regarding prediction, and requires a broad set of studies that will require a wide set of models and choices for initial land states. Activities such as Reanalysis 1 and 2, NCEP Regional Reanalysis, ECMWF ERA-40 reanalysis, the NLDAS and GLDAS multi-model off-line land surface model products and the GSWP 1 and 2 of the ISLSCP component of GEWEX all provide potential choices. Algorithms will have to be developed for transforming anomalies in the land surface states from the above sources, which have their own inherent preferential climatology, to that of the models that will initialize off of these 'data'. There needs to be an effort to develop "community" databases of land surface forcing fields, to make these land surface forcing data sets more readily and easily available to the larger body of land models, who can spin-up their own self-consistent initial conditions. The availability of the GAPP-supported University of Washington 50-year NLDAS retrospective data set with the VIC LSM through the UCSD Scripps supercomputer center is one example.

4. <u>Understanding land memory and variability across modeling scales</u>.

Expanding the current focus of Regional Climate Model (RCM) research to encompass prediction experiments based on GCM predicted lateral boundary conditions and predicted SST fields will be needed to make progress beyond potential predictability, and to understand how errors in the GCM-predicted SST states affect the land-memory predictability. Within this, there is a need to evaluate the ability of coupled hydrometeorological models to describe and predict climate and hydrological variables at both grid scales and regional scales, to understand the impact of RCM domain size, resolution, and the treatment and position of the RCM lateral boundaries. Regardless of the land memory phenomena involved, such tests will require multi-member ensemble experiments with high-resolution coupled models using well-specified observations of atmospheric forcing as model boundary conditions.

2.2 Implementation Activities

In the following sections, the current status of understanding of the different land memory phenomena are used to define the initial implementation priority for the research activity to be undertaken in GAPP.

2.2.1 Soil-moisture memory

GCIP has created a legacy of understanding and progress in the field of soil-moisture-related land memory that will benefit and guide the research to be undertaken under GAPP. In modeling studies, GCIP demonstrated conclusively that regional soil moisture status can change the rate at which water vapor is converted to precipitation and contributed to the persistent heavy rain and consequent flooding in the Mississippi River basin in 1993. However, in general, research into soil moisture-related land-memory processes remains inhibited by the comparative scarcity of soil-moisture data. It was this lack of relevant, regional scale observations of soil moisture that stimulated the Land Data Assimilation System (LDAS) initiative under GCIP (see Mitchell et al., 2004). That successful LDAS methodology will also be adopted and applied in the context of GAPP.

Notwithstanding the progress that has been made towards providing model-calculated soil-moisture fields using LDAS, the basic requirement for soil-moisture observations over extensive land areas remains. Given the scarcity and poor representativeness of point measurements of soil-moisture, the prospect of providing remotely sensed, area-average observations is a tempting option to pursue. GAPP will therefore seek to work with and draw benefit from ongoing research under the NASA-LSHP in support of the future HYDROS space mission to remotely sense soil moisture. While the NASA-LSHP focus will presumably be on enabling the technical feasibility of remotely sensing soil-moisture, GAPP's focus will be on investigating how such remotely sensed observations could best be used to improve prediction of climate and hydrologic variables at timescales from days up to seasonal, and what the likely improvement in predictability would be and their usefulness for water resources.

Currently, the primary limitation on exploiting soil moisture memory to improve climate/hydrometeorological predictions is the poor quantitative precipitation forecasts (QPF) in coupled hydrologic models. Even if observations of precipitation are available to improve the definition of initial soil moisture status, shortcomings in the simulation of rainfall in predictive runs can rapidly degrade the quality of the simulation subsequent evolution of the moisture store. The desire to improve simulation and prediction of the moisture available at the land surface therefore puts emphasis on the need for research to improve the representation of those atmospheric processes that generate precipitation. This need is particularly acute in GAPP because the new westerly focus of the program means that the poorly understood influence of topography on precipitation is emphasized.

Recognizing the current status and needs for research in soil-moisture land memory, the initial priorities for reach in this area within the GAPP program will therefore include:

- Research to quantify the role of soil moisture in seasonal predictability studies. There is a range of potential studies that potentially include statistical analyses based on GAPP-supported hydrologic data sets, modeling studies using RCM and GCM models, and testing whether LDAS-like model initializations result in improved prediction. It is necessary to determine whether improved predictions are useful on water management spatial and temporal scales. Initial GAPP foci will include studies on the NAME region, and the role of soil moisture and snow on the North American monsoon strength and persistence; the relationship between Spring-time soil moisture and summer precipitation across the GAPP region; and the role of soil moisture from LDAS-like systems on short-term precipitation prediction.
- Research in support of a soil moisture remote sensing mission to improve the initiation of predictive models, with emphasis on how such remotely sensed observations could best be used to improve prediction of climate and hydrologic variables at timescales from days up to seasonal, and on what the likely improvement in predictability would be.
- Initially, improve observations of precipitation in regions of the Americas where data are sparse, such as the mountainous regions of the western United States and northwestern Mexico, as the basis for improving models' representation of precipitation processes and to improve the performance of regional LDAS in the context of phenomena-specific (e.g. monsoon) predictability studies.
- Subsequently, research leading to improved understanding and more capable modeling of precipitation processes in the atmosphere and their interaction with

topography with (in the context of soil-moisture memory studies) special emphasis on warm-season convective processes.

2.2.2 Snow extent, amount and duration memory

Snow and ice cover "remembers" frozen precipitation, influences current surface radiation transfer, and dictates future melt-water availability. Although not a focus of attention for GCIP, the project nonetheless created a creditable legacy of progress and understanding in the field of snow and ice cover related land memory. In this context, one significant development is the now routine provision of snow-cover data products by the National Operational Hydrologic Remote Sensing Center and National Snow and Ice Data Center (http://www.nsidc.colorado.edu). Under GCIP, research results showed that improved model parameterizations for snow and frozen ground, and for sub-grid snow distribution snow improves the modeled regional and global climate.

Given the present standing of snow/ice land memory research, the evolving priorities for related studies in the GAPP program will be:

- Research to quantify the role of snow extent (spatially and into the Spring season) in seasonal predictability studies. There is a range of potential studies that potentially include statistical analyses based on GAPP-supported hydrologic data sets, sensitivity studies of the modeled climate and hydrologic variables to the amount and extent of frozen precipitation at timescales up to seasonal, using observations to prescribe regional snow/ice cover in the models; and testing whether LDAS-like model initializations result in improved prediction. It is necessary to determine whether improved predictions are useful on water management spatial and temporal scales. Initial GAPP foci will include studies on the NAME region, and the role of snow on the North American monsoon strength and persistence; and the potential relationship between Spring-time snow extent and summer temperatures and precipitation across the GAPP region.
- Initially, the development of improved snow/ice cover sub-models in LDAS, with emphasis on vegetation-covered areas, and testing these relative to existing or new observations at both plot and regional scale.

2.2.3 Vegetation and land cover memory

Over the last decade, there has been major progress in understanding and modeling the influence and importance of vegetation on surface exchanges of energy, water, and carbon. GCIP research demonstrated that including improved representation of vegetation, even in a simple form, can result in a significant improvement in the predictive capability of seasonal prediction models. Just as important, GCIP research also fostered an important new capability to estimate, from field data, the values of the several parameters required in more complete models of vegetation response. There were also some early studies using coupled models capable of representing the seasonal evolution of vegetation and the impact of climate on the vigor and amount of vegetation. The latter is a precursor for vegetation memory studies under GAPP.

However, because soil-vegetation-atmosphere transfer schemes (SVATS) with interactive vegetation, i.e., models that simulates the growth and die-back of vegetation, are comparatively recent, stand-alone testing, intercomparison, and, if required calibration against observations at selected sites are initially required. The next step is to test the ability of two-dimensional arrays of SVATS with interactive vegetation, when forced with spatially distributed climate data, and validate their ability to reproduce the regional patterns of vegetation growth and senescence observed by satellite sensors. Assuming these tests prove successful, in due course, investigations can be carried out on the effect of inter-annual variability in vegetation (e.g. time of leaf-out) on inter-annual climate variability, through multi-member ensemble integrations with regional, coupled hydrologic-atmospheric models, with and without interactive vegetation. Ultimately, such investigations will help determine whether including interactive vegetation improves the simulation of climate variables in the GAPP study area, and the relative roles of various land-memory processes in climate variability and prediction. Such integrations could also investigate whether including interactive vegetation modifies the relative sensitivity of the models to changes in sea surface temperatures versus land-memory processes in general.

Thus, given the still emerging status of soil-vegetation-atmosphere transfer schemes with interactive vegetation, the evolving priorities for vegetation memory studies in the GAPP program will be:

- Initially, sensitivity studies of the modelled climate need to be conducted to investigate the contribution of inter-annual vegetation variability on climate variability and the significance of vegetation 'memory' on model predictions. The initial focus is to better understand whether improved representation of seasonal dynamics and inter-annual variability in vegetation will lead to better seasonal climate and hydrologic predictions. Such studies will contribute to an understanding of the role of vegetation in seasonal climate phenomena, such as the North American Monsoon System.

3. HYDROMETEOROLOGY OF OROGRAPHIC SYSTEMS

Unlike the GCIP study area of the Mississippi River basin, the expanded GAPP region offers the opportunity for research into the relationship between topography, and climatic and hydrological variables. In regions with marked topography, climate conditions such as temperature, precipitation, and snow can be significantly modulated by orographic features that vary on different spatial scales. Our ability to predict regional scale seasonal climate anomalies therefore depends strongly on our understanding of the dynamic and thermodynamic effects of orography and its interactions with anomalies of large-scale circulation. Activities in this area help address the first GAPP science goal; namely, as it relates to the hydrometeorology of orographic systems:

To develop a capability to make reliable predictions of precipitation and land-surface hydrologic variables through improved understanding and representation of hydrometeorological and boundary layer processes.

The implementation strategy and activities for this element are organized around the following five activities: (i) Diagnostic analyses of existing hydrometeorological data; (ii) Investigation of the mean seasonal cycle and predictability of its variability; (iii) Integrate atmospheric elements with surface hydrologic components; (iv) Carry out hydrometeorological model experiments; and (v) Apply climate and hydrologic models in seasonal climate forecasting for basins with complex terrain. The research should result in improved predictive capabilities for precipitation due to orography, and a greater understanding of the role of complex terrain in hydrologic prediction.

3.1 Background

3.1.1 Science

The GCIP study area of the Mississippi River basin offers little opportunity for research into the relationship between topography, and climatic and hydrological variables. However, in regions with marked topography, climate conditions such as temperature, precipitation, and snow can be significantly modulated by orographic features that vary on different spatial scales. Our ability to predict regional scale seasonal climate anomalies therefore depends strongly on our understanding of the dynamic and thermodynamic effects of orography and its interactions with large-scale circulation anomalies.

A need for this understanding and prediction ability are motivated by the central GAPP goal to predict the spatial distribution of precipitation over the complex terrain of the western United States, to forecast precipitation for intermediate (seven to fifteen days) to long range (monthly to seasonal) time scales, and to interpret and transfer the results of improved seasonal predictions for water resources management. Improved understanding of the hydrometeorology related to orography is critical to improved predictions and successful use of short-term to seasonal climate forecasts for managing water resources in regions such as the western U.S. that are dominated by complex mountainous terrain. In river basins such as the Sacramento-San Joaquin and Columbia River, discernible signals of interannual variability of large-scale circulation associated with ENSO and regional scale effects of the complex terrain are clearly seen in historical streamflow and snowpack records that led to significant impacts on water resources (e.g., Redmond and Koch 1991; Cayan 1996; Cayan et al. 1999; Leung et al. 2003). Extending the GAPP study area to include the mountain ranges of the western U.S. and Mexico creates both the opportunity and the need to understand and capably model the effects of surface orography on the atmosphere and hydrologic cycle, and to exploit the weather and climate predictability at the scales that are important for water resources applications.

Two distinctively different regional climate regimes of the western U.S., both strongly affected by orography, are of particular interest. They are the maritime climate of the Pacific Northwest and Northern California and the semi-arid climate of the Southwest. In the maritime climate, precipitation shows a maximum during the cool season resulting in a significant snowpack stored in the mountains. Predicting both the amount and timing of precipitation and runoff requires accurate prediction of temperature, precipitation, and land surface processes. Skillful seasonal climate predictions depend on both the ability of global forecasts to establish anomalies of the large-scale circulation and of models to predict regional-scale precipitation anomalies that result from interactions of the large-scale circulation and regional-scale forcing (Leung et al. 2003; Ralph et al. 2003). Since predictability is highly variable in space and time in regions with complex orography, there is a need to establish the theoretical and empirical limits for seasonal forecasts.

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. 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 the role of blocking in determining the distribution of precipitation relative to a barrier (Yu and Smull 2000; Neiman et al. 2001) using coastal wind profilers and rain gauges and offshore observations from island-mounted wind profilers and from a NOAA P-3 aircraft.

Some challenges to dynamical modeling of cool season orographic processes include investigating the impacts of cloud microphysical processes (e.g., representation of advection of hydrometeors and seeder-feeder mechanism), orographic flow (e.g., blocking induced instability, barrier jet, and displacement of frontal air masses), thermodynamics effects of mountains, and numerical methods (e.g., effects of vertical discretization). In addition, experience in atmospheric modeling for weather and climate predictions has suggested that increasing model resolution does not automatically increase skill (e.g., Mass et al. 2002; Leung and Qian 2003). There remains a need for careful comparisons of different modeling approaches including regional climate models, simple dynamical models and/or subgrid parameterizations (e..g, Rhea 1978; Alpert 1986; Barros and Lettenmaier 1993&1994; Leung and Ghan 1995&1998), and statistical models (e.g., Chua and Bras 1982; Daly et al. 1994; Hutchinson 1995; Widmann et al. 2002) of orographic effects. Because existing networks of measurements do not adequately resolve precipitation in regions of complex terrain, statistical methods and regional reanalyses are useful for providing more accurate estimates of water budgets in mountainous river basins and evaluating orographic precipitation models.

In the southwestern U.S., rainfall associated with the North American Monsoon (NAM) is important for supplying water to the semi-arid region. The NAM system raises 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 that have not been properly parameterized.

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. 2001) that stem from oceanic convection studies (e.g., Grabowski et al. 1999). These models provide statistically meaningful results that contribute to the development of both climate models and statistical models.

3.1.2 Objectives

This new area of interest in GAPP aims to achieve the following five objectives.

1. Diagnostic analyses of existing hydrometeorological data.

There is a need for comprehensive analyses of existing GCIP datasets and data collected under GAPP to investigate the relationships between regional climate and orographic forcing in different climate regimes and the sensitivity of such relationships to interannual variability. The data for such analyses would include precipitation, atmospheric thermodynamic and momentum variables, radiation, humidity, and soil moisture for selected regions over complex orography, as well as other data such as the regional reanalysis products. The data is needed to diagnose precipitation and surface processes and to validate numerical models for complex terrain. The data used in this element should include precipitation observations as well as high accuracy estimates from orographic precipitation models that effectively diagnose precipitation from observable fields such as large-scale moisture transports and the distorting and moisture scavenging effects due to orographic flow distortion.

2. Investigation of the mean seasonal cycle and predictability of its variability.

Progress on the GAPP goal of improved prediction includes quantifying regional and remote atmospheric and land surface processes that determine the mean annual cycle, and its interannual variability, in complex terrain. The implementation of this science objective should emphasize implications of such studies for anomaly conditions, and focus upon synoptic scale and mesoscale atmospheric circulation and those surface variables, including precipitation, snow distribution, and streamflow that bear directly upon the hydrometeorology in regions of complex terrain. Such studies need to cover a range of scales because current studies have often focused on the interannual variability at large scales due to impacts of remote ENSO signals. There is a need to understand how changes in large-scale circulation induced by ENSO interact with topography at the mesoscale to generate complex precipitation anomaly patterns.

Besides the above sources of variability (or sources of anomalies), there are other mechanisms that result in variability that needs to be better understood as they relate to improved prediction. For example, the observed seasonal cycle contains pronounced winter-spring reversals from anticyclonic to cyclonic conditions. There is a strong likelihood that the season-to-season reversals are imposed by local land surface processes, including such influences as the winter to spring modifications of the mechanical blocking effect of topography and of the elevated orographic cold/heat source. Since the regular cycle is strongly determined by local surface influences, it is plausible that deviations from this cycle are also at least partly driven by anomalies of the local surface effect, and that predictions of related phenomena, including precipitation depend upon adequate treatment of the poorly understood surface influences.

3. Integrate atmospheric elements with surface hydrologic components.

GAPP needs to initiate studies with stand-alone hydrological models, using observed and/or model-calculated forcing fields, to investigate the influence of topography-dependent precipitation on the hydrological response of watersheds of differing spatial scales, and to carry out diagnostic studies of the hydrologic predictions from catchments dominated by complex terrain. The primary source of hydrologic prediction error is usually error in precipitation; hence the GAPP focus on improving predictability of precipitation should have benefits for streamflow forecasting and its implementation 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) and snowpack, the spatial distribution of precipitation and its form, and the timing and spatial variability of energy available for snowmelt.

4. Carry out hydrometeorological model experiments.

An important element of the GAPP implementation activities will be multi-member ensemble experiments with high-resolution, regional, coupled land-atmosphere models required in selected areas with marked topography to examine the sensitivity of model simulations to physics parameterizations and model resolution and to evaluate model performance against observational data. Such experiments need to be carefully designed and will result in a variety of approaches that range from: coupled models that resolve the fine scales on which precipitation is released and stored at the surface and allow feedback from local, highly resolved subdomains upon the larger scale ambient flow while permitting feedback of orogenically produced circulations upon the ambient state; to simpler modeling that contain subgrid parameterizations that account for the effects of subgrid variations in topography and land surface cover on precipitation and snow; and to more simpler statistical methods of precipitation downscaling. These methods are potentially useful alternatives to explicit modeling or model nesting, but have not been adequately validated against more complete methods that allow feedback from the more highly resolved subdomain to the ambient global state. The validation and intercomparison of all precipitation downscaling methods remain high priorities. All methods need to be carefully validated against observations.

5. Apply climate and hydrologic models in seasonal climate forecasting for basins with complex terrain.

The GAPP research goal related to making predictions useful for water managers needs to be tested by applying the hydrometeorological and climate models in forecasting for basins with complex terrain across a range of temporal and spatial scales. These forecasts must be assessed for forecast skill and impacts on water management.

3.2 Implementation activities

Implementation of this new area of interest within GAPP will require research in six priority areas, as follows:

1. Diagnostic analyses of existing hydrometeorological data.

As a first step, there is a need to evaluate climate data over complex terrain, with a focus on validation of both liquid and solid precipitation and the seasonal evolution of snowpack. As part of this, there is a need to evaluate the performance of different approaches to modeling orographic precipitation in different regions of complex terrain to determine their utility for filling data gaps at various temporal and spatial scales. These activities need to explore the utility of remote sensing methods for precipitation quantification, especially in regards to currently implemented technologies such as WSR-88D radars, which have a significant heritage but possess calibration problems related to terrain signal blocking over the western United States, and the implications to accuracy in predictions. Diagnostic activities need to explore the statistical relationship between topography and precipitation across the GAPP study area and investigate if and how this relationship varies with geographical/climatic location, from year-to-year, and for liquid and frozen precipitation, as well as a better understanding of the interannual variability of these relationships.

2. Investigation of the mean seasonal cycle and predictability of its variability.

Implementation activities within this element include both modeling studies and statistical analysis of seasonal and interannual variability of precipitation (both liquid and solid) and snowpack in orographic regions of the GAPP domain with a goal of better understanding the remote and local controls, in addition to ENSO, that are important for cold season precipitation and streamflow. The goals are to better quantify the fraction of explained variance of such controls for both precipitation and streamflow, to understand the time scales on which different remote/local controls act, and to quantify their potential lead times in prognostic applications. There is a need to diagnose the seasonal cycle and its interannual variability for precipitation and snowpack, including exploring relationships in terms of dynamical atmospheric metrics, as well as hydrologically relevant measures such as atmospheric moisture flux convergence and streamflow. Understanding how these relationships are captured by global and regional climate forecasts is important for developing models and application strategies.

3. Integrate atmospheric elements with surface hydrologic components.

Implementation activities that focus on the linkages between atmospheric and surface hydrometeorological processes and how these linkages address the GAPP prediction goal would include studies and analyses that (i) quantify the sensitivity of runoff generation to evapotranspiration, particularly changes that would be associated with lengthening of the snow-free season; (ii) investigate how the effect of topography on precipitation (including its influence on whether precipitation falls in liquid or frozen form) modify the magnitude and timing of hydrological flows in watersheds of differing spatial scales; and (iii) determine the extent to which seasonal soil moisture carry-over (from the end of the summer season through the following winter) and soil freeze/thaw state affects runoff generation during winter storms and spring snowmelt. These analyses and related data sets, in combination with mesoscale reconstruction of precipitation and associated hydrologic model forcings, would support studies focused on evaluation of hydrologic model parameterizations and hydrologic model predictions from mountainous regions within the GAPP domain.

4. Carry out hydrometeorological model experiments.

The objective of this element is to evaluate whether coupled land-atmosphere and regional climate models adequately reproduce the observed statistical relationships between precipitation and topography in the GAPP study area. Recognizing that systematic model experiments and diagnostic studies of model predictions against observations are required to understand the sensitivity of orography, scale to model predictions, and the prediction skill to the level of model parameterization, a limited number of well-focused experiments will be carried out. These experiments can include studies focused on (i) evaluating precipitation downscaling methods against available observations and comparing the different methods, including regional models of differing levels of complexity, with each other based on a common set of model diagnostics and measures of model skill; and (ii) evaluating whether coupled land-atmosphere and regional climate models adequately reproduce the observed statistical relationships between precipitation and topography in the GAPP study area, and whether more complex model parameterizations and increased spatial resolutions leads to improved skill. Through these controlled numerical simulations it is hoped that GAPP can quantify the relative dynamic and thermodynamic influences of the Western Cordillera upon the seasonal cycle and its anomalies and quantify the scale-transfer mechanisms associated with orographic modulation of the ambient state.

5. Apply climate and hydrologic models in seasonal climate forecasting for basins with complex terrain.

The implementation activity for this element needs to build upon the activities described above; especially those that evaluate model complexity and scale with respect to orographic precipitation and snowmelt. The implementation activities need to (i) evaluate whether more complex model parameterizations and increased spatial resolutions lead to improved skill, especially when applied to simulating the water budgets of major river basins in the western U.S. affected by orography and (ii) assess seasonal climate forecast skill through studies that will apply climate and hydrology models in river basins with complex orography and examine the impacts on water management. These studies will be done by applying a suite of climate models and precipitation downscaling methods to explore ways to improve seasonal predictions of precipitation anomalies through ensemble approaches and characterization of forecast uncertainty.

6. Linkages to other GAPP elements.

With the main objective of improving seasonal climate prediction for regions with complex orography, the research activities in Hydrometeorology of Orographic Systems will have significant interactions with other GAPP components including Land Memory and Variability Studies, Warm Season Precipitation, Operational Seasonal Climate Prediction, and Water Resources Applications described in Sections 2, 4, 6, and 7. Examples include understanding land memory effects resulting from snow and soil moisture associated with cool season orographic precipitation systems of the NAM, investigations of operational seasonal climate prediction skill over the western U.S. with potential areas for improvement specifically aimed at representing the hydrometeorology of orographic systems, and use of seasonal forecasts for water resource management in the western U.S.

3.3 Deliverables

The following will be delivered as a result of the research implementation activities:

- Assessment of observational requirements and limitations for mountainous regions;
- Improved understanding of the dynamic and thermodynamic effects of mountains;
- Comprehensive analyses and predictions of orographic precipitation;
- Analysis of skill in predicting large scale fluxes controlling orographic processes;
- Improved modeling tools for seasonal climate and hydrologic prediction in complex terrain; and
- Examined value of improved seasonal climate and hydrologic prediction for water management in the western U.S.

4. WARM SEASON PRECIPITATION

GAPP Warm Season Precipitation research addresses the first GAPP objective, pertaining to "*...monthly to seasonal predictions of precipitation and land-surface hydrologic variables...*". Operational seasonal-to-interannual predictive skill in the warm season is very low relative to winter predictability, especially when it is based just on oceanic boundary conditions. Because the relative effects of land-surface forcing are particularly pronounced during the warm season, it is logical for GAPP to focus on warm season prediction efforts. The GAPP Implementation strategy is based on improving the observational climatic data base and theoretical understanding of hydrometeorological processes in the core of the North American continental warm season precipitation regime, defined by the North American Monsoon System. The monsoonal implementation focus builds on the success of GCIP to the east in the Mississippi River Valley and meshes with the international CLIVAR focus on monsoonal systems throughout the Americas. The North American Monsoon Experiment (NAME) provides the principal operational focus for the implementation of GAPP research on warm season precipitation.

4.1 Background

4.1.1 Science

GAPP follows a successful study of the hydrologic cycle across the Mississippi River basin called GCIP. The GAPP study area, to the west of the Mississippi River basin, 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 precipitation variability. Documenting the major elements of the NAMS regime and its variability, within the context of the evolving land surface-atmosphere-ocean annual cycle, is fundamental for improving warm season precipitation prediction across the GAPP study area.

The NAMS displays many similarities (as well as some differences) with other regional monsoons, most notably the southern and eastern 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. 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 (both increases and decreases) that arise as a result of coastal geometry, topography and latitudinal distribution of the continents. The complex topography of the GAPP study area poses special challenges for parameterization of convective warm season precipitation in numerical models.

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.

Individual warm season 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 in the NAMS domain appears to be a response to subtle variations in the distribution of tropical sea surface temperatures (SSTs), but the continental response to these tropical anomalies is less robust in summer than in winter. 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.

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.

Recent research suggests that the strength of seasonal land surface-atmosphere interactions is strongly modulated on the decadal time scale. There are 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 are intimately intertwined with decadal and longer climate change.

4.1.2 Objectives

In order to achieve the first GAPP science objective with respect to warm season precipitation, and to maximize the contribution of GAPP research towards the second GAPP objective, improvements in three broad implementation areas must be accomplished.

1. <u>Improved simulation of convective precipitation in climate models.</u>

Recent GAPP research has highlighted the sensitivity of model simulations in the GAPP regions to choices of convective parameterization and model physics. There is general agreement that the GAPP science community cannot undertake the task of constructing new convection schemes in isolation. However previous GAPP research presents a major opportunity for engaging model development experts to make significant improvements in convective precipitation treatments that could potentially benefit the entire atmospheric sciences community.

2. <u>Improvements in sustained observations, derived products, and information dissemination.</u>

GAPP is funding major enhancements to warm season precipitation observations across the North American Monsoon domain as part of the NAME 2004 Enhanced Observing Period. Some observing system enhancements are already in place. Additional short term enhancements, such as a cooperative network of simple raingauges in the GAPP region, are anticipated. GAPP research must address issues pertaining to the long term observing and information dissemination systems associated directly with precipitation, and the land surface products that are essential for diagnostic studies of precipitation.

3. <u>Improvements in operational climate prediction of warm season precipitation.</u>

Recent exploratory diagnostic research on seasonal prediction of warm season precipitation has shown that promising suggestions of land surface-based prediction are not stationary in time. Such nonstationarity has inhibited operational acceptance of these empirical forecast techniques. Dynamical model research has emphasized sensitivity studies rather than true prediction as the fidelity of simulating warm season precipitation with these models is established.

4.2 North American Monsoon Experiment (NAME)

NAME is an internationally coordinated, joint CLIVAR-GEWEX process study aimed at determining the sources and limits of seasonal-to-interannual predictability of warm season precipitation over North America. NAME has a major emphasis on the role of the land surface and the role of the Great Plains and Gulf of California low-level jets. NAME integrates these GAPP-focused activities with studies of the role of oceanic forcing of continental climate anomalies, since ocean memory components evolve slowly and are to some degree predictable in their own right and warm season correlations between SST and continental precipitation are at least marginal.

NAME research is overseen and directed by a Science Working Group (SWG) that has been approved by the GAPP SAG, US CLIVAR Pan American Panel and SSC, and the International CLIVAR VAMOS panel. The SWG is charged with developing and leading cooperative international research to achieve the NAME science objectives. It is made up of scientists who are involved in the process study research and are committed to the success of the project.

The SWG has established the NAME 2004 Forecast Operations Centers (FOC's), organized jointly between the National Weather Service (Tucson WFO as lead) and the Mexican Weather Service (SMN). The FOC's have rotational teams of forecasters from the NWS, SMN, NCEP and DOD (tentatively) as well as private and retired forecasters. In support of the FOC, NAME is organizing a composite precipitation dataset that includes a wide variety of estimates (gauge, satellite, radar and multi-sensor) for comparative analysis and forecast verification during NAME 2004.

The NAME 2004 field campaign will operate for a period of four summer months (JJAS 2004) to coincide with the peak monsoon season and maximum diurnal variability. Proposed NAME 2004 field networks include the NAME Tier I Instrumentation and regional enhancements (Tiers II and III). The NAME Tier 1 network includes wind profilers, radars (SMN and NCAR S-Pole), radiosondes, research vessels, buoys, event logging raingauges, in-situ soil moisture sensors, and research aircraft operations. Regional enhancements include radiosondes in Mexico and the Southwest United States, a network of PIBALS, and a cooperative network of simple raingauges. Some enhanced monitoring activities (e.g., SMN radiosondes, simple raingauge network, and event logging raingauge network) will operate before, during and after the NAME 2004 Field Campaign.

Several recent international developments are indicative of a growing momentum in the meteorological, oceanographic, and hydrological communities of Mexico and Central America to improve observational networks in the region. The timing for the NAME field campaign in 2004 appears to be right for the synergism of international efforts in the region. The Mexican National Weather Service (SMN) has already made several major contributions to the NAME project, including Meteorological Infrastructure (synoptic stations, radiosonde observations, and radars), historical and real-time data, and a rotating team of forecasters for the NAME Forecast Operations Centers. NAME has also developed strong international partnerships with universities and institutions in northwest Mexico, who are contributing equipment and personnel for NAME and participating in data collection and research activities.

The VAMOS/NAME Project Office has been established at the UCAR Joint Office for Science Support (JOSS). The Project Office will (i) provide the requisite infrastructure for the design and implementation of the NAME 2004 field campaign, (ii) manage the NAME program field operations (including relevant communications) for the accomplishment of the NAME scientific objectives; (iii) provide scientific data management services to NAME, including data collection and dissemination; and (iv) provide specialized logistics support for the implementation of NAME, including administrative and fiscal support, workshop/conference/educational and specific training, coordination and implementation.

More information about these activities is available on the NAME webpage, hosted by UCAR JOSS, at http://www.joss.ucar.edu/name.

4.3 NAME modeling and data assimilation

NAME has organized a modeling-observations team, charged with

- providing guidance on needs and priorities for NAME 2004 field observations;
- identifying the path to improved warm season precipitation prediction; and
- identifying additional process studies necessary to reduce uncertainties in coupled models

One activity organized by this team is the North American Monsoon Assessment Project "NAMAP", an important opportunity to benchmark the ability of global and regional models to simulate the North American summer monsoon. Protocols for simulating the 1990 monsoon were established, and results are summarized in a NAME Atlas (http://www.joss.ucar.edu/name). Results serve as a benchmark and guide for NAME 2004 enhanced observations. It is anticipated that a NAMAP follow on activity (NAMAP2) will emerge following the NAME 2004 field campaign.

In order to identify the path to improved warm season precipitation prediction, the team assembled a "White Paper" entitled "NAME Modeling and Data Assimilation: A Strategic Overview" that will serve as a roadmap for NAME modeling, data assimilation and analysis, and predictability and forecast skill activities. The team identified three distinct roles that observations play in model development and assessment:

- to guide model development by providing constraints on model simulations at the process level (e.g. convection, land/atmosphere and ocean/atmosphere interactions);
- to help assess the veracity of model simulations of the various key NAMS phenomena (e.g. Gulf surges, low-level-jets, tropical easterly waves) and the linkages to regional and larger-scale climate variability; and
- to provide initial and boundary conditions, and verification data, for model predictions.

The latest version of the white paper is found on the NAME web page at: http://www.joss.ucar.edu/name/science_planning/name_modeling.doc

NAME multi-scale model development activities presume that deficiencies in how we model "local" processes that modulate deep convection are the leading factors limiting precipitation forecast skill in both global and regional models during the warm season. In order to achieve the desired improvements, NAME will focus on:

- moist convection in the presence of complex terrain and land/sea contrasts;
- land/atmosphere interactions in the presence of complex terrain and land/sea contrasts; and

- ocean/atmosphere interactions in coastal regions with complex terrain.

NAME development efforts are envisaged to be both “bottom–up” (i.e. process-level modeling that is scaled-up to address parameterization issues in regional and global models) and “top-down” (i.e. regional and global models are scaled-down to address issues of resolution and the breakdown of assumptions that are the underpinnings of the physical parameterizations).

NAME is currently organizing a Climate Process Team whose phenomenological focus is the diurnal cycle of convection in complex terrain; the team is identifying one or two key physical processes that are deficient in global and regional models (e.g. orographic forcing of deep convection). These activities will contribute to CPPA science objectives and to the emerging NOAA Intraseasonal-to-Interannual Prediction (ISIP) Program.

Assimilated data sets in NAME will:

- enhance the value and extend the impact of the NAME Tier I observations to address issues of model quality and monsoon variability on larger scales (e.g. the out-of-phase relationship between the Southwest and the Great Plains of the U.S.); and
- provide an important framework for quantifying the impact of the Tier I observations on the quality of analyses, and for identifying model errors and attributing them to model deficiencies.

Current and proposed global and regional reanalysis activities will be critical in this process. Regional data assimilation (e.g., the NCEP Regional Reanalysis) will be critical for improved understanding of key components of the NAMS (e.g., surges and jets). Global data assimilation will be critical for linkages to the large scale and the roles of remote boundary forcing.

Key issues for NAME predictability and forecast skill activities are:

- to determine the extent to which model improvements translate into improved dynamical predictions; and
- to determine the impact on predictions of improved initial and boundary conditions.

This will allow NAME to address key questions (ultimately critical for improved warmseason precipitation prediction).

Specific objectives of NAME Predictability Research (includes both Hindcast experiments and NAME 2004 case studies) are:

- to investigate the relative importance of oceanic and land-surface boundary forcing on warm season precipitation prediction;
- to examine whether observed connections between the leading patterns of climate variability (MJO, ENSO) and the NAMS are captured in global models; and

- to determine the predictability and prediction skill over the NAMS region associated with the leading patterns of climate variability.

NAME will endeavor to preserve and strengthen its linkage to the operational centers (e.g. NCEP) by including NWS meteorologists in the NAME FOC's and on the NAME SWG, and by including EMC physical parameterization experts in the NAME Modeling-Observations Team.

4.4 Deliverables

The NAME Program will deliver the following:

- Observing system design for monitoring and predicting the North American monsoon system;
- More comprehensive understanding of North American summer climate variability and predictability;
- Strengthened multinational scientific collaboration across Pan America; and
- Measurably improved climate models that predict North American monsoon variability months to seasons in advance.**4.5 Linkages to other programs**

GAPP research on warm season precipitation will contribute to the North American component of the Coordinated Enhanced Observing Period (CEOP). CEOP and NAME are coherent in terms of timing (2004 is the CEOP second annual cycle period). A key issue for CEOP is an international commitment and cooperation on data collection and exchange. NAME has very strong international collaboration between the US and Mexico, and between both GEWEX and CLIVAR. Other anticipated benefits of a strong NAME-CEOP linkage include joint international experience in the exploitation of new in-situ and satellite data; the production of consistent data sets that can act as test beds for the validation of numerical model products and remote sensing data; advancements in coupled model development over land and ocean areas; and advancements in the development of the climate observing system.

GAPP must maintain strong ties to:

- Other monsoon-related projects, such as the international CLIVAR VAMOS Monsoon System South America (MESA) program, and CLIVAR/GEWEX sponsored studies of the Asian monsoon systems. These ties will be facilitated greatly through joint research efforts supported by the merged PACS-GAPP program that is part of NOAA's Intraseasonal-Interannual Prediction (ISIP) Program;
- The U.S. and International CLIVAR programs, which are conducting considerable warm season precipitation research over the oceans (e.g. EPIC, VOCALS), complementing GAPP's emphasis on continental precipitation;
- NASA's Global Precipitation Monitoring Project to strengthen long-term precipitation monitoring activities;

- The NOAA RISA programs, which will help GAPP ascertain promising targets for enhanced precipitation monitoring, prediction, and information dissemination, thereby linking GAPP warm season precipitation research to the second GAPP objective pertaining to water resources management;
- NRCS and USGS for more extensive land surface data sets; and
- The DOE ARM program for high-quality data on cloud and radiation variability that would enhance GAPP research on warm season precipitation.

5. CEOP

The overall goal of the World Climate Research Programme's (WCRP's) Coordinated Enhanced Observing Period (CEOP, see IGPO 2001) is to understand and model the influence of continental hydroclimatic 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 model output from 1 July 2001 to 31 December 2004. In-situ measurements are being archived at UCAR as GAPP's contribution to CEOP data management. Many GAPP researchers are contributing major amounts of in-situ data, global model output and remote sensing products to UCAR's and other international CEOP data archive centers. GAPP researchers will be making major contributions to the analysis of the CEOP data set as part of the CEOP Water and Energy Simulation and Prediction (WESP) studies, Monsoon Studies (MS), and remote sensing studies.

CEOP studies will help GAPP to achieve its first objective:

"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-related hydrometeorological and boundary layer processes in climate and prediction models"

5. 1 Background

5.1.1 Science

CEOP (see e.g. Bosilovich and Lawford 2002) is focused on the measurement, understanding, and modeling of water and energy cycles within the climate system. It is motivated by the synchronism of the new generation of Earth observing satellites and GEWEX Continental Scale Experiments (CSEs). Its primary goal is to develop a consistent data set for 2001-2004 to support research objectives in climate prediction and monsoon system studies. The requirements of the international climate research community at large have been taken into account in planning the assembly of the data set. CEOP data will also contribute to studies of global atmospheric circulation and water availability. CEOP has gained the interest of a broad range of international organizations, as evidenced by the proposal for a Water Cycle theme within the framework of the International Global Observing Strategy Partnership (IGOS-P). CEOP aims to integrate the many streams of data coming from new space and ground-based observation and model assimilation systems into a coherent database relevant to CEOP science issues.

There are two international science working groups under CEOP: (1) Water and Energy Simulation and Prediction (WESP) studies, and (2) Monsoon studies (MS).

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? and (3) What is our skill in predicting hydroclimatological water and energy budgets? As a contribution to CEOP/WESP, GAPP will develop continental water and energy budget studies, land data assimilation studies, and transferability experiments.

MS 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, MS are focusing on developing CEOP Inter-Monsoon Model Studies (CIMS). Validation data will be derived from CEOP reference sites, which include GEWEX continental scale experiments (CSE) as well as from planned CLIVAR field campaign sites. A hierarchy of models including general circulation models, regional climate models, and cloud resolving models will be used. The North American Monsoon Experiment (NAME; Section 4) will be GAPP's major contribution to MS.

5.1.2 Objectives

As part of CEOP, GAPP will:

1. Provide in-situ, remote sensing and global and regional land and coupled assimilation water and energy budget products for GAPP and CEOP global regions.

Associated studies will include analysis of physical processes on diurnal to seasonal time scales using the extensive data collected at the GAPP CEOP Reference Sites.

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.

To effectively participate in CEOP, GAPP will need access to new satellite products, for example, detailed land cover, vegetation mapping and derived products from LANDSAT-7 and the suite of surface and atmospheric observations provided by the Earth Observing System (EOS) and other orbiting platforms.

3. Evaluate the performance of global and regional coupled and uncoupled, atmosphere-land models across a spectrum of continental climatic zones and forecast time scales.

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 will also improve the quality of CEOP data archives over GAPP and other regions.

5.2 Implementation activities

CEOP has undertaken an internationally coordinated effort to develop in-situ data, remote sensing products, and model output from 1 July 2001 to 31 December 2004. The CEOP observation and data collection time period (IGPO 2001) takes advantage of the maturing capabilities of the GEWEX Continental Scale Experiments (Lawford et al. 2003). Besides GAPP, the regional experiments include: the Baltic Sea Experiment (BALTEX), the GEWEX Asian Monsoon Experiment (GAME), the Large-scale Biosphere Atmosphere Experiment in Amazonia (LBA), the Mackenzie GEWEX Study (MAGS), and the Murray Darling Basin (MDB). 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. Specific information about the GAPP contribution to the CEOP remote sensing algorithm development and application is provided in Section 8.

Three spatial scales (local, regional, global) are of interest to the CEOP community. At local scales, in-situ data from several international tower sites, along with level II and level III satellite data plus numerical model and 4DDA output for these same sites, will be consolidated into useful data sets for studying water and energy budgets. At regional and global scales, regional and global networks of more standard observations, as well as model and 4DDA output, are also needed for closing regional and global water and energy budgets and understanding monsoon interactions over land and ocean. Again, GAPP will contribute to CEOP/MS in collaboration with NAME (see Section 4).

In the rest of Section 5, we describe the initial GAPP in-situ data and model output and WESP studies that will be undertaken as part of GAPP.

5.2.1 In-situ data (5 GAPP sites)

The GAPP data management program at UCAR archives all of the international CEOP in-situ data, meaning that GAPP users will not only be able to access this data over US regions, but also other global climate regions. The sites listed below will provide comprehensive local information but additional ones are encouraged in order to more fully develop a true continental and global synthesis.

The three NOAA GEWEX air SURFace eXchange sites (SURFX) sites were established to provide detailed measurements and information about the physical and biological processes that occur at the land/surface interface. Key observations from these sites include the turbulent fluxes of heat, water vapor, momentum, and carbon dioxide. Mean atmospheric state variable (i.e. radiative flux, air temperature, relative humidity, etc.) are also measured. The sites were selected to provide detailed information for common land use types in the continental U.S.

The Department of Energy’s (DOE’s) U.S. Southern Great Plains (SGP) site was the first field measurement site established by DOE's Atmospheric Radiation Measurement (ARM) Program. The SGP site consists of in-situ and remote-sensing instrument clusters arrayed across approximately 55,000 square miles (143,000 square kilometers) in north-central Oklahoma. The ARM SGP site is the largest and most extensive climate research field site in the world and can be viewed as a real “laboratory without walls.” It should also be mentioned that the two other DOE sites will also be part of the international CEOP in-situ data archive.

The Mount Bigelow project is the first study to document, analyze, and model the water, energy, and (related) carbon exchanges of the Sky Island Forest ecosystem. The observations have year-round value. Data gathered in winter aids understanding of how water resources are replenished by winter snow and rain. Data collected in spring aids understanding of the partitioning of water between deep drainage and the near-surface environmental water resource that sustains the forest; while data gathered in the summer and fall aids understanding of the evolution of the environmental water resource as it is depleted by evapotranspiration but replenished by monsoon storms.

5.2.2 Model output

At least three US Numerical Weather Prediction (NWP) centers are currently participating in providing global data to the CEOP Model Output Archives at the Max Planck Institute for Meteorologie (MPIM). These include the NASA Global and Modeling Assimilation Office (GMAO), the National Centers for Environmental Prediction Center (NCEP/EMC), and the Scripps Experimental Climate Prediction Center (ECPC). However, additional modeling center contributions are encouraged, especially in regards to focused regional model output over the GAPP region. In that regard, the pending NCEP regional reanalysis will provide a useful regional analysis counterpart to the global model analyses being provided to the international CEOP model output archives at MPIM. Besides comprehensive 3-D model output, these centers will be providing Model Output Reduced Grids (MORDS) and Model Output Location Time Series (MOLTS).

NCEP global and regional reanalysis products will be available during CEOP. Data sets include: (1) Global Reanalysis I (L28T62 grid); (2) Regional Reanalysis (32-km, 45-layer); (3) operational Eta/EDAS forecasts and 4DDA (MOLTS point-wise time series, and MORDS 40-km gridded fields); (4) operational MRF/GDAS forecasts and 4DDA; (5) weekly global SST (1-deg resolution); and (5) daily sea-ice cover (N.H., nominally 50-km, provided via NESDIS). Also during CEOP, NCEP will contribute analyses of precipitation, SST, snow cover and sea-ice, as follows: (1) global, 2.5-degree, 5-day, gage/satellite precipitation analysis in real-time, and reanalysis to January 1979; (2) U.S., 0.25-degree, daily, gage-only precipitation analysis in real-time, and reanalysis to January 1948; (3) U.S., 4-km, hourly, radar/gage precipitation analysis in real-time, with archive to July 1996; (4) Mexico, 1.0-degree, daily, gage-only precipitation analysis in real-time, and reanalysis to January 1948; (5) global, 1.0-degree, weekly, SST analysis in real-time, and reanalysis to November 1981; and (6) N. Hemisphere, 25-km, daily, snow cover and sea ice analysis in real-time, with archive to January 1997 (via NESDIS partners).

ECPC works with NCEP to help develop and analyze their global models. In particular, ECPC model output data sets include: (1) NCEP/DOE global Reanalysis II (L28T62 grid); and (2) a more recent Seasonal Forecast Model (SFM) model initialized from Reanalysis II (L28T62 grid). ECPC is making a special effort to develop an extensive archive of 3-D water and energy processes and variables that will fully satisfy the CEOP WESP request.

The NASA GMAO is in the process of finalizing and releasing a new operational data assimilation system, called the Finite Volume Data Assimilation System (FVDAS). The FVDAS is more computationally efficient than its predecessor. GMAO expects to be producing 0.5-degree resolution operational analyses by 2003 (the current system is running at one degree global resolution). Output diagnostics produced by the GMAO have historically included complete data to evaluate budgets and the impact of the analysis increments. GMAO is currently developing and testing the ability to assimilate total precipitable water and precipitation (monsoon research), and land surface temperature (energy cycle research). These advances are going to be added incrementally to the operational system. Therefore, the operational data time series may be significantly fragmented as new data or improvements to the system are added and NASA may eventually undertake a CEOP reanalysis.

Finally, 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 LDAS (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). A corresponding Global Land Data Assimilation System (GLDAS) that uses various new satellite and ground based observation systems within a land data assimilation framework to produce optimal output fields of land surface states and fluxes has been subsequently developed by NASA (Houser et al. 2001). The added advantage of GLDAS is its use of satellite-derived observations (including precipitation, solar radiation, snow cover, surface temperature, and soil moisture) to realistically constrain the system dynamics. This allows it to avoid the biases that exist in near-surface atmosphere fields produced by atmospheric forecast models, minimize the impact of simplified land parameterizations, and to identify and mitigate errors in satellite observations used in data assimilation procedures.

5.2.3 Research activities

CEOP will increase the value of GAPP (and GEWEX) data sets for the academic and operational communities in the US by providing opportunities for global and regional climate modelers to have access to detailed information about water and energy processes for not only the GAPP region but also other similar and diverse climate regions around the world. In particular, besides the above-mentioned data production activities, NAME (Section 4) and remote sensing studies (Section 8) GAPP will foster Water and Energy Budget Studies (WEBS), Land Data Assimilation System (LDAS) studies, and transferability research.

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 extension of GAPP to the entire US, it is reasonable to ask what the corresponding water and energy budgets are for this larger and climatically more diverse region from the “best available” observations and models. CEOP will provide new in-situ and remote sensing measurements as well as a number of global analyses/forecasts and the recently completed regional reanalysis (Mesinger et al. 2003).

Four central scientific questions are being addressed by the LDAS community: (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?

GAPP regional modeling results have been developed and evaluated largely from the data obtained within the US region. The extension of these regional models to other geographic and climate regions is an important prerequisite to transferring the atmospheric land components to global NWP and climate models. Adapting scientific results achieved at one scale to applications on another scale is also a critical aspect of transferability and the development of global parameterizations as a result of regional studies will follow. CEOP is 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 global model data assimilation and forecast systems over the entire globe. GAPP will pay special attention to the Americas as part of its CEOP regional model transferability contributions. In particular, there has already been established the Project for Intercomparison of Regional Climate Simulations (PIRCS; see Takle et al. 1999) over the US and the La Plata Basin transferability study (Berbery and Colini 1999) over South America, which will take advantage of the CEOP data sets to assess the capability of current global and regional models to simulate and eventually predict hydroclimatic variability. Other transferability studies are encouraged.

5.3 Deliverables

As part of its contribution to CEOP, GAPP is providing observations from five high-quality in-situ US sites, atmospheric model output from three US NWP centers, and surface hydrometeorological output from many US centers. Additional in-situ observations and model output are encouraged. The US remote sensing data contribution to CEOP is still being developed and is discussed in Section 8. As previously mentioned, data sets and research being developed for NAME (Section 4) will also make substantial contributions to CEOP MS goals. There are also a number of additional GAPP research activities being developed that will contribute to CEOP WESP goals.

WEBS comparisons and other studies are being developed to understand hydrometeorological vertical, diurnal, seasonal, interannual characteristics, and whether these characteristics can be adequately simulated and predicted by regional and global models. Comparisons of NCEP/NCAR, NCEP/DOE, NASA/DAO and other global and regional reanalyses with observations are being developed to assess the differences that can arise in various analysis systems and how different model parameterizations may contribute to these structural differences.

There are a number of regional as well as a global LDAS projects underway as part of GAPP and additional ones are encouraged. By their nature, LDAS intrinsically involves comparisons between a number of models, which show similar but distinctly different responses to observed forcings. These multiple responses thus provide a possible envelope of modeling and observational uncertainty.

Models need to be applied in different settings. It is important to not only analyze global and regional models over GAPP and other regions but to also test models developed in other regions over the GAPP region. Two initial regional model transferability experiments have been identified, but additional community and individual studies with global and regional models are encouraged.

6. OPERATIONAL SEASONAL CLIMATE PREDICTION: COMPONENTS FROM GAPP

The strategic mission of GAPP is to A) demonstrate skill in predicting changes in water resources (streamflow, precipitation, snowpack, soil moisture) at intraseasonal-to-interannual time scales and B) operationally implement that skill in the operational seasonal prediction suites of GAPP operational partners, such as NCEP, NASA, and IRI. Achieving this mission requires both a prediction component and a decision-support component. The prediction component is comprised of both an atmospheric prediction component and a surface-hydrology prediction component. Section 6 presents the GAPP implementation strategy for improving the operational atmospheric prediction component, by means of 1) providing improved land-model components for the coupled land/atmosphere prediction models, 2) developing and implementing global and regional land data assimilation systems, and 3) developing, demonstrating and implementing regional climate models. Section 7 subsequently provides the implementation strategy for the surface-hydrology prediction component and water-resource decision support.

6.1 Background

6.1.1 Science

This section describes an infrastructure for constructing and achieving a multi-scale, multi-model, end-to-end, ensemble seasonal prediction system – to be first demonstrated in hindcast mode and then secondly transitioned into operations. Henceforth, "seasonal prediction" here in this section is understood to span intraseasonal (1-2 months) to seasonal (3-8 months) to annual (9-12 months). The infrastructure advocated by GAPP for the end-to-end seasonal prediction system is depicted in Figure 6.1. Though this infrastructure is described further below, for a more extensive discussion of the scientific rationale and existing research base for this prediction system, readers are encouraged to examine Chapter 8 of the forerunner GAPP Science Plan (available online at http://www.ogp.noaa.gov/mpe/gapp/background.pdf).

Figure 6.1 is an extension of the widely cited 'Shukla Downscaling Staircase' presented by J. 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 seasonal prediction/predictability infrastructure in Figure 6.1 is composed of free-running prediction models and 4-D data assimilation systems (4DDA) ingesting in-situ and satellite observations into assimilating "background" models. The models in the prediction and companion 4DDA components of Figure 6.1 are frequently and ideally the same model. For both the prediction and data assimilation capabilities, the comprehensive infrastructure of Figure 6.1 includes:

- land, atmosphere, and ocean,
- global and regional,
- coupled and uncoupled,
- retrospective and real-time

The pathfinder research already accomplished by the GEWEX program, and its sub-programs such as GHP, GCIP, ISLSCP, GMPP, 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 the integrated, end-to-end, multi-scale, land-ocean-atmosphere seasonal prediction system.

The key extension added in Figure 6.1 to the traditional depiction of the 'Shukla staircase' is the companion suite of land, atmosphere, and ocean data assimilation components to initialize the atmospheric, ocean and land states of the prediction models. The figure begins in the upper left corner 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 modeling suite in the upper left (denoted OAL-GCM) is a coupled global ocean/atmosphere/land general circulation model. The second modeling suite in the lower left (denoted AL-GCM) is a coupled global atmosphere/land general circulation model (possibly at higher resolution then the OAL-GCM). The AL-GCM suite has no coupled ocean component, but rather uses time-dependent SST fields externally provided by either the OAL-GCM of the upper left (or another OAL-GCM suite from another center) or by empirically predicted SST fields. The third modeling suite in the lower right is a high resolution, imbedded, coupled atmosphere/land regional climate model (RCM), using the same externally provided SST fields as provided to the parent OAL-GCM/AL-GCM. The fourth modeling suite in the upper right is a high-resolution, uncoupled, land-only macroscale hydrology model (MHM), such as those discussed in Section 7.

While the ultimate objective of GAPP is to achieve more skillful seasonal prediction by implementing and improving the land, RCM and MHM components of Figure 6.1 in operational realtime systems at centers like NCEP or IRI, such an operational system must be accompanied by an extensive multi-year hindcast system, in order to cast the predictions more skillfully in terms of anomalies from the models' own climatologies. The hindcast system in turn can double as 1) a system for a priori demonstration of prediction skill to justify transition to operations and 2) as a powerful research testbed to carry out land-memory predictability studies, land-atmosphere coupling studies and physical process studies, such as those called for in the prior Sections 2-5.

As an example of the role of a priori demonstration of prediction skill in the hindcast mode of Figure 6.1, the RCM component will be retained in actual operations as a dynamical downscaling component only if the RCMs demonstrate in hindcast mode useful additional skill over and above the parent GCMs (especially empirically or statistically downscaled and bias-corrected GCMs).

6.1.2 Objectives

The global atmospheric and ocean prediction components of Figure 6.1, including their companion global atmospheric and ocean data assimilation components, are already in place at several operational and research centers. Instead, the GAPP program seeks to develop, improve, demonstrate and transition to operations the added predictive value of the following four components of Figure 6.1:

1. <u>Global and regional land data assimilation systems (LDAS),</u>
2. <u>Improved land surface models (LSMs) for the coupled global andregional models,</u>
3. <u>High resolution regional climate models (RCMs), and</u>
4. <u>High resolution, uncoupled, regional macroscale hydrology models (MHMs)</u>.

This section presents the implementation activities for achieving objectives 1 – 3 in A) demonstration hindcasts and B) transition to operations. Section 7 then follows with the implementation activities to achieve objective 4.

6.2 Implementation activities

Within the setting of Figure 6.1, GAPP will execute studies to demonstrate the following:

- the relative value to seasonal predictability and prediction from improvements to the initialization and physical realism of land models, land processes and land-atmosphere coupling, and
- the relative value to seasonal atmospheric predictability and prediction from the successive dynamical downscaling by the AL-GCM suite and/or the RCM suite (relative to empirically or statistically downscaling and bias correcting the OAL-GCM ensembles).

The four modeling suites in Figure 6.1 (OAL-GCM, AL-GCM, RCM, MHM) need not all be in place at a given institution for that institution to contribute model or assimilation research and demonstrations in support of the figure's implementation strategy. In the U.S. for example, under the umbrella of U.S. seasonal prediction centers (such as NCEP, IRI, GFDL, NSIPP) and the NOAA OGP-sponsored Applied Research Centers (ARCS, such as COLA, ECPC), which are partially funded by OGP programs such as CDEP, GAPP, and PACS, it is likely that the real-time and hindcast global system for the coupled ocean/atmosphere/land prediction model -and the companion global ocean 4DDA and global atmospheric 4DDA -- will be in place at only a handful of institutions (e.g. NCEP, IRI, GFDL, NSIPP). Yet the global SST predictions and global atmospheric predictions provided from the OAL-GCM component of these latter institutions can be provided to a host of GAPP collaborating institutions to drive their own experiments, research and demonstrations in the following components of Figure 6.1:

- the global and regional land data assimilation systems (LDAS),
- the regional climate models (RCMs), and
- the macroscale hydrological models (MHMs).

Two keys roles of GAPP will be to offer coordination and planning mechanisms (see Section 10) to unify the above LDAS, RCM, and MHM efforts around common goals and strategies, and joint experiments, studies, or demonstrations, culminating with technology infusion into NOAA and NASA operations. Next, Sections 6.2.1 and 6.2.2 describe how these GAPP roles can be fulfilled now and in the near future for the LDAS and RCM components, respectively, by building upon and leveraging important infrastructure put in place for modeling, observations and new-products by GAPP's predecessor program, known as GCIP. Section 7 similarly addresses the MHM components.

One component that is important to the aforementioned two roles of GAPP is the NOAA GAPP Core Project, as cited earlier in Section 1.3. The NOAA GAPP Core Project is comprised of NCEP, OHD, and NESDIS entities and has the responsibility for NOAA's operational implementation of the components of Figure 6.1 that are most central to GAPP (LDAS, RCMs, and MHMs). In turn, the Core Project is crucially aided by numerous GAPP collaborators, including PIs from NOAA labs, NASA and numerous GAPP-sponsored university PIs. Moreover, the GAPP Core Project is and will act to spur and oversee the transition into NCEP and OHD operations of demonstrated improvements and methods from the GAPP research community in the components of LDAS, RCMs, and MHMs.

6.2.1 Land data assimilation

A hallmark of GAPP, and its predecessor GCIP, is its flagship role in the development and demonstration of both global and regional land data assimilation systems, both coupled and uncoupled. The OGP-funded North American Land Data Assimilation System (NLDAS) project (Mitchell et al., 2004) spearheaded by the NCEP component of the GAPP Core Project is a demonstrated example of success in this area. The recent GCIP3 special issue of JGR includes ten papers (see Table 1 Mitchell et al., 2004) presenting extensive results and validations of four different land models in the NLDAS setting, both realtime and retrospective, via the simultaneous application of a wide host of new GAPP products and deliverables. Hence the benchmark pilot system for the regional LDAS component of Figure 6.1 has been delivered by GAPP.

Simultaneously, the GLDAS initiative (Rodell et al., 2004) spearheaded by NASA/GSFC/HSB in partnership with NCEP (plus COLA and Princeton University) is making rapid progress in developing and demonstrating a real-time and retrospective uncoupled GLDAS, as well as transitioning the uncoupled GLDAS to NCEP operational platforms for application in the NCEP execution of the Figure 6.1 infrastructure. The joint NLDAS and GLDAS thrusts of NASA and NCEP have been formally included in the new NCEP-NASA-DOD Joint Center for Satellite Data Assimilation (JCSDA), which will provide external PIs access to the NLDAS and GLDAS infrastructure for research purposes. The NCEP and NESDIS components of the GAPP Core Project will utilize the JCSDA infrastructure as a platform to transition GAPP-sponsored LDAS research and development into NCEP seasonal prediction operations.

An LDAS is the crucial land component that will provide the initial conditions of soil moisture, soil temperature, snowpack and vegetation state 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. The application of the coupled LDAS approach in the NCEP North American Regional Reanalysis or NARR (Mesinger et al., 2004), via the Noah LSM and precipitation assimilation incorporated into NARR by the GAPP Core Project, provides a clear demonstration of the benefits of using LDAS in regional data assimilation (see example figures provided at http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/narr_landsfc.ppt).

A key thrust in global LDAS initiatives will be to demonstrate whether the state-of-the-art in the assimilation of satellite-derived estimates of precipitation, cloud water and water vapor in global coupled land/atmosphere data assimilation is sufficient to overcome the typically severe precipitation and cloud-cover/solar-insolation biases that characterize such present-day coupled 4DDA systems. In the early phases of GAPP, while awaiting demonstration that such a fully coupled land/atmosphere assimilation system can produce realistic precipitation and cloud-cover/solar insolation pattern with little bias, the LDAS for the integrated seasonal prediction system will likely be uncoupled or quasi-coupled, wherein satellite-based precipitation and solar insolation fields are used directly in forcing the land surface. The latter "quasi-coupled" approach to coupled land/atmosphere assimilation is akin to the "flux-correction" approaches (Ji et al., 1994) employed in the early years of coupled ocean/atmosphere data assimilation.

A second key thrust of GAPP LDAS initiatives is the development of algorithms for the assimilation of satellite-derived land-state information (soil moisture content, vegetation state, snow pack water content, land surface skin temperature) (Houser et al., 1998; Reichle, 2000). This effort will include the development of adjoint models and Kalman Filter (KF) models needed by variational assimilation methods. In this context, new forward radiative models for land surface emissivity are being developed by GAPP-sponsored PIs to transform LDAS land states and surface characteristics into the satellite radiance channels (e.g. microwave bands) measured by the growing number of satellite instruments in the EOS era. Section 8 discusses the various current and near-future satellite platforms that will provide remotely sensed observations relevant to land-state assimilation.

6.2.2 Regional climate modeling

As stated prior to Section 6.2.1, two keys roles of GAPP, including the GAPP Core Project, will be to offer coordination and planning mechanisms (see Section 10) to unify the LDAS, RCM, and MHM efforts around common goals, strategies and joint experiments, studies, or demonstrations.

One such mechanism would be for the GAPP, PACS, and CDEP programs of OGP to jointly support, coordinate and launch second phases for the Project to Intercompare Regional Climate Simulations, or PIRCS (Takle et al., 1999) and the North American Monsoon Model Assessment Project, or NAMAP (Gutzler et al., 2004). The already completed first phase of both the PIRCS and NAMAP initiatives utilized RCMs executed in "simulation mode" – that is, they used analyzed SST and analyzed lateral boundary conditions (from NCEP global reanalysis). RCMs executed in simulation mode are suitable for carrying out important physical process studies and inter-comparisons of such across different models. Nevertheless, the follow-on phases of such initiatives must embrace not only simulation mode but actual prediction modes as well. Altogether, such follow-on RCM initiatives must embrace each of the three following modes:

- simulation mode (analyzed lateral boundary conditions and observed SST)
- quasi-predictive mode (GCM predicted lateral boundary conditions and observed SST), and
- fully-predictive mode (GCM predicted lateral boundary conditions and predicted SST)

In the latter fully-predictive mode, the GCM predictions must also use predicted SST (via OAL-GCM with dynamically predicted SST, or AL-GCM with empirically predicted SST). NCEP for one is striving to construct, execute and demonstrate all the prediction components of Figure 6.1 in fully-predictive mode, together with NWS OHD for the MHMs component of Figure 6.1.

While there is a plethora of RCM simulation mode studies (Seth and Giorgi, 1998; Hong and Leetma, 1999; Takle et al., 1999; Gutzler et al., 2004; to name but a few of many), and a growing body of quasi-predictive RCM studies (Fennessey and Shukla, 1999; Leung and Ghan, 1999), fully-predictive RCM studies are sparse, though some are emerging (Kim et al., 2000). GAPP and sister programs of GAPP must spur RCM studies to meet the pressing need for a much wider demonstration of fully-predictive RCMs.

The success of imbedded RCMs in simulation and quasi-predictive modes comes from the ability of their higher resolution 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 precipitation anomalies.

The full potential of the RCM approach still requires substantial research and development to address the issues and problems of model spin-up, choice of convection schemes, 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. Despite these issues, Fennessey and Shukla (1999) have already shown quasi-predictive RCM seasonal skill for precipitation and temperature anomalies that surpasses that of the parent AGCM. It is notable that while the global modeling community continues to seek to improve numerous weak aspects of global model performance in dynamical seasonal prediction, this has not prevented the current generation of global models from being used for operational dynamical seasonal predictions, such as at NCEP and ECMWF. Similarly, PIs in RCM research feel that the RCM simulation-mode and quasi-predictive mode capabilities that have been demonstrated to date are more than sufficient to justify that GAPP spur initiatives to launch widespread RCM seasonal forecast experiments in "fully predictive mode".

The need for "fully-predictive mode" RCM experiments cannot be overemphasized. Prior to the last several years, most RCM research studies were executed in "simulation mode", with an eye toward such objectives as physical process studies, or defining and addressing RCM systematic biases, or providing an upper limit of RCM predictability. Instead, the strategy in this section proposes to additionally spur a suite of fully-predictive RCM seasonal prediction experiments, which would use predicted SST fields (either empirically predicted or dynamically predicted by OGCMs) and OAL-GCM or AL-GCM predicted lateral boundary conditions. The dual benchmark for determining the "value added" of the fully-predictive RCM seasonal predictions over and above those of the OAL-GCM or AL-GCM suites must be 1) the empirically or statistically downscaled and bias-corrected global predictions of the parent OAL-GCM or AL-GCM that provided the predicted lateral boundary conditions and 2)_empirical seasonal prediction tools, such as ENSO compositing, Optimal Climate Normals (OCN), or CCA (Canonical Correlation Analysis).

The foremost challenge of executing a meaningful set of fully-predictive RCM seasonal forecasts (e.g. a new 10-20 member ensemble of 4-month long RCM predictions launched monthly) is that such experiments MUST be preceded by a vast suite of multi-decade, fully-predictive hindcasts of the candidate RCMs. The long RCM hindcast set is critical for quantifying the RCMs' ability to capture realistic interannual variability and to cast the RCM predictions more skillfully in terms of anomalies from the RCM's climatology.

Though the latter is a daunting task in computer resources, file storage space and manpower, GAPP should begin now with a more modest pilot initiative that would attempt to produce a 10-year RCM hindcast database for one summer month (July) and one winter month (January). As the mechanism for such a pilot RCM retrospective, GAPP should seek to expand the scope of the PIRCS initiative to include a fully-predictive 10-year RCM hindcast thrust to complement the 10-year RCM simulation-mode experiments now underway in PIRCS. The latter fully predictive RCM hindcasts would then be examined to answer the following four questions with respect to the parent OAL-GCM/AL-GCMs:

- Is the spatial character of the interannual variability improved (at the regional scale)?
- Are the details provided by the higher resolution predictable, or are they just 'noise' on top of the regional signal provided by the parent OAL-GCM / AL-GCM?
- Is probabilistic information changed/improved (i.e. tighter and/or more reliable PDFs) regionally and/or locally?

- Is temporal character of variability improved (i.e. precipitation frequency, frequency of extreme events and wet/dry spells)?

The above GAPP-spearheaded, fully-predictive RCM seasonal forecasts experiments would be coordinated closely with the RCM research requirements and guidance provided by other OGP programs, including the Climate Diagnostics and Experimental Prediction program (CDEP) and the CDEP-sponsored Applied Research Centers (ARCs, e.g. COLA, ECPC, etc) and CDEP-sponsored initiatives in RCM prediction at IRI and NCEP. Indeed, recent discussions between GAPP authors of this section and CDEP principals of IRI, NCEP, ECPC and COLA yielded much of the framework embodied in the RCM experimental strategy outlined near the end of above section.

6.2.3 Companion predictability, physical process, and energy/water budget studies

In the prediction range of 1-12 months, pathfinder efforts at extended-range dynamical 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; Barnston et al., 1994) can yield extended-range predictability of time-mean regional anomalies of temperature and precipitation, especially in the Northern Hemisphere 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 prior Sections 2-5 of this science and implementation plan, GAPP will play a leading role in determining the predictability of warm-season anomalies in precipitation and temperature. GAPP will focus on land-state initialization, land-surface process studies and land-atmosphere coupling and feedbacks to complement the ocean-atmosphere coupling focus of CLIVAR.

With the exception of the ocean data assimilation component in Figure 6.1, every other modeling component of this figure includes a land-surface component (OAL-GCM, AL-GCM, LDAS, RCM, MHM). Thus we cannot over-emphasize that the extensive hindcast capabilities that must accompanying the infrastructure of Figure 6.1 (including the three modes of simulation, quasi-prognostic, and fully-prognostic) represents an optimum research testbed for

- GAPP investigations into the impact of land-memory (soil moisture, snowpack, vegetation) on seasonal predictability (Section 2), the relative ability of RCMs versus GCMs to resolve the hydrometeorology over rugged mountainous terrain (Section 3), physical process studies critical to achieving skill in seasonal forecasts of warm season precipitation, including monsoon systems (Section 4), and studies to assess the transferability and the surface water/energy budgets of land models across various climatic regions worldwide (Section 5), and
- GAPP participation in GEWEX land-memory and land-atmosphere coupling research within the GEWEX components of CEOP (Section 5), GABLS, and

GLASS (GSWP, PILPS, GLACE) and the North American Monsoon Model Experiment and North American Model Assessment Project (NAMAP) addressed in Section 4.

In summary, the hindcast mode of the infrastructure of Figure 6.1 provides the optimum research testbed for all seven research components illustrated earlier in Figure 1.1 of Section 1.

6.2.4 Improved land surface models

The physical process studies and water and energy simulation and prediction studies (WESP) cited above in Section 6.2.3 and in Sections 2-5 will yield improved land surface models (LSMs). The LSM improvements that emerge from the process studies and WESP studies will be robustly tested in both the uncoupled land-only LDAS systems of Section 6.2.1 and the coupled RCMs of Section 6.2.2. Both the NLDAS and GLDAS systems employed by GAPP investigators today are already configured to execute multiple LSMs in parallel. Such parallel LSM executions in LDAS will in turn yield still further improvements in the LSMs, as already demonstrated in the NLDAS studies of Mitchell et al. (2004). Once specific LSM improvements have been demonstrated in the uncoupled land-only LDAS setting, their validation can then be extended to the coupled setting of the RCM tests in Section 6.2.2 and OAL-GCM and AL-GCM executions.

Several areas of LSM improvement will receive particular attention in GAPP. Two areas are dynamic vegetation models and snowpack models, as emphasized in Section 2. The hallmark of the implementation activities for LSM improvement in this section will be the broadening of the scope of this LSM assessment by leveraging the hindcast infrastructure of Figure 1.1, to include multiple years and seasons, in both uncoupled (LDAS and MHM) and coupled modes (RCM and GCM) on both regional and global domains, and in a hindcast setting that can mimic the operational data streams that characterize actual operations.

6.3 Deliverables

As a product of the GAPP implementation activities described in Section 6.2, GAPP will deliver:

- Land Data Assimilation Systems (LDAS) on both the North American domain (NLDAS) and the global domain (GLDAS) that can execute in both hindcast mode and real-time operational mode with multiple land models in parallel. Additionally, GAPP will deliver NLDAS and GLDAS infrastructures, and their required input databases, that can be transferred to and executed at the home institutions of individual GAPP-sponsored PIs. The NOAA Core Project for GAPP, along with its NASA collaborators, will provide a central role in the provision, support, execution and validation of the NLDAS and GLDAS, as well as in land-memory predictability studies (see Section 2) to demonstrate the value of initial land states from LDAS on the seasonal predictability of GCMs and RCMs.

- Coupled land-atmosphere Regional Climate Models (RCMs) that have been validated and inter-compared with each other and with their parent GCMs in simulation, quasi-predictive, and fully-predictive modes at seasonal time scales over multiple hindcast years.
- Improved land surface models (LSMs), wherein improvements are demonstrated within a hierarchy of settings that begin with single flux stations, and then extend to regional, continental and global uncoupled domains in the NLDAS and GLDAS settings, and finally extend to regional and global coupled domains in RCMs and GCMs at seasonal prediction time scales. Two areas of focus will be improvements to the treatment of vegetation cover and snowpack. One key criteria for success in both of these physical processes will be to reduce the considerable disparity across several LSMs in their transpiration and snowmelt responses when provided with the same surface forcing, thus yielding more confidence in the surface energy and water budgets derived from these land models.

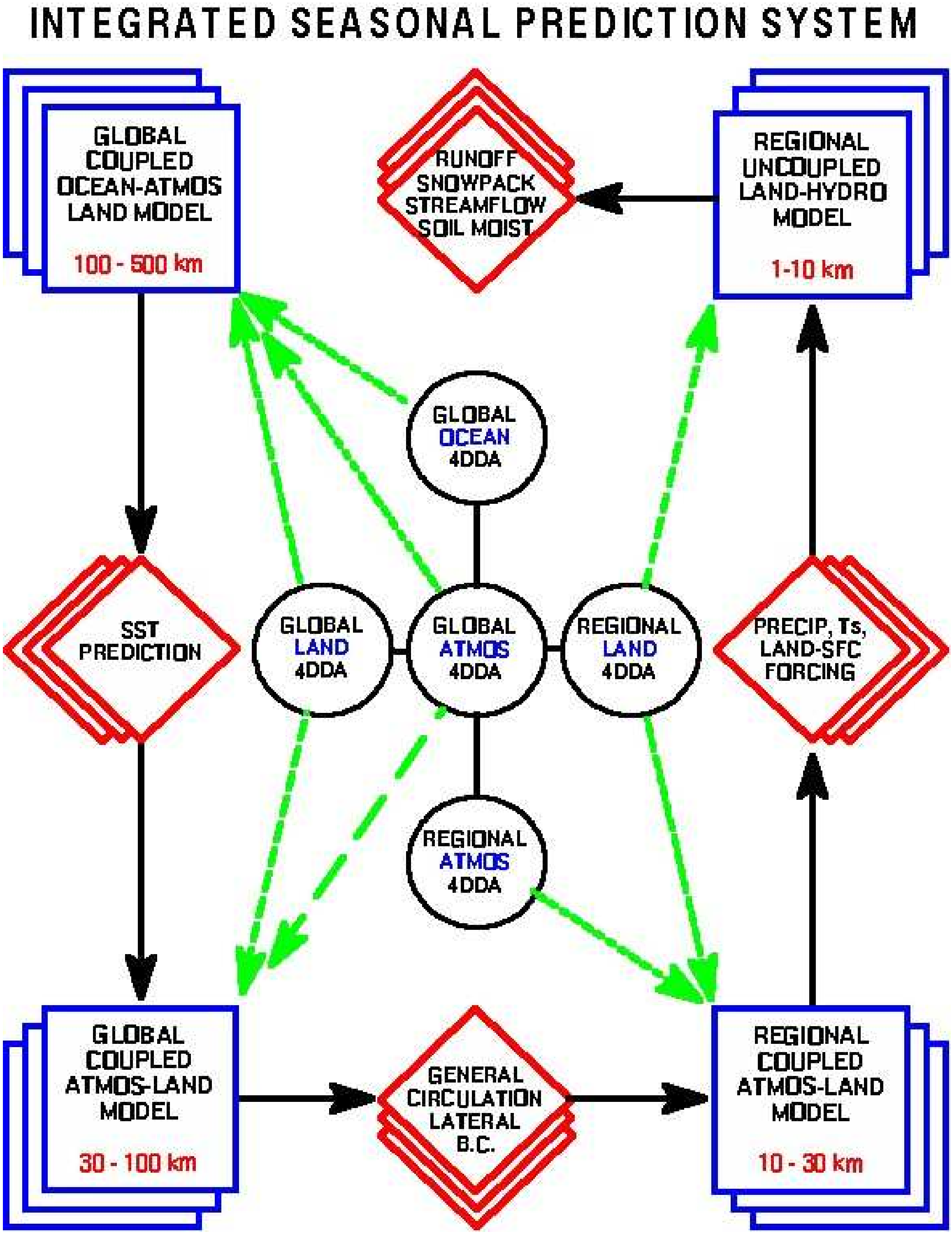

Figure 6.1: Multi-scale end-to-end seasonal prediction system.

7. HYDROLOGY AND WATER RESOURCES APPLICATIONS

The GAPP science and implementation activities for hydrology and water resources seek to address the second of GAPP's two primary science objectives:

To interpret and facilitate the transfer of the results of improved seasonal predictions to users for the optimal management of water resources.

The GAPP science and implementation plan for hydrology and water resources applications recognizes that linkages between the science (hydrology) and applications (water resources) activities are particularly important, and expects to see increased integration between the scientific components of the program and the water resources applications. To accomplish this, GAPP will complement its scientific projects, on hydrologic prediction and predictability and hydroclimatic forecasting technologies, with applications activities designed to evaluate and understand issues related to operational implementation of seasonal forecasting. GAPP is particularly interested in implementation activities that partner GAPP's scientific activities with NWS, and other non-GAPP water users and agencies.

7.1 Background

7.1.1 Science

Improvements in seasonal climate prediction obtained by GAPP, through better understanding and representation of land surface memory processes in climate prediction models, have the potential to improve management of water resources systems. The challenge is to translate information on seasonal to interannual variations in climate into information on the probability of future streamflow conditions. Regional land surface moisture states, as well as climate variations, contribute to the hydrologic predictability on seasonal to interannual time scales. Hydrologic forecast technologies are now emerging that can provide reliable forecasts with lead times of weeks or months. Since such forecasts are inherently probabilistic, an additional challenge for water managers is to understand the nature of probabilistic forecasts, and adapt management decision-making for such information.

Interpreting seasonal climate impacts on water resources requires coupling of climate and hydrologic models. Usually, the coupling is one-way, with outputs from a climate forecast model used to produce the surface forcing for the hydrologic model. The hydrologic forecasts then become input to a water resources decision model. Figure 7.1 illustrates this prototypical approach for GAPP water resources applications.

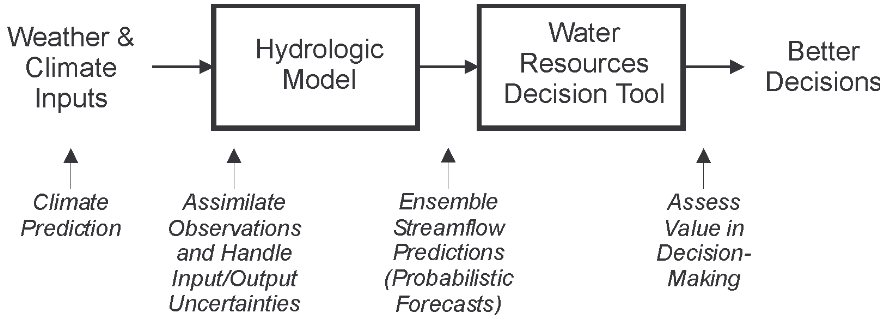

Figure 7.1: Integration of seasonal climate prediction for ensemble streamflow forecasting and water resources decision-making.

Operational hydrologic models used at NWS River Forecast Centers are generally lumped or semi-distributed in their representation of hydrologic processes. Key contributions of GCIP and GAPP research are the study of alternate modeling schemes for streamflow forecasting. In particular, the development of macroscale hydrological models (MHMs), which explicitly utilize data on land surface characteristics (e.g., topography, soils, and vegetation), can represent spatially distributed hydrologic processes in a physically realistic way at scales relevant for water resources applications. MHMs also offer a pathway for investigation of coupled land-atmosphere models for streamflow forecasting.

Two issues of concern in using a hydrologic model for streamflow forecasting are the assimilation of observations and the handling of inputs and output uncertainties. Advances in land surface data assimilation are needed to initialize hydrologic model states. Reliable streamflow forecasts for water resources require that inherent biases in inputs (from climate predictions) and outputs (from hydrologic model predictions) be removed.

Improved climate and hydrologic prediction have value for water resources when the information leads to better operational decisions. Decision tools are needed to interpret probabilistic hydrologic forecasts for water resources decision-making. For straightforward decisions based on probabilistic forecasts, such as a decision to implement water restrictions for drought conditions, simple analytical decision tools that weigh the economic costs and potential losses may be used. However, many decisions related to water resources, such as the operation of a reservoir for multiple objectives, require sophisticated decisions tools to both interpret probabilistic hydrologic forecasts and to directly utilize ensemble traces to exploit the probabilistic information contained in the forecasts.

7.1.2 Objectives

Demonstrating the ability to make seasonal to interannual predictions of value to water resources, as outlined above, will require research to advance our understanding of (1) hydrologic prediction and predictability, (2) hydroclimatic forecasting technologies, and (3) water resources decision-making based on probabilistic hydrologic forecasts. GAPP science objectives in these three areas are as follows.

1. Hydrologic prediction and predictability: *Determine the key factors governing the ability to predict streamflow, evapotranspiration, and soil moisture, and the extent to which incorporation of improved process understanding into hydrologic models results in more accurate hydroclimatic predictions.*

The predictability of land surface hydrologic processes is thought to be attributable primarily to (1) persistence of land surface moisture (e.g., soil moisture, groundwater, snow and/or ice), and (2) recycling of moisture on or near the surface and its influence on the atmosphere. Strong geographical variations in both the controlling mechanisms and predictability exist, due to a combination of orography, vegetation, and surficial geology, and their interactions with regional climate. GAPP research in hydrology and water resources will seek to improve prediction of hydrologic processes, quantify regional variations in predictability, and identify regions where predictability can lead to better water management. In particular, research on hydrologic prediction at climate time scales is needed to address how best to represent relevant hydrologic processes in a distributed or semi-distributed model over a range of spatial scales (e.g., MHMs), develop strategies for estimation of hydrologic model parameters (including regionalization and parameter transferability), and understand the role of hydrologic prediction in coupled land-atmosphere modeling.

2. Hydroclimatic forecasting technologies*:* *Infuse new technologies into hydroclimatic forecasting systems, and assess their potential for both short-term and long-term improvements in operational forecasting.*

Over climate time scales (weeks to years), hydrologic predictions are necessarily probabilistic forecasts. GAPP research will examine alternate pathways of linking climate predictions with hydrologic forecast models for probabilistic forecasting. In particular, ensemble forecasting techniques provide a direct means for linking climate and hydrologic prediction, and generating probabilistic forecasts that account for sources of prediction uncertainty (see Figure 7.1). Opportunities also exist for improved initialization of hydrologic model states through land data assimilation techniques. The expanding capabilities of North American Land Data Assimilation System (NLDAS) offer a pathway for studying (and implementing) initialization techniques over a range of basin scales. Still, understanding the statistical nature and sources of systematic errors (biases) in both climate and hydrologic predictions, and finding methods for correcting model biases, remains a significant challenge for operational hydroclimatic forecasting. Retrospective climatological analysis of climate and hydrologic predictions will play an important role in identifying systematic errors and developing correction techniques for linking climate, hydrologic, and water resources models. Robust verification methods are also needed both to assess the effectiveness of bias-correction for climate and hydrologic ensemble forecasts and to provide hydrologically-relevant measures of forecast quality for operational forecasters and water resource managers.

3. Water resources decision-making: *Find avenues to transfer science contribution of GAPP to the operational hydrology and water resources communities, through demonstration of end-to-end seasonal hydrologic prediction and the use of probabilistic hydrologic forecasts in decision-making.*

GAPP research seeks to understand how scientific contributions in areas such as coupled land-atmosphere modeling, land data assimilation, and ensemble forecasting, can best be transferred to operational hydrologic forecasting and water resources management activities. A significant challenge for transfer of GAPP science advances is that existing operational infrastructure for hydrologic forecasting and water resources decision-making is not always compatible with new generation forecasting technologies (e.g., MHMs, ensemble streamflow predictions). The strategy of parallel research and operational pathways, demonstrated so successfully in GCIP and GAPP's interactions with the weather and climate forecast communities, should be adopted and extended to interactions with the operational hydrologic forecast community. These activities should focus on demonstrating "end-to-end" seasonal hydrologic prediction capabilities — from rescaling climate forecasts for input to hydrologic models and assimilating observations for hydrologic model initialization to producing streamflow ensembles, processing forecasts to account for biases, and verifying probabilistic forecast skill for water resources decision-makers. In addition, GAPP will facilitate some collaborative activities with operational hydrologic forecasters and water managers to serve as templates for translating advances in climate predictions on intraseasonal to interannual time scales to water resources decision-making. Such efforts must not only deal with the hydroclimatic forecasting issues, but also with the use of probabilitistic hydrologic forecasts in a decision framework.

7.2 Implementation activities

To effectively achieve the GAPP science objective related to the transfer of improved seasonal climate predictions to water resource management, there are three implementation priorities. First, GAPP needs to effectively utilize research across its program — in model development, orographic precipitation research, land memory research, and so forth — to develop and evaluate end-to-end prediction systems for seasonal hydrologic forecasting and water resources management. Secondly, GAPP should support the development of collaborative activities with appropriate state and federal agencies, as well as the academic and private sector that have interests in GAPP forecast products. GAPP is particularly interested in fostering collaboration with the NWS Office of Hydrology and the NWS River Forecast Centers, with a focus on seasonal forecasting of streamflow, snow pack and soil moisture, and with the NWS's Advanced Hydrologic Prediction Service (AHPS) initiative. Thirdly, GAPP should build on the strong and successful linkages with water users that have been developed as part of the NOAA Regional Integrated Sciences and Assessments (RISA) program.

7.2.1 Fostering integrated GAPP activities

Previous GAPP and GCIP research on water resources has focused on individual projects and case studies addressing one or more components of the framework illustrated in Figure 7.1 without the benefit of integration or collaboration amongst GCIP/GAPP investigators. Notable exceptions were the North American Land Data Assimilation System (NLDAS) activities and the Water and Energy Budget Study (WEBS), the latter which successfully analyzed the budgets of the Mississippi River basin. For GAPP to realize its scientific goals, especially in the area of water resources applications, a more structured approach for transferring research results across the program will be required.

GAPP should encourage implementation activities that promote such an integrated project approach. Hydrologic prediction and predictability is one topic where GAPP research into land memory processes (see Section 2), orographic precipitation (see Section 3), and seasonal climate prediction (see Section 6) have significant implications for activities in hydrology and water resources applications. Land surface memory accounts for a significant portion of predictability of hydrologic processes over seasonal to interannual time scales. In particular, the persistence of dry soil moisture states leads to significant skill in low flow (drought) forecasting. In contrast, skill in high flow (flood) forecasting for seasonal predictions requires climate predictability (e.g., predicting the occurrence of anomalous precipitation). Integrated investigations linking with GAPP land memory research and seasonal climate prediction are needed to understand their relative roles on hydrologic predictability, and assess predictability for water resources applications as a function of lead time, spatial scale, and geographic location. Hydrologic model intercomparsions are also needed to assess how alternate model formulations affect predictability. This work will help in understanding the spatial variations in hydrologic predictability over the GAPP domain, and target regions and water resources applications where predictability could provide information and value to water resources management.

Many areas of hydrologic prediction and predictability would benefit from an integrated approach. For instance, land surface memory associated with soil moisture states suggests that there may be significant opportunities for improving drought forecasting over seasonal to interannual times scales. GAPP research can address issues of prediction and predictability of low flow and drought through integrated activities that include model development (e.g. better formulation and calibration of baseflow hydrologic processes), seasonal prediction of precipitation (including both orographically dominated GAPP regions and monsoon-dominated regions), and water resources applications. Retrospective studies are also needed to understand seasonal and interannual variations in baseflow, their predictability based on climate forcings, and their modulation by the land surface.

GAPP will encourage activities that not only build across its program elements (science and applications), but also between GAPP investigators and related non-GAPP applications-oriented programs. Some additional examples of integrated activities are provided in the next three sections.

7.2.2 Community efforts in forecast technologies

As stated above, previous GAPP and GCIP research on water resources has focused on individual projects and case studies. Applications case studies have ranged from medium (e.g., Des Moines River, Lower Colorado River in Texas, and the Truckee/Carson River basin) to large watershed scales (e.g., the Missouri River and Ohio River basins). Still, GAPP research needs to develop community-based integrated research activities. Examples include the selection of one or more case study locations within the GAPP domain for end-to-end prediction experiments, perhaps in collaboration with a Regional Integrated Sciences and Assessment (RISA) activities to leverage existing ties to the water resources community, or alternatively, to select forecast locations throughout the United States to investigate predictive capabilities over a diverse range of hydroclimatic regimes. Forecast sites could be selected in collaboration with NWS River Forecast Centers to facilitate interactions and transfer of GAPP technologies to the operational forecasting community.

One possible way to implement this second approach would be to develop an experimental long-range hydrologic forecasting system for the continental United States. Progress made though the GCIP/GAPP NLDAS project provides a logical starting point for a baseline national long-range (one month to one year lead time) hydrologic forecast system. Such a forecast system could utilize NLDAS real-time and retrospective forcings, with ensemble climate forcings during the forecast period derived from NCEP Global Spectral Model ensembles or ensembles from other sources. The forecasting system would be able to make both real-time forecasts for evaluation by operational agencies, as well as retrospective forecasts (or hindcasts) needed for scientific evaluation of forecast skill. Initially, the forecasts would be produced using a small number of forecast models, such as those currently participating in NLDAS (NOAH, Mosaic, VIC, and the NWS Sacramento model). Over time, however, it would be beneficial to incorporate additional models (both hydrologic and climate), which would enable incorporation of the “superensemble” concept.

7.2.3 Collaborative linkages with the operational forecasting community

Operational forecasts of river conditions provide vital information for flood warning, water management, navigation, and recreation. Several federal and local agencies are involved in hydrologic forecasting to various degrees for operational decision-making. However, NWS is the only agency whose river forecasting activity covers the entire United States, and it is their responsibility for issuing river forecasts and flood warnings to the public. Many federal and local water agencies directly rely on NWS river forecasts to meet their operational forecasting needs. By forging a strong collaboration in streamflow forecasting research with the NWS Office of Hydrology (OH) and the NWS River Forecast Centers (RFCs), GAPP would have a broad impact on the water resources community.

The Advanced Hydrologic Prediction Service (AHPS) initiative of NWS offers unique opportunities for GAPP to demonstrate accomplishments towards its broad water resources related goals. GAPP welcomes collaborative efforts with the NWS hydrology program that could demonstrate the potential of GAPP research to meet AHPS science infusion requirements. In a manner similar to its current arrangement with NCEP, GAPP is open to the development of parallel research and operational pathways with the NWS/OH and RFCs. The research pathway will involve targeted hydrologic research conducted primarily by scientists in the academic and government research laboratory community. The operational pathway would be conducted within NWS/OH and its RFCs and would deal primarily with the implementation of improved long-range hydrologic forecasting capability developed through GAPP.

Implementation activities can follow the successful GCIP structure for coupled model development, which implemented a strategy with parallel research and operational paths. For GAPP water resource applications, the implementation activities should evaluate the ability to make seasonal to interannual predictions of value to water resources. This would include research projects done in cooperation with operational hydrology and water resources agencies. Some of these projects might have a demonstration component while others might focus on specific research issues important for water resources applications.

The Hydrological Ensemble Prediction Experiment (HEPEX) offers another avenue for collaborative linkages with operational forecasters. HEPEX is a newly proposed initiative. Its objective is to bring the international hydrological community together with the meteorological community to demonstrate how to produce reliable “engineering quality” hydrological ensemble forecasts that can be used with confidence to assist the water resources sector to make decisions. Representatives of operational hydrological services and operational water resources agencies are expected to participate in helping to define and execute the project. A goal of the project will be to develop a pilot capability for hydrological ensemble prediction that could be used by hydrological services throughout the world. The NWS Advanced Hydrologic Prediction Services (AHPS) would serve as one of the test beds for evaluating end-to-end forecast technologies. Science questions guiding the project are directly relevant to GAPP activities in hydrologic forecasting out to monthly and seasonal time scales. These include understanding how weather and climate information, including ensembles, can be used reliably for hydrologic forecasting, and assessing the relative role of weather and climate forecasts and initial hydrologic conditions on hydrologic forecast skill.

7.2.4 Collaborative linkages in water resources applications

Facilitating the transfer of improved seasonal predictions into water management operations is a challenge for GAPP. Forging relationships with water managers often takes time and two-way interaction to reach a common understanding of the role and value of forecasts in decision-making. However, examples of established relationships exist within the NOAA/OGP Regional Integrated Sciences and Assessments (RISA) Program. Explicit in the RISA program is the partnership between the scientific community and the users (decision-makers or “stakeholders”) of scientific knowledge. Many RISA projects focus on the role of climate variability and water resources decision-making. Where appropriate, GAPP implementation activities should build on the strong and successful linkages to water users developed through the RISA program centers. By combining the season prediction capabilities demonstrated by GAPP, with the regional and local knowledge on user decision-making developed at the RISA centers, both programs would more effectively implement their applications research for the benefit of interested users. For successful GAPP/RISA partnerships, the NOAA National Climate Transition Program many also provide opportunities for transitioning research applications to operations.

7.3 Deliverables

In its first few years, implementation of proposed GAPP research activities will:

- Establish collaborative activities with the NWS Office and Hydrology and River Forecast Centers to improve seasonal hydrologic forecasting techniques; and
- Establish collaborative linkages with selected water management partners to demonstrate utility of seasonal predictions for water resources management.

Over the long-term, GAPP research in hydrology and water resources will:

- Develop improved models and techniques for making probabilistic hydrologic forecasts that integrate with GAPP research in land memory process, orographic process, remote sensing, and climate predictions; and
- Demonstrate end-to-end hydroclimatic forecasting technologies at seasonal climate time scales.

8. GAPP REMOTE SENSING APPLICATIONS

Breakthrough advances in techniques to observe continental and regional precipitation, surface soil-moisture, snow, surface soil freezing and thawing, surface inundation, river flow, and total terrestrial water-storage changes, combined with better estimates of evaporation, now provide the basis for a concerted integrated GAPP remote sensing research effort. To answer the GAPP science questions, vertical water fluxes (i.e. *precipitation and evaporation*), the amount of land water storage (i.e. *soil moisture, inland water bodies, etc*), and lateral land water fluxes (i.e. *river flow)* must be integrated and interpreted. GAPP remote sensing data must be: (a) Spatially and temporally rectified to allow intercomparison and quality evaluation of disparate model and observation data, (b) Physically rectified or constrained using four dimensional data assimilation and modeling techniques, and (c) used to interconnect the products of disparate research teams. A central focus of the GAPP remote sensing activities will be the Coordinated Enhanced Observation Period (CEOP), which is an international effort focused on the measurement, understanding, and modeling of water and energy cycles within the climate system.

8.1 Background

8.1.1 Science

The central objective of the GAPP research strategy is to demonstrate skill in predicting water resource changes at intraseasonal-to-interannual time scales as an integral part of the climate system. Changes and variations in weather and precipitation patterns, and related hydrologic responses, are the most important and anticipated consequences of climate change. Furthermore, the ability to provide probabilistic forecasts of rainfall and snowfall at various time and space-scales is at the center of all potential applications of climate-change science. The ultimate GAPP contribution to the public from these research activities and predictions are protecting human health and assets, and supporting water system management and infrastructure planning. As such, the time scales of interest are those that cover the responses of the water cycle to natural and human forcing, from seasonal to multi-decadal.

Through their regulation of water and energy transfer between the land and atmosphere, the dynamics of terrestrial water stores are an important “choke-point” on the global water cycle at weather and climate timescales. As the primary input of water to the land surface, precipitation defines the terrestrial water cycle. The partitioning of this precipitation between infiltration (and subsequently evapotranspiration) and runoff is determined by surface physics, vegetation, snow and soil-moisture conditions, and soil-moisture dynamics. Breakthrough advances in techniques to observe continental and regional precipitation, surface soil-moisture, snow, surface soil freezing and thawing, surface inundation, river flow, and total terrestrial water-storage changes, combined with better estimates of evaporation, now provide the basis for a concerted integrated GAPP remote sensing research effort.

Satellite data sets provide a valuable extension to conventional in-situ ground-based observations. Because of their limited spatial coverage, traditional in-situ ground observations have limitations for input, validation and assimilation in models. Point data are difficult to interpret in the validation, calibration, and assimilation of models which range from 10's of meters for the high resolution hydrologic application models to 100's of kilometers for global climate models. Satellite data provide continuous spatial coverage and repeat temporal coverage, which simplifies their use in modeling and assessment studies. NASA Earth Observing Satellites (EOS) provides research data sets for a large number of atmospheric and land surface variables could be especially valuable for GAPP land-atmosphere modeling activities.

8.1.2 Objectives

Remotely sensed satellite data will be used to help GAPP meet the following objectives:

- Provide forcing and parameters for 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.
- Validate model outputs (fluxes and states) such as surface temperature and soil moisture content.
- Provide model state constraints for data assimilation and prediction systems.
- Compare satellite derived land surface products with observations made during field experiments.
- Contribute to an understanding of the global water cycle through participation in studies like CEOP.

8.2 Implementation activities

8.2.1 Land surface

Satellite-derived soil moisture fields have been derived through analysis of the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) [Engman, 1995; Jackson, 1997]. The Advanced Microwave Scanning Radiometers (AMSR) aboard the Aqua and ADEOS II satellites will provide additional C-band microwave observations that may be useful for soil moisture determination. The TRMM-TMI, which is very similar to AMSR, is much better suited to soil moisture measurement (because of its 10 Mhz channels) than SSM/I, and is also currently available. All of these sensors have adequate spatial resolution for land surface applications, but have a very limited quantitative measurement capacity, especially over dense vegetation. Because satellite derived soil moisture fields are sporadic and prone to uncertainty, producing optimal global fields of soil moisture will require various types of observations to be merged and/or assimilated into sophisticated models to account for the errors and to extend the information in time and space.

Cryospheric processes are known to vary over different timeframes, specifically, short duration (days to 1-10 years) through medium duration (10-100 years) to long term variations (>100 years). Over short durations, seasonal snow storage is an important process which is often measured in terms of snow cover area and snow water equivalent. Snow aerial extent can be routinely monitored by many operational platforms, including MODIS, AVHRR, GOES and SSM/I (e.g. Hall et al, 2002). Furthermore, recent algorithm developments permit the determination of the fraction of snow cover within Landsat TM or MODIS pixels [Rosenthal and Dozier, 1996; Kaufman *et al.*, 2002]. However, direct, high accuracy measurement of snow water equivalent by satellite is not yet feasible. Cline et al. [1998] and Chen et al. [2001] describe approaches to retrieve SWE from the joint use of remote sensing and energy balance modeling. The feasibility of implementing this approach for GAPP should be pursued.

Satellite observations of surface waters and terrestrial water storage are also relevant to achieving the GAPP objectives. Birkett (1995, 1998) demonstrated the potential of satellite radar altimeters to monitor height variations over inland waters, including climatically sensitive lakes and large rivers and wetlands. Such altimeters are currently operational on the ERS2, TOPEX/POSEIDON, ENVISAT and JASON satellites. The Gravity Recovery and Climate Experiment (GRACE) satellite mission, launched 17 March 2002, provides extremely accurate global maps of Earth's gravity field on a monthly basis. Wahr et al. [1998] and Rodell and Famiglietti [1999, 2001] have demonstrated the potential to infer changes in total terrestrial water storage (groundwater, soil moisture, snow, ice, surface water, and wet biomass) over large regions (>200,000 km^2) based on gravity maps.

8.2.2 Vertical fluxes

The accurate measurement of the spatial and temporal variation of precipitation remains one of the critical unsolved problems for GAPP and is a lynch pin in our understanding of the water, energy and biogeochemical cycles. Precipitation data are required for other purposes such as: to constrain the rate of development of weather systems and initialize weather forecasts; to validate water budget and flux estimations by general circulation models (GCM); to quantify land water budgets and drive hydrologic process models, and to determine a major surface forcing of the ocean thermohaline circulation. However, there is general consensus that available rain-gauge data are insufficient to meet these scientific needs and reach definite conclusions regarding changes in regional and global precipitation patterns and trends. Therefore, satellite-based estimates are the best hope for comprehensive and consistent records to detect global trends and quantify variability. Past and current remote-sensing methods infer precipitation from passive microwave and infrared observations. The most effective remote sensing techniques are based on measuring microwave radiation that penetrates precipitating clouds and contains information on cloud microphysical properties (liquid and solid water content, cloud particle size distribution). Finer time scale (3-hr) analyses on a quasi-global scale are in the beginning stages of being utilized and validated, and show promise in providing valuable information to climate and hydrologic studies.

NASA contributes significantly to the observation of global precipitation. For example, the Tropical Rainfall Measuring Mission (TRMM), launched in late 1997 [Kummerow et al., 2000; Adler et al., 2001] has been used to improve the longer record of satellite precipitation estimation through improvement of the algorithms used with passive microwave satellites flying since 1987 and by re-calibrating long-term (1979-present) data sets such as from the Global Precipitation Climatology Project (GPCP). The WCRP/GPCP [Huffman et al., 1997] combines information from multiple satellites with rain gauge data with to produce a series of global products useful for climate studies, including monthly and pentad analyses from 1979-present and a daily product from 1997-present. In addition to precipitation, TRMM is also being used to observe atmospheric water vapor, ocean surface wind speed, sea surface temperature (SST) in clear and cloudy areas, lightning information, cloud microphysics and information related to soil moisture and vegetation. The Advanced Microwave Scanning Radiometer (AMSR), on both NASA's AQUA mission and Japan's ADEOS II satellite (now discontinued) complement TRMM in terms of precipitation observation and add significantly to the observation of other hydrologic variables, especially soil moisture. In addition, Sea surface temperature (SST) observation, even under clouds will be extended into middle and high latitudes (important for ocean evaporation estimates, described in the next section). Another key NASA instrument is the Atmospheric Infra-Red Sounder (AIRS) instrument [Aumann and Pagano, 1994]. The combination of AIRS and complementary microwave instruments deployed on the Aqua mission is expected to greatly enhance the accuracy of atmospheric temperature and humidity profiles, and approach globally the accuracy of operational balloon soundings. NASA also leads the development of imaging multispectral radiometers, such as the Moderate-Resolution Imaging Spectroradiometer (MODIS) on EOS Terra and Aqua. MODIS provides measurements of a variety of basic water and energy cycle variables, from sea- and land-surface temperature to cloud amount and optical properties, and radiation fluxes. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) in developing the next-generation operational instruments, and the realization of the NPOESS Preparatory Project, is a joint experimental satellite mission that will test the prototypes of these instruments.

In the future, a major new observational initiative is anticipated that would significantly enhance climate-related variability in the global water and energy cycle: a Global Precipitation Measurement program (GPM). The scientific premise for a global precipitation measuring system is to combine observations from at least one active precipitation radar in inclined orbit to a constellation of several (6-8) passive microwave imaging radiometer spacecraft in staged polar orbits and surface-based rain gauges. A constellation of passive sensors is needed to provide frequent sampling of precipitation events, at intervals of about 3 hours.

To meet its objectives, GAPP must compile, integrate, evaluate and enhance relevant precipitation observation activities utilizing TRMM, AMSR and current operational satellites. In the wake of knowledge gained through the integration, synthesize and application of current precipitation missions, the GAPP researchers should work closely with the integration and planning of data management and dissemination, scientific needs and application potential of the next-generation precipitation measurement systems to ensure their optimal and efficient utilization.

Evaporation from continents and ocean surfaces serves as the crucial link between the surface water and energy budgets. In addition, the biological processes associated with transpiration are strongly tied to the terrestrial carbon budget. Moreover, evaporation from the ocean serves as the primary source of water to the atmosphere, which in turn is deposited over continental regions via precipitation and restores fresh-water storages. Thus, in order that we can faithfully and confidently characterize and understand the GAPP water cycle teleconnections (such as monsoons), it is critical to quantify the magnitudes and variations of evaporation over the globe.

To date, efforts have aimed to provide bulk-formula estimates of ocean evaporation from remotely-sensed data of the SSM/I (Special Sensor Microwave/Imager) measuring near-surface humidity and winds (e.g. Chou et al., [1997]). However, the veracity and scientific utility of these estimates are primarily limited by the quality and absence of the SSM/I retrieved data such as near-surface winds and humidity. Therefore, the first priority at improving these estimates would be to revisit the SSM/I time series and assess the extent of the missing bulk-formula terms from SSM/I (i.e. near-surface wind speed and humidity) and to rectify them. The problem lies in the inability of the SSM/I instrument to penetrate regions of strong precipitation, thus hindering the ability to retrieve near-surface quantities. The effect on the bulk-formula estimate of ocean evaporation is, in general, to underestimate ocean evaporation during westerly wind bursts and to underestimate evaporation during periods of widespread, convective events.

Over land, the observing of evaporation fluxes is much more complex, primarily due to the rich heterogeneity of the land surface and the more complex bio/geophysical processes that control the evaporative exchange of water between the land and atmosphere. At present, our best promise for land evaporation estimates lies in the assimilation of satellite data into global land-model assimilation systems. Therefore, GAPP must work to compile and assimilate all relevant satellite retrievals that foster the highest quality evaporation products and global land assimilation systems. However, monthly, regional scale evapotranspiration rates are one potential derivative of the GRACE satellite mission. Given GRACE-derived changes in terrestrial water storage, precipitation, and river flow measurements, the average rate of evapotranspiration could be estimated as the residual of a terrestrial water budget analysis [Rodell, 2000].

Therefore, GAPP must take a two-fold effort to improve our capabilities to estimate evaporation from satellite retrievals (via algorithmic formulas and data assimilation). First, the surface and near-surface atmospheric quantities which are required as input for algorithms or desired for model assimilation will be enabled – particularly by exploiting data from current and pending missions. However, equally important will be to rectify the previous satellite-based estimates. The potential will then exist to combine newly acquired and updated historical estimates of land and ocean evaporation quantities that would result in long, contiguous time series of high quality data. What is also needed is improved and contemporaneous in-situ data that can validate satellite-based estimates – which will be achieved through the integration of CEOP data.

8.2.2 Horizontal fluxes

Knowledge of horizontal water fluxes are important for quantifying the variability of the global water cycle; these include river runoff, atmospheric water vapor transport, ocean circulation, glacier flow, groundwater flow, etc. Excellent assessments of atmospheric water vapor transport are available via the assimilation of atmospheric observations in numerical weather prediction systems. Unfortunately, estimates of glacier and groundwater flow are more elusive.

Streamflow observations are widely available from select countries, and from streamflow archiving activities such as the Global River Discharge Database [Vörösmarty et al., 1996], the Global River Discharge Data (http://cpep.meteor.wisc.edu/pages/available.html), and the Global Runoff Data Center (GRDC). Altimetry data should be assembled from satellites such as Seasat, Geosat, ERS, TOPEX/POSEIDON, Envisat and JASON-1 for selected GAPP studies.

8.3 The Coordinated Enhanced Observation Period (CEOP)

Motivated by the synchronism of the new generation of Earth observing satellites and multiple GEWEX continental scale experiments during the 2003-2004 timeframe, GEWEX initiated the Coordinated Enhanced Observation Period (CEOP) as an international effort focused on the measurement, understanding, and modeling of water and energy cycles within the climate system. CEOP supports studies of climate variability and prediction, monsoon systems, global atmospheric circulation, and changes in water resources. This initiative has gained the interest of a broad range of international organizations. Among other goals, CEOP aims to integrate many streams of data into a coherent database relevant to CEOP science issues.

The anticipated GAPP activities undertaken in cooperation with CEOP include: (1) A test bed for evaluating multiple land surface models; (2) Long term land model baseline experiments and intercomparisons; (3) Linking and inclusion of reference site observations with globally consistent observation and modeling to enable GEWEX-CSE land transferability studies; (4) Land initialization for seasonal-to-interannual coupled predictions; (5) Evaluation of numerical weather and climate predictions for land; (6) Integration of remotely sensed land observations in land/atmospheric modeling for use in CEOP and higher level understanding; (7) A quality control check on observations; (8) 4DDA "value-added" LDAS datasets; (9) The production of MOLTS; and (10) A long-term archive function.

8.4 Deliverables

In order to answer the GAPP science questions, vertical water fluxes (i.e. *precipitation and evaporation*), the amount of land water storage (i.e. *soil moisture, inland water bodies, etc*), and lateral land water fluxes (i.e. *river flow)* must be integrated and interpreted. For this purpose, we define 3 primary deliverables:

1. ***Spatial and temporal rectification to allow intercomparison and quality evaluation of disparate model and observation data.*** The first order data integration technique used by GAPP will be to simply interpret relevant data to a common time and space domain for intercomparison and visualization. This will enable assessment of data set error and bias, as well as potential water cycle variability, uncertainty, and predictability. Involving disparate data in a global water-balance assessment will further interrelate the data, highlighting gaps in our knowledge.

2. ***Physical rectification or constraint of data and its error using four dimensional data assimilation and modeling techniques.*** Data assimilation merges a range of diverse data fields with a model prediction to provide that model with the best estimate of the current state of the natural environment so that it can then make more accurate predictions. This is an integration process that uses data from many sources, resolutions, and errors to constrain a model simulation. The resulting model data reflects a combination of the assimilated data and the physical laws of the model. Data assimilation systems for GAPP data integration should be implemented in cooperation with weather/climate prediction centers.

3. ***Interconnection of disparate research teams***. Because of the highly specialized nature of water cycle research, it is common for disparate research groups to be unaware of each other's activities. Therefore, enabling groups to share data, ideas and techniques can be the most important integrating function. For example, disparate research groups often create similar

products that can be validated and improved when compared, or model simulated water variation can be validated when compared to observations. By collecting and distributing disparate water cycle data, creating summary water cycle assessments, and interacting with users, the GAPP will enable cross-group data sharing and integration.

9. GAPP DATA MANAGEMENT

The accomplishment of GAPP goals and major science objectives involves the development of a comprehensive and accessible database for the Continental-scale GAPP study area and the establishment of an evolving program of model development that will permit observations and analyses to be extended spatially within GAPP or applied globally with new observations. 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.

GAPP will organize a GAPP Data Management Committee whose responsibility will be to compile and update the Data Management Plan as necessary. Data Management Committee is composed of members representing various GAPP scientific interests and data sources/types participating in GAPP. The GAPP will take advantage of the capabilities at several of the existing data centers to implement a distributed data management system, much like the framework of GCIP. Data access will be through the GAPP Central Data Information Source (CDIS), which is coordinated through UCAR's Joint Office for Science Support (JOSS).

9.1 Background

The accomplishment of GAPP goals and major science objectives involves the development of a comprehensive and accessible database for the Continental-scale GAPP study area and the establishment of an evolving program of model development that will permit observations and analyses to be extended spatially within GAPP or applied globally with new observations. 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. Some retrospective data sets (in addition to the data sets previously collected for the GEWEX Continental-scale International Project [GCIP]) may be necessary for development of hypotheses and models. 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 and available through established data centers. However, GAPP will make arrangements to ensure that particularly "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 groundwork and infrastructure accomplished by GCIP which relied upon and enhanced existing operational/research meteorological and hydrological networks (i.e. upgraded facilities such as doppler radars, wind profilers, automatic weather stations, and soil moisture measurements). GAPP will also collaborate with other related programs such as the CLIVAR Pan American Climate Studies (PACS) and DOE Atmospheric Radiation Measurements (ARM); and projects such as the International Water Vapor Project (IHOP-2002) and the North American Monsoon Experiment (NAME).

The GAPP Data Management Plan will take advantage of the work accomplished by GCIP. Volume I of the GCIP Implementation Plan (IGPO 1993) contained information that (i) identified the sources of observations from existing and planned networks; (ii) suggested further enhancements of those networks where necessary; and (iii) assisted in developing data sets accumulated from existing observational systems and derived from operational model outputs, such as the NOAA/NCEP Eta operational model. The strategic portion of the data management planning (IGPO 1994) established the implementation strategies needed to achieve the GCIP data collection and management objective. The details of this implementation will be developed and provided in the GAPP Data Management Plan. This plan will contain, at a minimum, specifics regarding data set descriptions (e.g. detailed network observations), metadata and data submission guidelines, and descriptions of any special composite data sets or products. The GAPP Data Management Committee (described below) will assume the responsibility to compile and update the Data Management Plan as necessary. It is envisioned that this Plan will be a "living" document updated routinely during the GAPP data collection period.

9.2 GAPP data management committee

Because of the complex nature of the data management issues involved, GAPP established a Data Management Committee (DMC) to address a number of data related issues and activities and help define data requirements to accomplish the GAPP scientific objectives. The terms of reference of the DMC are to: (i) coordinate with the GAPP scientific community to define the needs for GAPP data; (ii) design a distributed data management system to provide access to existing data sets; (iii) prepare a data management plan describing the GAPP data strategy and implementation; (iv) review and recommend augmentation of existing GCIP data sets to include the continental-scale region required of GAPP; (v) recommend assembly and oversee the production of new data sets as needed to achieve the GAPP objectives; (vi) collection of data to ensure a permanent archive upon completion of the program; and (vii) coordinate and collaborate with other field projects/programs.

The DMC is composed of members representing various GAPP scientific interests and data sources/types participating in GAPP. The initial list of members (and organization) are provided in Table 1. An e-mail alias (gapp-dmc@joss.ucar.edu) has also been established to facilitate communication between the members. Also, a WWW page (http://www.joss.ucar.edu/gapp/dmc/) has been established and is maintained by UCAR's Joint Office for Science Support (JOSS) to facilitate exchange of information (i.e. draft documents) between the members. These page(s) also contain the terms of reference, complete contact information for the members, various data links relevant to GAPP, and other links as appropriate.

TABLE 1 GAPP Data Management Committee

NAME	ORGANIZATION
Wayne Faas	NOAA/NCDC
Jin Huang	NOAA/OGP
Pat Hrubiak	NASA/GSFC
Roy Jenne	NCAR/SCD
Bill Kirby	USGS/WRD
Raymond McCord	DOE/ARM
Tilden Meyers	NOAA/ARL
Alan Robock	Rutgers University
Dan Tarpley	NOAA/NESDIS
SteveWilliams, (**Chair**)	UCAR/JOSS

9.3 Data policy

The World Meteorological Organization (WMO) Resolution 40 (adopted by the XII Congress on 26 October 1995) comprises the basis for the GAPP data protocol to be adopted and practiced by each of the GAPP data modules and affiliated Data Archive Centers:

"As a fundamental principle of the World Meteorological Organization (WMO), and in consonance with the expanding requirements for its scientific and technical expertise, the WMO commits itself to broadening and enhancing the free and unrestricted international exchange of meteorological and related data and products".

In general, users will have free and open access to all the GAPP data subject to procedures in place at the various distributed data centers involved (see Section 9.4). Further details on data set compilation and attribution are provided (see Section 9.5).

9.4 Data access

The GAPP will take advantage of the capabilities at several of the existing data centers to implement a distributed data management system, much like the framework of GCIP. This system will provide single-point access for search and order of GAPP data from data centers operated by different agencies with the capability to transfer small data sets electronically from the data center to the user. By transition from GCIP into GAPP, the system will begin collecting information on the data and add the data services (access) capability as the project matures and data requirements become better defined. The system will have the capability to implement a one-stop “shopping” for data services using the World Wide Web (WWW) as a method of data access known as the GAPP Central Data Information Source (CDIS), which is coordinated through UCAR’s Joint Office for Science Support (JOSS). The CDIS WWW page is located directly at: http://www.joss.ucar.edu/gapp/ and also accessible via the GAPP “Home” Page. The CDIS contains general information on the data activities on-going in GAPP (i.e. documents, reports), the GAPP Data Management Committee activities, links to related programs and projects, and data access via the three data “categories” or modules of in-situ data, satellite data, and model output.

The data sets residing at UCAR/JOSS will be archived and distributed through the existing JOSS Data Management System (CODIAC). CODIAC offers scientists access to research and operational data. It provides the means to identify data sets of interest, facilities to view data and associated metadata, and the ability to automatically obtain data via internet file transfer or magnetic media. The user may browse data to preview selected data sets prior to retrieval. Data displays include time series plots for surface parameters, skew-T/log-P diagrams for soundings, and GIF images for model analysis and satellite imagery. CODIAC users can directly retrieve data. They can download data via the Internet directly to their workstation or personal computer or request delivery of data on magnetic media. Data may be selected by time or location and can be converted to one of several formats before delivery. CODIAC automatically includes associated documentation concerning the data itself, processing steps, and quality control procedures.

Contact Information:

Contact:	CODIAC (codiac@joss.ucar.edu).
Mailing Address:	P.O. Box 3000, Boulder, CO, USA, 80307
Shipping Address:	3300 Mitchell Lane (Suite 175), Boulder, CO, USA, 80307
Telephone:	(303)497-8987 [FAX (303)497-8158]
Internet Access:	http://www.joss.ucar.edu/codiac/

9.5 Data compilation

The costs for data management, including data reproduction costs, will be kept to a minimum, primarily through use of existing data centers. The costs incurred for the initial compilation of information on the data will be borne by the Project. Costs for data sets that are compiled for general use by investigators involved in the Project will also be borne by the Project. The incremental costs for preparing data sets designed to individual specifications will, in general, be borne by the user making the request for the data. For purposes such as resource planning and the assignment of costs, 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 agreed to at the project level on a year-by-year basis. Funds will be identified and committed by the Project for each standard data set at the time the specifications are agreed to in a formal manner. The primary purpose of the standard data sets is to give wide distribution, especially 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. Funds will be identified and committed for each custom data set at the time the request is approved by the Project management.

The primary purpose of the as requested data set is to enable any user 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 user making the request.

9.6 Investigator requirements

The first step in organizing the data management support is to understand what data are required from the various scientific components of the program. JOSS has developed and distributed an initial data questionnaire to survey the GAPP participants to document this information. All GAPP investigators are requested to complete this questionnaire. The questionnaire is located directly at: http://www.joss.ucar.edu/cgi-bin/gapp/q_dataneeds or linked through the CDIS. Response information is also available through the CDIS. This questionnaire information with input from other GAPP science committees and sample data sets will be used to obtain detailed information regarding the various data sets (e.g. data format, data set size, data frequency and resolution, real time operational requirements, etc.). This will assist the DMC (and collaborating Data Archive Centers) in handling and processing the data as well as developing any format converters necessary. The PIs (and data sources) will be requested to adequately document data sets in accordance with standard metadata standards agreed upon by the project.

10. ORGANIZATIONAL ELEMENTS

The GAPP program is an inter-agency research program sponsored by NOAA's Office of Global Programs through its Climate Prediction Program for the Americas (CPPA) and by NASA's Terrestrial Hydrology Program (NTHP). GAPP is one of the World Climate Research Programme's GEWEX Continental Scale Experiments. The sponsoring agency program managers are responsible for overall implementation, but receive scientific guidance and advice from the GAPP Scientific Advisory Group (SAG). In addition there is a GAPP Data Management Committee, which coordinates data-related activities for GAPP, and GAPP Working Groups (WG), that coordinate the transfer of research results across the program elements. All funded investigators are members of at least one WG. The WGs have the responsibility to produce the GAPP research synthesis products that document the progress of GAPP research to the research goals of CPPA and NTHP. Currently there are **14** GAPP synthesis products.

10.1 GAPP management structure

GAPP is managed by program managers from its sponsoring agencies, i.e., NOAA and NASA. The program management structure includes the GAPP Science Advisory Group (SAG) which provides scientific advice to sponsoring agency program managers, a Data Management Committee, and several working groups.

GAPP is an inter-agency program with support from NOAA and NASA and is one of the GEWEX Continental-Scale Experiments (CSEs). NASA supports GAPP through its Terrestrial Hydrology Program. Beginning in 2004, NOAA support to GAPP will be through the new NOAA Climate Prediction Program for the Americas (CPPA).

The sponsoring agency program managers are responsible for overall implementation of the GAPP Program. Implementation by agency program mangers is based on science and implementation priorities identified by the GAPP science and implementation plans and is consistent with the priorities of each agency's relevant mission goals.

Science Advisory Group (SAG) provides scientific guidance for GAPP and provides advice to both NOAA and NASA. The members of SAG are scientists currently working with GAPP program managers and GAPP funded scientists.

10.2 Data management committee

The data management committee coordinates data-related activities for GAPP. Specifically, the Data Management Committee will:

- coordinate with the GAPP scientific community to define the general needs and specific requirements for GAPP data;
- design a distributed data management system to provide access to existing datasets;
- prepare a data management plan describing the GAPP data strategy and implementation;

- determine how to build on the pre-existing GCIP datasets for the new GAPP efforts;
- oversee production and collection of data to achieve the GAPP objectives; and
- coordinate and collaborate with other agencies on data issues.

10.3 GAPP working groups

Previous GCIP research focused on individual projects and case studies addressing one or more science goals, without the benefit of integration or collaboration amongst GCIP investigators. Notable exceptions were the North American Land Data Assimilation System (NLDAS) activities and the Water and Energy Budget Study (WEBS). For GAPP to realize its scientific goals, a more structured approach for transferring research results across the program elements and with the GAPP core projects will be required. This will be done through the establishment of working groups inside GAPP. Each funded PI at present will be a member of at least one working group. Each working group has a chair. The working groups will be responsible for the development of GAPP Synthesis Products, which are based on GAPP research results and are critical products that demonstrate GAPP research progress and usefulness to NOAA's Climate Prediction Program for the Americas (CPPA). The working groups will report to the GAPP SAG, program mangers and Data Management Committee. There are currently four working groups as follows:

- Predictability (P)
- Water resources (WR)
- Data and Observations (DO)
- Joint GAPP-PACS NAME (N)

10.4 GAPP synthesis products

An important product of the GAPP research activities are the synthesis products that show the progress the program is making to the Climate Prediction Program for the Americas (CPPA). It is envisioned that all funded investigators have a responsibility to contribute to these products and that the working groups will take leadership in developing and producing these products. GAPP Synthesis Products will be developed to address specific GAPP scientific questions that, when answered, will help achieve the two GAPP goals described in Section 1.1.

In the following tables an initial set of synthesis products are shown for five science questions relevant to GAPP. In the first column is an indication of the working group that will further develop and coordinate, amongst its members, the development of the 'synthesis products'. The last column indicates the timeframe for an initial product. It is envisioned at this time that the products will be a report (and journal paper) summarizing the GAPP research results, and that the report will indicate the progress towards resolving the underlying science question and areas of needed further research or application.

These products will help GAPP program managers and others to demonstrate the progress being made within the program and potential usefulness of the research results to operational agencies.

GAPP Science Question: ***What are the key factors governing hydrologic predictability, and in particular, the ability to predict streamflow, evapotranspiration, and soil moisture?***

P	Quantify the influence of land and ocean states on the seasonal prediction skill of precipitation and temperature within the GAPP domain.	2-4 years

GAPP Science Question: ***What is the role of hydrologic prediction in coupled land-atmosphere modeling?***

P	Quantify the sensitivity of seasonal climate predictions to land states, including soil moisture, snow, orography and vegetation.	2-4 years
N	Assess and improve predictions of onset of the North American monsoon.	2-4 years
DO	Provide a regional reanalysis of the atmospheric and land surface states using state-of-the-science numerical modeling and data assimilation systems.	1-2 years

GAPP Science Question: ***How can improved modeling strategies, including land data assimilation and ensemble forecasting, best be implemented in a hydrologic prediction framework?***

WR	Quantify seasonal climate forecast skill and accuracy requirements for water resources applications.	2-4 years
DO	Develop and test procedures to assimilate new data products (e.g. satellite data sets) and off-line model outputs (e.g., from LDAS systems) to provide improved weather and seasonal forecasts.	1-3 years
P	Quantify the value added to seasonal prediction skill from ensemble regional climate models relative to predictions from their parent global model within the GAPP domain.	2-4 years

GAPP Science Question*:* ***How can the scientific contributions of GAPP, in areas such as coupled land-atmosphere modeling and seasonal forecasting, best be transferred to the operational hydrology and water resources community?***

WR	Develop and evaluate the usefulness of seasonal hydrologic forecasts systems for water resources applications.	2-4 years
P	Develop operational hydrologic forecasts incorporating the use of climate forecasts.	2-4 years

GEWEX-GAPP Science Question*: Can we understand and predict the variations in the regional and global hydrological regime and water resources and its response to changes in the environment?*

DO	Develop a historical understanding of the water and energy budget and its variability within the GAPP domain based on data and modeling, including Reanalysis-2.	2-4 years
DO	Develop an understanding of the GAPP water and energy budget, through data analysis and modeling studies, and its relationship to the global water and energy budget, with particular focus on GEWEX CSEs domains.	2-4 years
WR	Determine the transferability of climate and hydrologic models across different climate/hydrologic regimes.	1-3 years
N	Carry out field experiments leading to improved understanding of the North American Monsoon system.	2 years
N	Quantify surface fluxes and land-atmosphere climate feedbacks across the North American monsoon domain.	2-4 years

APPENDICES

A. References

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B. Acronyms

4DDA	Four Dimensional Data Assimilation
AL-GCM	atmosphere/land general circulation model
AHPS	Advanced Hydrologic Prediction Systems
AIRS	Atmospheric InfraRed Sounder
AMSR	Advanced Microwave Scanning Radiometer
ARC	Applied Research Center
ARM	Atmospheric Radiation Program
BALTEX	Baltic Sea Experiment
CALJET	California Land-falling Jets
CART	Cloud and Radiation Testbed
CCA	Canonical Correlation Analysis
CCSP	U.S. Climate Change Science Program
CDEP	Climate Dynamics and Experimental Prediction
CEOP	Coordinate Enhanced Observing Period
CliC	Climate and Cryosphere
CLIVAR	Climate Variability and Predictability
COLA	Center for Ocean Land Atmosphere
CPPA	Climate Prediction Program for Americas
CSE	Continental-Scale Experiments
DOD	Department of Defense
DMSP	Defense Meteorological Satellites Program
ECPC	Experimental Climate Prediction Center
ENSO	El Niño Southern Oscillation
EOS	Earth Observing System
EPIC	Environmental Protection Information Center
ESMF	Earth System Modeling Framework
FOC's	Forecast Operations Centers
GABLS	GEWEX Atmospheric Boundary Layer Study
GAME	GEWEX Asian Monsoon Experiment
GAPP	GEWEX Americas Prediction Project
GCIP	GEWEX Continental-scale International Project
GCM	General Circulation Model
CSE	Continental-Scale Experiments
GCIP	Continental-Scale International Project
GHP	GEWEX Hydrometeorology Panel
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Lab
GHP	GEWEX Hydrology Panel
GLACE	Global Land-Atmosphere Coupling Experiment
GLASS	GEWEX Land Atmosphere Scheme Study
GLDAS	Global Land Data Assimilation System
GMAO	Global Modeling and Assimilation Office
GMPP	GEWEX Modeling and Prediction Panel
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Measurements
GRACE	Gravity Recovery and Climate Experiment
GrADS	Grid Analysis and Display System
GRDC	Global Runoff Data Center
GSFC	Goddard Space Flight Center
GSWP	Global Soil Wetness Project
HELP	Hydrology for Environment, Life and Policy
HEPEX	Hydrological Ensemble Prediction Experiment
HSB	Hydrological Sciences Branch
IGBP	International Geosphere-Biosphere Programme
IOP	Intensive Observation Period
IRI	International Research Institute
ISIP	Intraseasonal-to-Interannual Prediction Program

ISLSCP	International Satellite Land Surface Climatology Project
JCSDA	Joint Center for Satellite Data Assimilation
JGR	Journal of Geophysical Research
JOSS	Joint Office for Science Support
KF	Kalman Filter
LBA	Large Scale Biosphere Atmosphere Experiment in Amazonia
LBC	lateral boundary conditions
LDAS	Land Data Assimilation System
LSM	Land Surface Model
MAGS	Mackenzie GEWEX Study
MDB	Murray Darling Basin
MESA	Monsoon System South America
MHM	Macroscale Hydrological Model
MODIS	Moderate Resolution Imaging Spectroradiometer
NAMAP	North American Monsoon Assessment Project
NAME	North American Monsoon Experiment
NAMS	North American monsoon system
NAO	North Atlantic Oscillation
NARR	North American Regional Reanalysis (NCEP)
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite and Data Information Service
NLDAS	North American Land Data Assimilation System
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NSIPP	NASA Seasonal to Interannual Prediction Program
NWS	National Weather Service
OCN	Optimal Climate Normals
OAL-GCM	ocean/atmosphere/land general circulation model
OGP	Office of Global Programs
OHD	Office of Hydrological Development
PACJET	Pacific Land-falling Jets
PACS	Pan American Climate Studies
PDF	probability density function
PILPS	Project for Intercomparison of Land-surface Parameterization Schemes
PIRCS	Project to Intercompare Regional Climate Simulations
PLATIN	Hydrometeorology of the La Plata Basin
RCM	Regional Climate Model
RFC	River Forecast Center
RISA	Regional Integrated Sciences and Assessments
SGP	Southern Great Plains
SSM/I	Special Sensor Microwave Imager
SMN	Mexican Weather Service
SST	sea surface temperature
SURFX	SURFace eXchange sites
SWE	Soil Water Equivalent
SWG	Science Working Group
TOGA	Tropical Oceans Global Atmosphere Program
TM	Thematic Mapper
TRMM	Tropical Rainfall Measuring Mission.
UNESCO	United Nations Educational Science and Culture Organization
USWRP	United States Weather Research Program
VAMOS	Variability of the American Monsoon System
VOCALS	VAMOS Ocean-Clouds-Atmosphere-Land Study
WCRP	World Climate Research Programme
WEBS	Water and Energy Budget Studies
WRAP	Water Resources Applications Project