# **J6.1** A RETROSPECTIVE AND OUTLOOK FOR GCIP/GAPP CONTRIBUTION TO LAND SURFACE AND LAND ATMOSPHERE MODELING

By R. G. Lawford
NOAA Office of Global Programs
Suite 1210, 1100 Wayne Avenue
Silver Spring, MD 20910
lawford@ogp.noaa.gov

## 1. Introduction

Modeling land surface processes over all relevant space and time scales is a complex challenge requiring a comprehensive, integrated interdisciplinary efforts combining filed studies and model development. The GEWEX (Global Energy and Water Cycle Experiment) Continental-scale International Project (GCIP) and its follow-on the GEWEX Americas Prediction Project (GAPP) have been designed to develop better land surface models and to use this capability in the study of water and energy budgets, including the land surface water budgets on a continental-scale. GCIP research activities were fully implemented in the Mississippi River Basin in the 1995 to 2001 period with funding from NOAA and NASA.

## 2. Programmatic Context for GCIP

The ultimate goal of GCIP is "to demonstrate a capability to predict changes in water resources on time scales up to seasonal, annual, and interannual as an integral part of a climate prediction system" (NRC, 1998). The long-term strategy involves the development of comprehensive land surface models that can become an integral part of a global climate model (GCM). These models are needed for climate prediction, and for the development of scenarios that project the climatic consequences of greenhouse gas increases and land use change. A first step in demonstrating a predictive capability involves quantifying regional water and energy budgets on seasonal to annual time scales as a basis for model validation. For GCIP the contributions of process studies, observations and models have been highly integrated around the program paradigm shown in Figure 1. Observations were considered to be an important part of the project because of their contribution to model development and validation.

In order to address a broad range of issues using the limited resources available, GCIP undertook its research program n four phases. Each phase was associated with a different sub-basin and involved extensive data set development for that sub-basin. Each component of the Mississippi River Basin was identified as a Large Scale Area (LSA) (IGPO, 1994). The periods for which extensive data sets were or are being acquired are shown in Figure 2.

**Figure 1 Schematic outlining the modeling paradigm implemented in GCIP (IGPO, 1994).**

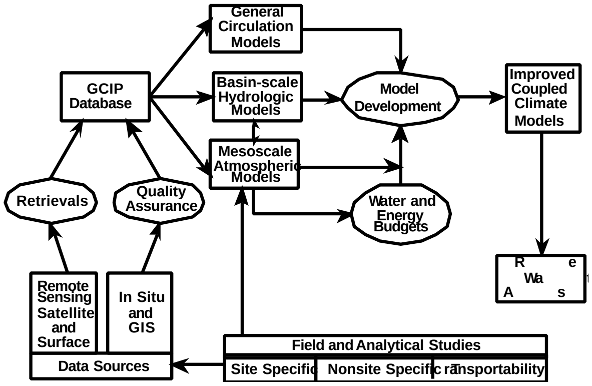
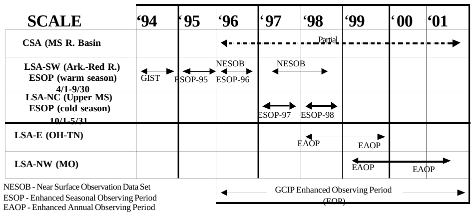


**Figure 2 Periods for which special GCIP large-scale data sets are available (IGPO, 1999).**



Models have played an important role in GCIP and GAPP because they provide a synthesis of the information known at any point in time and allow that knowledge to be used to examine a range of initial conditions. They also facilitate sensitivity studies, and provide a capability to predict future conditions or states based on different forcing functions. Models are also useful frameworks within which new process understanding can be codified and utilized.

In this role they allow one to interpolate or extrapolate from areas with extensive observations into ungauged areas as needed.

In general, the development of Land Surface Models (LSMs) in GCIP has involved the following approaches:

- Improving representation of physical processes in models through process studies.
- Carrying out special studies and analyses to estimate parameters for use in the models.
- Comparing model outputs and observations for the same period and location to determine where the model needs improvement.
- Undertaking model intercomparisons to assess the sensitivity of various land-surface schemes to their process representations and parameter values.

The development of regional scale coupled land-atmosphere models in GCIP has progressed on a number of fronts. Academic studies have been examining the role of various processes using a range of models. Within this community the following models and land surface schemes are being developed and applied: RAMS, MM5, Simple Biospheric Model (SSiB), Biosphere-Atmosphere Transfer Scheme (BATS), Eta, MAPS, GEM, OSU Land Surface Model and Surface Water Budget (SWB) model. Through the GCIP NOAA Core Project and other related initiatives, Koren et al. (1999) and (Smirnova, personal communication) have incorporated a number of techniques developed through academic research into their developmental and operational models.

## 3. Model Development to Improve Data Assimilation Products

Within GCIP three operational models have been used to produce data assimilation products that were then stored in an archive at the National Center for Atmospheric Research (NCAR). The three models are the Eta model run at the National Centers for Environmental Prediction (NCEP), the Mesoscale Analysis and Prediction System (MAPS) model being developed at the Forecast System Laboratory (FSL), and the Global Environmental Multiscale (GEM) Model used at the Canadian Meteorological Center. Through their academic research efforts, GCIP investigators have assessed the sensitivity of outputs from these models to changes in the representation of soil moisture, snow, ground frost, snow melt, vegetation, and boundary layer processes. This feedback to the operational centers has been valuable in identifying priorities for model development.

The Eta model is one of the main tools used by the National Weather Service in providing routine forecasts. These comparisons between model output and data have resulted in a number of improvements to the NCEP Eta model in the past five years.

The improved representation of soil moisture processes in the Eta model resulted in significant improvements in the temperature and specific humidity simulations (Yucel et. al, 1998). The benefits of this approach were most evident in improvements to the level of accuracy in surface air temperature fields.

## 4. Challenges in Model Development

A number of modeling challenges have arisen within GCIP, some from the nature of the problems being addressed and others from the complexities of the land surface processes being represented in the models. These challenges include model initialization, model structure and parameter specification (Gupta et al., 1999).

### 4.1 *Initialization*

GCIP's longer-term mission of monthly to seasonal predictions of water cycle variables is its most challenging model development issue because seasonal forecasting entails both initial conditions and boundary conditions. At the seasonal time scale the memory in variables such as soil moisture will persist to the extent that erroneous initial soil moisture fields could cause errors to propagate for many months unless the conditions of the land are “reinitialized” by a climate extreme (such as heavy rains or floods) resulting from major external forcing such as an El Niño event.

One of the most critical initialization problems involves establishing correct soil moisture fields when observations of this variable are very limited. The importance of initial soil moisture fields has been stressed in a number of studies including Viterbo and Betts (1999), and Koster and Suarez (1999). In the absence of observations this parameter is frequently initialized with a model derived value. Snow cover and snow pack are also important initial fields for models.

### 4.2 *Model Structure*

A second major challenge in model development involves model formulation. Regional LSMs frequently rely on tuning the model to land surface conditions in a particular region so it accurately simulates processes important in that region (e.g. snow or tropical rainforest). GCIP has emphasized the testing of model modifications in a mesoscale model framework because it is possible to see the spatial and temporal influences of the change without having to wait for the results of a multi-year model run as would likely be the case if a full GCM model was used.

Hydrologic models can produce different results arising from their formulation. The structure and calibration requirements for distributed models are different from lumped parameter models. Lumped parameter models are one-dimensional consequently a catchment may have a single average value for the precipitation input, a single equation to describe the rainfall-runoff relationship and no representation of the internal dynamics of the basin. Furthermore, the vegetation, hydraulic conductivity and topography are all represented by single values in spite of the heteorgeneity of these parameters across the basin.

The development of macroscale distributed hydrological models that incorporate more process understanding is a goal for GCIP. Distributed hydrologic models are also able to make use of the high resolution distributed data fields available from radar and satellite data systems. Within GCIP, significant effort is being directed to the development of a Land Data Assimilation System (LDAS) initiative involving the use of distributed hydrologic models as well as SVATS. The current system uses the Eta model as its basic framework and then allows land surface schemes and hydrologic models such as MOSAIC, Surface Water Balance (SWB) and VIC models to be interfaced with it interchangeably.

### 4.3 *Parameter Specification*

The third major challenge in model development involves the estimation of parameters that represent certain physical processes in models. In some cases the parameters (and even the variables in the models) have no counterparts in the physical world. This is seen as an acceptable approach where neural networks are used to develop statistical representations of reality based on correlations between variables (Cotton, personal communication). In other cases a surrogate for a physical parameter is used in a model. For example, soil wetness is a modeled parameter that is used in place of soil moisture in a number of models (Entin et al., 1999).

The issue of parameter specification is important for both atmospheric and hydrologic models. However, the approach often differs according to the model being used. For many physical processes, physical constants are not constrained by the model format so the equations can be transferred from one model to another. Scale effects are often dealt with by setting terms that are negligible at the model's operating resolution to zero. Many hydrological models require the derivation of parameter values that are specific to the watershed being modeled.

When modifications are made to models, they are often made by changing the value of one parameter at a time. However, model performance depends on the relationship between all the parameters.
Consequently, attention must be given to the interaction between parameters when making a change to even one parameter. GCIP research on parameter estimation by Gupta et al. (1999) includes the development of techniques for optimizing model calibrations by determining how all the parameters should be changed to accommodate changes in the parameter of interest. These techniques are being applied to SVATS (specifically BATS and NOAH, the LSM used in the Eta model).

## 5. Critical Land Surface Processes:

GCIP has supported research to more effectively represent physical processes related to vegetation, soil moisture, surface heterogeneity, cold season and runoff processes. As we move forward with GAPP, the focus will change to land memory processes with special emphasis on vegetation.

### 5.1 *Vegetation:*

Vegetation contributes to the complexity of land-atmosphere interactions due to its spatial heteorogeneities, and its strong diurnal and seasonal cycles. Plant-atmosphere interactions are very complex because plants change from being photosynthetically active during the day to being less active at night. Their effects influence the water budget through transpiration and the energy budget through albedo effects. The sensitivity of summer convection to vegetation effects in coupled models has been demonstrated by Xue et al. (1996). They found that a more realistic representation of the phenology of the vegetation cover during the summer months leads to more negative values of the lifted index (a commonly used index of atmospheric instability) and hence, more convective precipitation.

### 6.2 *Soil Moisture:*

Soil moisture is a critical control on the feedback between the land and the atmosphere. Under sunny conditions dry soil is characterized by warmer temperatures and larger sensible heat fluxes while wet soil is characterized by cooler temperatures and larger latent heat fluxes. GCIP has had success in reproducing vertical profiles of soil moisture with one-dimensional water balance models. However, the large heterogeneity of soil moisture, even on small spatial scales, has been a major obstacle in moving beyond a one-dimensional representations of soil-atmosphere interactions.

Koster and Suarez (1999) have shown that the inclusion of actual estimates of soil moisture over the USA in place of climatological soil moisture has a greater impact on seasonal predictions of summer precipitation than the use of measured Sea Surface Temperatures (SSTs) in place of climatological SSTs. This indicates that soil moisture has a memory effect that influences the land surface boundary condition during the spring and summer months. However, for seasonal prediction of precipitation, both initial and boundary conditions must be considered.

### 5.3 *Surface Heteorogeneity:*

The Regional Atmospheric Modeling System (RAMS) is being used to demonstrate the effects of shape and size of sub-grid surface heterogeneities in soil moisture and other surface features on mesoscale circulations (Avissar and Liu, 1996). According to their analysis these mesoscale heterogeneities can be responsible for creating mesoscale circulations with their own localized precipitation patterns. This effect could reduce the confidence often placed in simple linear procedures used to average properties from heterogeneous fields.

### 5.4 *Cold Season Processes:*

Studies in the North Central area of the Mississippi River Basin have been directed at quantitatively describing the snow covered land surface and its interactions with the atmosphere. During winter, the surface is relatively decoupled from the atmosphere. With the onset of spring, the snow melts, the ground thaws, the surface warms, and the processes of sensible heating and evaporation once again become important to the climate. Data on ground heat fluxes, snow melt rates, meltwater ponding on the surface, and ground melting are being provided by Baker et al. (1999) for use in calibrating and evaluating these models. The results of studies of ground frost have led to the development of new parameterization schemes for the winter season (Koren et al., 1999). Liston et al. (1999) and Yang et al. (1997) have made considerable progress in representing snow processes in the RAMS and BATS models.

### 5.5 *Runoff/Discharge:*

Stream discharge is an important variable for model validation. Modeling runoff represents a robust test of the extent to which a given land surface scheme can represent the land surface processes. The PILPS 2c model intercomparison, which included both SVATS models and distributed hydrologic models, assessed the ability of these models to simulate runoff (Lohmann et al., 1998). Results from PILPS 2c showed that many land surface schemes produce reasonable runoff estimates but do not adequately represent the process whereby the runoff is generated because the amount of water coming from base flow is either dominant or virtually non-existent. However, models that represent hydrologic processes such as the Variable Infiltration Capacity (VIC) model seemed to reproduce a reasonable balance between surface runoff and base flow. Hydrometeorological processes will in mountainous areas also receive more attention.

## 6. Summary:

The improvement of land surface models is an important activity in GCIP and GAPP. Advances in model development have been facilitated by establishing data sets that are comprehensive and relevant for the needs of model development; data delivery systems that are affordable and readily accessible; and model development work that has clear relevance to, and a strong influence on, operational NWP models. Where data are missing for model initialization and parameter estimation, specialized models have provided the necessary inputs. In addition to assisting in closing regional water and energy budgets, models have been successfully used within GCIP to quantify surface processes; to provide predictions for water resource applications, and to produce research quality data assimilation products for climate studies. These developments have also benefited operational weather services that have adopted a number of model innovations originating in the academic community.

## 7. References:

*Avissar,* R., and Y. Liu, 1996: A three-dimensional numerical study of shallow convective clouds and precipitation induced by land-surface forcing, J. Geophys. Res., 101, 7499-7518.

*Baker,* J. M., K. J. Davis, and G. C. Liknes, 1999: Surface energy balance and boundary layer development during snowmelt, J. Geophys. Res., Vol. 104, No. D16, 19,611-19, 621.

*Entin,* J. K., A. Robock, K. Y. Vinnikov, V. Zabelin, S. Liu, A. Namshai, and T. Adysaures, 1999: Evaluation of Global Soil Wetness Project Soil Moisture Simulations. J. of Meteor Soc. of Japan, Vol., 77, No. 1B, 183-199

*Gupta,* H. V., L. A. Bastidas, S. Sorooshian, W.J. Shuttleworth, and Z-L. Yang, 1999: Parameter estimates of a land surface scheme using multi-criteria methods, J. Geophys Res., Vol.104, No. D16, 19,491-19,503.

*International GEWEX Project Office,* 1999: GCIP Major Activities Plan for the Large Scale Area-Northwest (Missouri River Basin), IGPO Publication Series No. 33, International GEWEX Project Office, Washington, DC.

*International GEWEX Project Office*, 1994: Implementation Plan for the GEWEX Continental-scale International Project (GCIP); Volume II, Research. International GEWEX Project Office, Washington, DC.

*Koren,* V., J. Schaake, K. Mitchell, Q.-Y. Duan, F. Chen, and J. M. Baker, 1999: A parameterization of snowpack and frozen ground intended for NCEP and climate weather models, J. Geophys. Res., Vol. 104, No. D16, 19,569-19,585.

*Koster, R.D. and M.J. Suarez,* 1999: A Simple Framework for examining the interannual variability of land surface mositure fluxes, Journal of Climate, 12:1911-1917.

*Liston,* G. E., R. A. Pielke, Sr., and E. M. Greene, 1999: Improving first-order snow-related deficiencies in a regional climate model, J. Geophys Res., Vol. 104, No. D16, 19, 559 - 19, 567.

*Lohmann*, D., D.P. Lettenmaier, X. Liang, E.F. Wood, A, Boone, S. Chang, F. Chen, Y. Dai, C. Desborough, R. E. Dickinson, Q. Duan, M. Ek, Y.M. Gusev, P. Irannejad, R. Koster, K.E. Mitchell, O.N. Nasonova, J. Noilhan, J. Schaake, A. Schlosser, Y. Shao, A.B. Shmakin,

D. Verseghy, K. Warrach, P. Wetzel, Y. Xue, Z.-L. Yang and Q.-c. Zeng., 1998: The Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS): Phase 2c, Red-Arkansas River basin experiment, 3, Spatial and temporal analysis of water fluxes, Global Planet Change, 19, 161-176.

*National Research Council*, 1998: GCIP: A Review of Progress and Opportunities, National Academy Press, Washington, 93 pp.

*Sun,* S., J. Jin, and Y. Xue, 1999: A simple snow-atmosphere-soil transfer (SAST) model, J. Geophys. Res., Vol., 104, No. D16, 19,587-19,598.

*Viterbo, P.* and A.K. Betts, 1999: Impact of the ECMWF reanalysis soil water on forecasts of the July 1993 Mississippi flood, J. Geophys. Res., Vol. 104, No. D16, 19,361-19,366.

*Xue,* Y. M. Fenessey, and P. J. Sellers, 1996: Impact of vegetative properties on U.S. summer weather prediction. J. Geophys. Res., 101, 7419-7430.

*Yang,* Z. –L., R. E. Dickinson, A. Robock, and K. Y. Vinnikov, 1997: Validation of the snow-sub-model of the Biosphere –Atmosphere Transfer Scheme with Russian snow cover and meteorological observational data, J. Clim., 10 353-373.

*Yucel,* I., W. J. Shuttleworth, J. Washburne, and F. Chen, 1998: Evaluating NCEP Eta model derived data against observations, Mon. Weather Rev., 126, 1977-1991.

## Appendix A Acronyms

| | |
|---|---|
| ARM | Atmospheric Radiation Measurement |
| BATS | Biosphere-Atmosphere Transfer Scheme |
| BOREAS | Boreal Ecosystem Atmosphere Study |
| CART | Clouds and Radiation Testbed |
| CSE | Continental Scale Experiment |
| EROS | Earth Resources Observation Satellite |
| FSL | Forecast Systems Laboratory |
| | GAPP GEWEX Americas Prediction Project |
| GCIP | GEWEXContinental-scale International Project |
| GCM | Global Climate Model |
| GEM | Global Environmental Multiscale (Model) |
| GEWEX | Global Energy and Water Cycle Experiment |
| IGPO | International GEWEX Project Office |
| LDAS | Land Data Assimilation System |
| LSM | Land Surface Model |
| MAPS | Mesoscale Analysis and Prediction System |
| MM5 | Mesoscale Model (NCAR) |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Center for Atmospheric Research |
| NCEP | National Centers for Environmental Prediction |
| NDVI | Normalized Difference Vegetation Index |
| NOAA | National Oceanic and Atmospheric Administration |
| NRC | National Research Council |
| NWP | Numerical Weather Prediction |
| OSU | Oregon State University |
| PILPS | Project for the Intercomparison of Land Surface Parameterization Schemes |
| RAMS | Regional Area Modeling System (Colorado State University) |
| SSiB | Simple Biosphere Model |
| SST | Sea Surface Temperature |
| SVATS | Soil Vegetation-Atmospheric Transfer Scheme |
| SWB | Surface Water Budget |
| VIC | Variable Infiltration Capacity (Hydrologic Model) |
| WCRP | World Climate Research Program |