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WATER RESOURCES SIMULATION IN THE RIO GRANDE BASIN USING COUPLED MODELS

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ABSTRACT

Regional assessments of water resources under global climate change require models that can resolve management, land use, and climate effects. Los Alamos National Laboratory is developing a coupled model of water resources that places a river basin in its global context. The upper Rio Grande basin above El Paso, Texas is the testbed for this model. The model structure and computational approach are emphasize and issues such as nonlinear feedback between components and spatial and temporal scaling of processes are discussed. Using simulations of regional meteorology, the effects of high spatial resolution simulations on the distribution of precipitation are demonstrated.

INTRODUCTION

Demands for water are rapidly increasing in arid and semiarid regions around the world at the same time that global climate variability and anthropogenic changes to the climate are altering regional precipitation patterns and amounts. For instance, population growth and economic shifts that bring traditional agricultural uses of water into conflict with industrial and municipal demands have left the southwestern United States vulnerable to climate variability and land use changes (Lins and Stakhiv, 1998). No-flow days at the mouth of the Yellow River in China increased by two orders of magnitude between 1970 to 1990 (Yang et al. 1998). As demands for water in arid and semiarid regions grow, the effects of climate variability are magnified and water resource management must increasingly deal with unprecedented situations. High-resolution computational models can predict the effects of climate variation and socio-economic trends on regional water and energy balances. Models that couple regional atmosphere, surface and subsurface hydrology through physically accurate non-linear feedbacks can capture subtle differences in responses of river basins to variations in climate and land use.

Los Alamos National Laboratory is developing a coupled model of water resources that places a river basin in its global context. The upper Rio Grande basin above El Paso, Texas is the testbed for the Los Alamos model. A river basin is a natural unit of analysis 1) because its surface and subsurface hydrology are more or less closed systems, and 2) because most water resource management decisions are made at regional and local scales.

The Los Alamos coupled model is composed of four interacting components: a regional atmospheric model that is driven by global climate data, a land surface hydrology model, a subsurface hydrology model, and a river routing model. The regional atmospheric model (currently RAMS, the Regional Atmospheric Modeling System) acts as a down-scaling interface between global and regional climates and provides meteorological variables, especially precipitation, to the land surface model. The land surface model (currently SPLASH, the Simulator for Processes of Landscapes, Surface/Subsurface

Hydrology) partitions precipitation into evaporation, transpiration, soil water storage, surface runoff, and subsurface recharge. Surface and subsurface runoff is routed through the river channel model, and the subsurface hydrology model (currently FEHM, Finite Element Heat and Mass) is linked to the land surface and channel flow components to simulate saturated and unsaturated flow and changes in groundwater due to natural and anthropogenic effects. The software is designed so that alternative component modules can be substituted for RAMS, SPLASH and FEHM. The system runs on an open partition of the 6,144 processor Blue Mountain supercomputer at Los Alamos.

In this paper we emphasize model structure and computational approach because we are still in the process of building the coupled modeling tool. In particular, we discuss our approach to the fundamental physical science issues of nonlinear feedback between components and spatial and temporal scaling of processes. Using simulations of regional meteorology, we demonstrate the effects of high spatial resolution simulations on the distribution of precipitation. Additionally, we discuss the computational model of processing that we are using to implement the coupled model.

BACKGROUND

Projected increases in global climate variability and their environmental impacts have provoked considerable research and comment in scientific and policy communities, not to mention the general public. Until recently, however, most computer simulations have been conducted at too coarse a scale to evaluate the impacts of increased climate variability on localities. The challenge is to down-scale global simulations to the regional level where the consequences of climate variation will be felt and must be managed. The U. S. Global Change Research Program (USGCRP) has emphasized that regional climate prediction and consequence assessment will be research priorities for the next decade because detailed regional analysis is needed by decision-makers (USGCRP 1998). The Climate Variability and Change in the Southwest Workshop sponsored by U. S. Department of the Interior, recommended better hydrologic models to predict regional water budgets and improved downscaling of long-term forecasts (Merideth et al. 1998).

Existing Models

Climate and hydrologic models differ on their representations of elements of regional water balances. Climate models often simplify hydrology by ignoring lateral movement of water across the landscape and groundwater processes. On the other hand, energy balance components in hydrologic models are frequently nonexistent or else the parameterizations are oriented towards evapotranspiration without consideration for radiation transfers. Efforts are underway to incorporate more realistic hydrology into climate models. Liang et al. (1994) described the variable infiltration capacity (VIC) model that includes a runoff routing scheme between grid cells used in a global climate model (GCM). Further refinements and applications of the VIC model including estimation of parameters are given in Abdulla and Lettenmaier (1995a,b). Kite (1998) described the issues in using a land surface parameterization with a GCM or climate model. He concluded that hydrologic models contain a large amount of knowledge and experience, and 3) because management decisions generally have large-scale implications that nonetheless, do not extend outside the basin. and throwing them away is not the solution.

Rio Grande

The upper Rio Grande above El Paso, Texas was selected for model development and testing because it is typical of arid and semiarid river basins throughout the world and it is a major river system in the southwestern United States. The upper basin extends from the San Juan mountains of southern Colorado to Elephant Butte Reservoir north of Las Cruces, New Mexico. It covers 92,000 km^2 and includes the Santa Fe and Albuquerque, New Mexico metropolitan areas. River flows are maintained by seasonal precipitation that is often highly localized, especially in summer. Recharge from groundwater is also localized and discharge from the river to the groundwater system is common. Spring snowmelt and summer monsoon storms are the main sources of water. The Rio Grande system provides water for flora, fauna, agriculture, domestic consumption, recreation, business and industry. Increasing demand from competing uses may eventually deplete groundwater resources and affect surface resources. Furthermore, global climate variability may alter water balances by modifying the regional hydrologic cycle through timing and amount of precipitation. Indeed, stress on water availability is already important under the current climatic regime (Lins and Stakhiv, 1998). Groundwater is the primary source of water for metropolitan areas, although Santa Fe and Albuquerque, New Mexico are attempting to augment their groundwater supplies with previously unused surface sources. Sustainability requires understanding the conjunctive use of ground and surface water, especially groundwater recharge from different sources including mountain fronts, agricultural fields and urban areas, and the effects of groundwater withdrawals on stream levels. Despite its practical importance, most climate models have not included the groundwater resource in any significant way.

Costigan et al. (1998) reviewed the different climatic features of the Rio Grande Basin and their origins relative to major forcing factors such as El Niño. Streamflows in the northern Rio Grande and its tributaries are dominated by snowmelt runoff, but as one moves south in the basin, the North American Monsoon becomes prevalent, particularly on the tributaries. The combination of these different climate regimes over the Rio Grande is important to its water resources because shifts in climatic patterns will alter the quantity and regimen of water supply for both surface and groundwater. As noted, the system is already stressed, so interruption in weather patterns or decreases in precipitation can have significant effects. The Rio Grande has been subjected to lengthy drought periods over the last 100 years, and a major drought occurred in the 1950s that caused a rapid shift in forest and woodland zones on the Pajarito Plateau (Allen and Breshears, 1998).

METHOD

A coupled model of the regional atmosphere and hydrology is an alternative to the current trend of embedding parameterizations of land surface and subsurface processes in climate models. A coupled model retains the essential physics of all elements of a water balance and allows feedback between them. Models of regional water balance generally require high resolution because they are meant to support analysis of fine-scaled processes like land-use change, soil moisture distribution, localized groundwater recharge, erosion and flooding. Grid resolutions of 5 km on a side or less seem necessary to represent the convective storms that are common in semi-arid regions, while grids of less than 100 m are needed to represent the spatial variability of vegetation classes. This raises three issues for coupled models. First, high resolution demands a large amount of computation. A high-resolution simulation of a single year of the upper Rio Grande Basin's water balance requires on the order of 10^{17} arithmetical operations and is dominated by the atmospheric simulation (Table 1). Many such simulations are needed if Monte Carlo simulations will be used to bound uncertainties arising from the data supporting simulations. Second, disparate processes must be scaled to each other. It is not, for instance, necessary to represent atmospheric processes at the 100-m scale needed to represent land surface processes like runoff and vegetation class. Third, large amounts of detailed data are required to support high resolution simulations. High performance computing has made it feasible to construct river basin models with sufficient spatial and temporal resolution to address regional problems. For instance, a one year simulation of the Rio Grande Basin can run in about one hour on a one hundred tera-ops (10^{14} operations per second) which makes Monte Carlo simulations based on hundreds of realizations feasible. Faster than one tera-ops computers have already been built at Los Alamos National Laboratory and elsewhere.

Table 1 – Computational Requirements of High Resolution Basin-Scale Land Surface/Atmosphere Simulation

	RAMS		SPLASH
Machine speed (operations/second)		10^{17}	
Basin size (km^2) – Upper Rio Grande		92,000	
Duration of simulation		1 year	
Resolution	1 km		100 m
Number of grid cells	92,000		9,200,000
Number of vertical layers	50		2
Floating point operations per grid cell	200		100
Time step	1 second		1 minute
Total number of operations	3×10^{17}		3×10^{14}
Total time (seconds)	3×10^{3}		3

Model Components

Our approach is to link a regional climate model with surface and subsurface hydrologic models in a data flow (Figure 1). This model allows us to retain essential dynamics of hydrologic processes as suggested by Kite (1998). The regional model is placed in a global context through boundary conditions affecting the regional climate model. Boundary conditions can be set by either observed data such as sea surface temperatures or by output from a GCM.

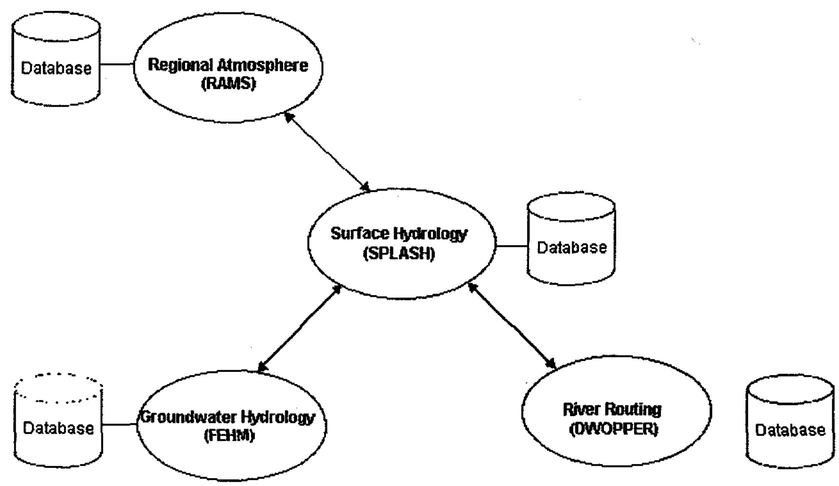

Figure 1. Data flow for coupled atmospheric and hydrologic model.

Regional Atmosphere. The regional climate component of our model uses the Regional Atmospheric Modeling System (RAMS) described in Pielke et al. (1992) and Cram et al. (1992). RAMS applies a finite difference solution of the Navier-Stokes equation to predict potential temperature, mixing ratio of water, pressure, and horizontal and vertical components of wind. We use a dynamical atmospheric model because 1) there are insufficient observations in complex terrain to provide adequate resolution for the required meteorological variables to simulate the water balance and 2) for scenario analyses climate can become nonstationary through natural or anthropogenic forcings. These non-stationary effects enter RAMS through the boundary conditions. The capability to simulate a non-stationary process is important for design and policy as related to regional analyses. RAMS provides precipitation, temperature, humidity, and wind data to the surface water hydrology component.

Land Surface. The Simulator for Processes of Landscapes, Surface/Subsurface Hydrology (SPLASH) is the surface water component. SPLASH is described in Ustin et al. (1996). SPLASH uses a grid-based discretization to partition precipitation into evaporation, transpiration, soil water storage, surface runoff, and subsurface recharge. Infiltration is computed using the Green and Ampt (1911) equation, and surface runoff is routed by a kinematic wave algorithm. SPLASH uses a soil profile database to simulate shallow subsurface return flow. Evapotranspiration estimates are based on model of Running et al. (1988). Runoff and infiltration are produced by precipitation (both snow and rainfall) obtained from RAMS and by snow accumulation and melt algorithms that are internal to SPLASH.

River Routing. The channel routing component is an important element of regional assessments in a river basin. Lins and Stakhiv (1998) noted that reservoirs and their operations are critical to determining regional effects of climate variation because management of the water resource can alleviate or modify the impact of variability through storage and operation. In some cases, the operation of a reservoir may be a stronger signal than that introduced by the climate. Our initial approach was to use the National Weather Service's Dynamic Wave Operational Model (DWOPER) for our channel and river routing (Fread 1988) since we planned to simulate basins under natural or unregulated flow conditions as a test for the model. However, natural or unregulated flow conditions do not provide the data needed by water resource managers. We are evaluating other codes for their ability to include reservoirs and dendritic drainage patterns.

Subsurface Hydrology. Groundwater represents a major water resource that is not considered in current climate models. The Finite Element Heat and Mass code (FEHM) described by Zyvoloski et al. (1997) is a three-dimensional multi-phase flow code that we use for both the vadose zone and aquifers. As indicated by its name, FEHM solves the porous media flow equation using finite elements. The upper boundary condition for FEHM is supplied by either SPLASH, through a subsurface recharge term, and the channel code through streambed infiltration. Mountain front streambed infiltration is an important source of groundwater recharge in arid and semiarid regions (Shun and Duffy,1999).

Data. Data for the coupled model of the Rio Grande is obtained from several sources. RAMS requires data on soils, vegetation, and sea surface temperature for the entire western United States. These data are developed from products such as the STATSGO database developed by the USDA Natural Resource Conservation Service and various USGS products. FEHM depends on hydrogeologic frameworks that include structure, stratigraphy, and sources as well as hydraulic conductivities. An initial framework model for the Española sub-basin north of Santa Fe has been developed.

<u>Computational Approach</u>

The individual component models are implemented as loosely coupled processes on the Blue Mountain parallel computer at Los Alamos National Laboratory. Each process is assigned a number of physical processors depending (currently) on the complexity analysis of Table 1. The Blue Mountain machine is a collection of forty-seven 128 node Silicon Graphics Origen 2000 shared memory multiprocessors (along with one 64 node and two 32 node Origen 2000's) linked by a high-bandwidth bus. Each Origen 2000 has a total of 1.3 GB (or 520 or 260 MB) of memory. We are using only a small fraction of Blue Mountain's 6144 processors during development. Despite data transmission rates of 100-200 MB/s, the bus is the main bottleneck in computations and one of the goals of our software development is to minimize the size and frequency of messages. Other research focuses are 1) refining the allocation of processors to processes including dynamic re-allocation as the computation progresses and 2) co-location of processes as a function of their coupling, i.e., the amount of data they exchange.

We call our model of computation Communicating Asynchronous Parallel Processes (CAPP). It is very similar to the Communicating Sequential Process model (Hoare,1978) except that the processes are parallel. RAMS is implemented as a message-passing system using MPI. The other components are parallelized using the shared memory model that is native to Origen 2000's. The software essentially implements the dataflow shown in Figure 1. Model components run independently and asynchronously except for occasional exchanges of data. Processing is synchronized by passing data in the form of messages using a system developed at Los Alamos. A process that requires data waits until the producing process sends a message containing the needed data. The advantages of this approach are that it does not require extensive re-writing of existing model component software or development of a complicated control structure

Spatio-temporal Resolution

One advantage of our computational approach is the ability to simulate large river basins with high spatial resolution. High resolution is essential to retain the pertinent physics of coupled hydro-meteorological processes (both within individual physical domains and at their interfaces where feedback can lead to significant nonlinearities), as well as to determine the relative importance of land use versus climate variability. Regional water balances are sensitive to the spatial and temporal distributions of precipitation, and high spatial resolution is required to simulate meteorological variables in mountainous terrain.

Costigan et al. (1998) reported on a RAMS simulation that provides one example of the insight gained from high resolution spatial simulations. They used interactive nested grids for Rio Grande simulations. The largest grid at 80 km resolution provided a synoptic view of the western United States but did not resolve the Rio Grande valley. The nested grids were 20 km and 5 km. At 5 km the major mountain ranges within the Rio Grande Basin were resolved and agreement between predicted and observed precipitation generally improved as the RAMS grid resolution increased(Costigan et al., 1998). We expect to experiment with 1-km grids in simulations of convective summer storms and evaluate the sensitivity of frontal storms to increased grid resolution.

However, the 5-km atmospheric grid does not represent land surface processes and changes sufficiently. The spatial grid for SPLASH will be 100 m which allows land use variation within a watershed and along the surface flow path to be examined. The higher resolution of the land surface component requires that the meteorological variables be downscaled from 5 km to 100 m. We use a hybrid statistical approach for the downscaling (Campbell, 1999) in which the variates (whether precipitation, temperature or humidity) are treated as a random variable, but deterministic components such as elevation are included in the downscaling approach. The RAMS values for the meteorological variables are calculated for the center of a 5-km grid cell. The resolution of the 100-m digital elevation model (DEM) means that points can lie above and below the center point of the RAMS grid. The downscaling algorithm uses nearest grid cells and topographic information from the refined (100 m) DEM for estimation. Eventually we expect to resolve land surface characteristics to 30 m, and we will use those simulations to evaluate the sensitivity of the water balance to increased information.

SUMMARY AND CONCLUSIONS

In collaboration with the Bureau of Reclamation and others, Los Alamos National Laboratory is building a coupled atmospheric and hydrologic model to assess the regional consequences of climate variability and land use on water resources. This model provides detailed simulations that have not been available on a river basin scale because of limitations that have existed in computational power. The model is being implemented on the Blue Mountain supercomputer at Los Alamos. The advantages of this approach are:

High spatial resolution allows land management influences to be considered as part of the assessment, and topographic features are better represented.

A physically-based atmospheric model allows global climate effects to enter through boundary conditions so non-stationary effects due to climate shift can be included.

High resolution allows land and atmospheric processes to be represented at scales that are faithful to their physics.

High resolution also allows dynamical couplings between processes that reflect nonlinearities in exchanges of mass and energy, and do not require lumping sensitive parameters.

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