The Role of Multi-Scale Land Surface Heterogeneity in Land-Atmosphere Interactions

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Abstract

Data analyses from field experiments have confirmed the high spatial variability of surface fluxes and soil moisture in association with land surface heterogeneity that is not resolvable by climate models. How does land surface heterogeneity at different spatial scales affect atmospheric processes such as precipitation, and land surface hydrology such as soil moisture and runoff? If subgrid spatial variabilities play an important role in land-atmosphere interactions at the local and regional scales, how can they be represented in coupled land-atmosphere models?

This proposal discusses an approach that uses modeling and observational studies to (1) develop a generalized subgrid parameterization that describes the land surface heterogeneity and the processes affected by it, (2) understand the role of multi-scale land surface heterogeneity in precipitation recycling and land-atmosphere interactions, and (3) explore the use of spatially distributed land surface data with the subgrid representation of land surface heterogeneity to improve hydrologic predictions. The studies will utilize a wide array of in-situ and remote sensing data from two GEWEX Continental Scale Experiments: the GCIP LSA-E over the Appalachians and the GAME HUBEX over the Huaihe River Basin in China. Both regions are marked by diverse orography and land surface cover, and both are ideal testbeds for demonstrating the values of improved hydrologic predictions because of the significant seasonal-to-interannual variability in precipitation that leads to episodic floods. The research will make use of a regional climate model and a hydrologically-based land surface model. A generalized subgrid parameterization will be developed based on an existing and well tested subgrid orographic precipitation scheme to account for the effects of subgrid topography, land surface cover, and soil properties on precipitation, surface fluxes, soil moisture, and runoff. Sensitivity experiments will be performed to determine the impacts of multi-scale land surface heterogeneity on precipitation recycling and other land-atmosphere interactions.

1. INTRODUCTION

- Land surface heterogeneity is a prominent characteristic over many regions of the world. At the larger scale typified by orographic features such as mountains and valleys, topographic variation directly affects precipitation and surface temperature which are the main driver of surface hydrology through its impacts on local and regional atmospheric circulation, vertical distribution of atmospheric moisture and temperature, and condensation. At the smaller scale, topographic variation can modify surface and subsurface runoff through downslope redistribution of soil water. Besides surface topography, spatial heterogeneity associated with soil properties, land cover, and localized precipitation also influences soil moisture and surface fluxes.

- **How can we enhance our predictive understanding of the multi-scale and multi-process nature of land surface heterogeneity and utilize spatially distributed land surface data for improvements in atmospheric and hydrologic predictions over regions with spatially complex surface conditions?**

2. OBJECTIVES

To use numerical modeling and observational analysis to:

- To generalize a subgrid parameterization in a coupled land-atmosphere model to account for the effects of subgrid variability of topography, vegetation, and soil on precipitation, surface fluxes, soil moisture, snow, and surface and subsurface runoff based on the existing framework of a subgrid parameterization of orographic precipitation.

- To apply the coupled land-atmosphere model with the subgrid parameterization to determine the impacts of multi-scale land surface heterogeneity on precipitation and land-atmosphere interaction processes.

3. APPROACH

To accomplish the objectives, four main tasks will be performed.

- A coupled land-atmosphere model will be developed by implementing the hydrologically-based land surface model, VIC-3L, in the Pacific Northwest National Laboratory Regional Climate Model, PNNL-RCM.

- A subgrid parameterization will be further developed to account for subgrid orographic and convective precipitation, land cover, soil properties, and hillslope flow.

- Numerical experiments and observational analyses will be conducted over the Appalachians and the Huaihe River basin to evaluate the coupled land-atmosphere model, and particularly the subgrid parameterization.

- Sensitivity experiments will be performed to elucidate the role of land surface heterogeneity on land-atmosphere interactions.

Why LSA-E and Huaihe River?

- Both the Appalachians (Figure 1) and the Huaihe River basin are marked by diverse orography and land surface cover. This study will take advantage of the comprehensive data archived for the GCIP LSA-E and GAME HUBEX experiments based on in-situ, remote sensing, and analyses data.

- Both regions display strong seasonal-to-interannual precipitation signals in association with El Nino-Southern Oscillation (ENSO). Improved representation of land-atmosphere interactions may lead to improvements in seasonal climate and hydrologic forecasts.

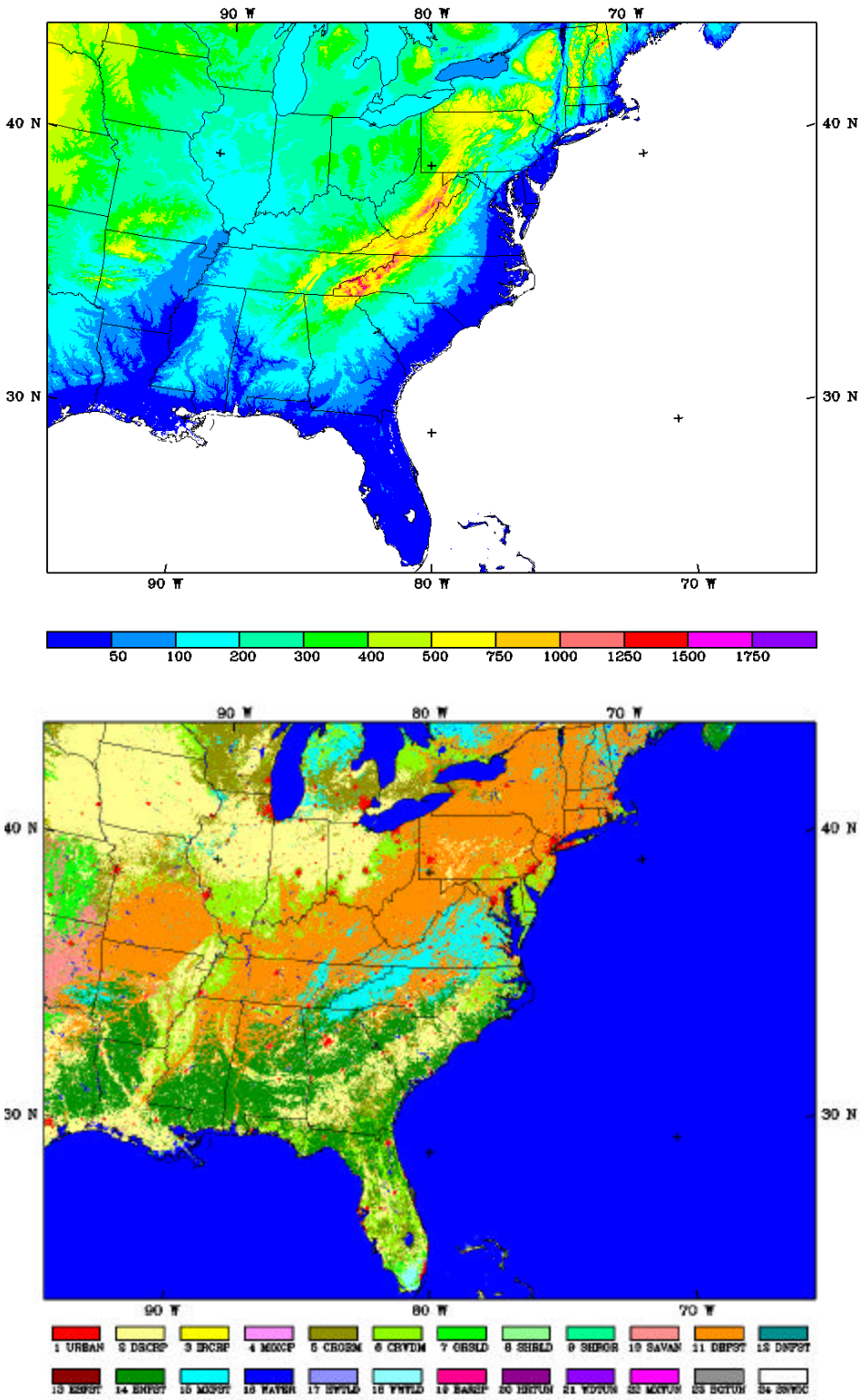

Figure 1. Surface topography and land cover in the RCM domain centered at the Eastern Mississippi at 1.5 km spatial resolution.

Description of Models

PNNL-RCM

- PNNL-RCM was developed based on the Penn State/NCAR Mesoscale Model (MM5) (Grell et al., 1993). One notable feature of the regional climate model is the subgrid parameterization of orographic precipitation (Figure 2) (Leung and Ghan, 1995; 1998). The subgrid method significantly improves the simulation of surface temperature, precipitation, and snowpack over mountainous areas.

- The subgrid parameterization provides high spatial resolution atmospheric inputs for driving land surface processes. Simulations performed with a fully distributed hydrology model (DHSVM, Wigmosta et al. 1994) driven by the RCM meteorology show good agreement with observed streamflow and snowpack (Leung et al., 1996).

VIC-3L Description

- The Three-Layer Variable Infiltration Capacity model (Liang et al., 1994; Liang et al., 1996a), VIC-3L, is a water-energy balance model with explicit representation of multiple land cover types (Figure 3). VIC-3L incorporates a representation of subgrid spatial variability of precipitation with infiltration to simulate runoff, soil moisture, and surface fluxes (Liang et al., 1996b).

- VIC-3L and its earlier two-layer version have been tested and applied to various basins of different scales (e.g., Nijssen et al., 1997; Wood et al., 1997) and intercompared with other land surface schemes in the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS). The model has performed consistently and the simulations compared very well with observations (e.g., Wood et al., 1998; Liang et al., 1998; and Lohmann et al., 1998).

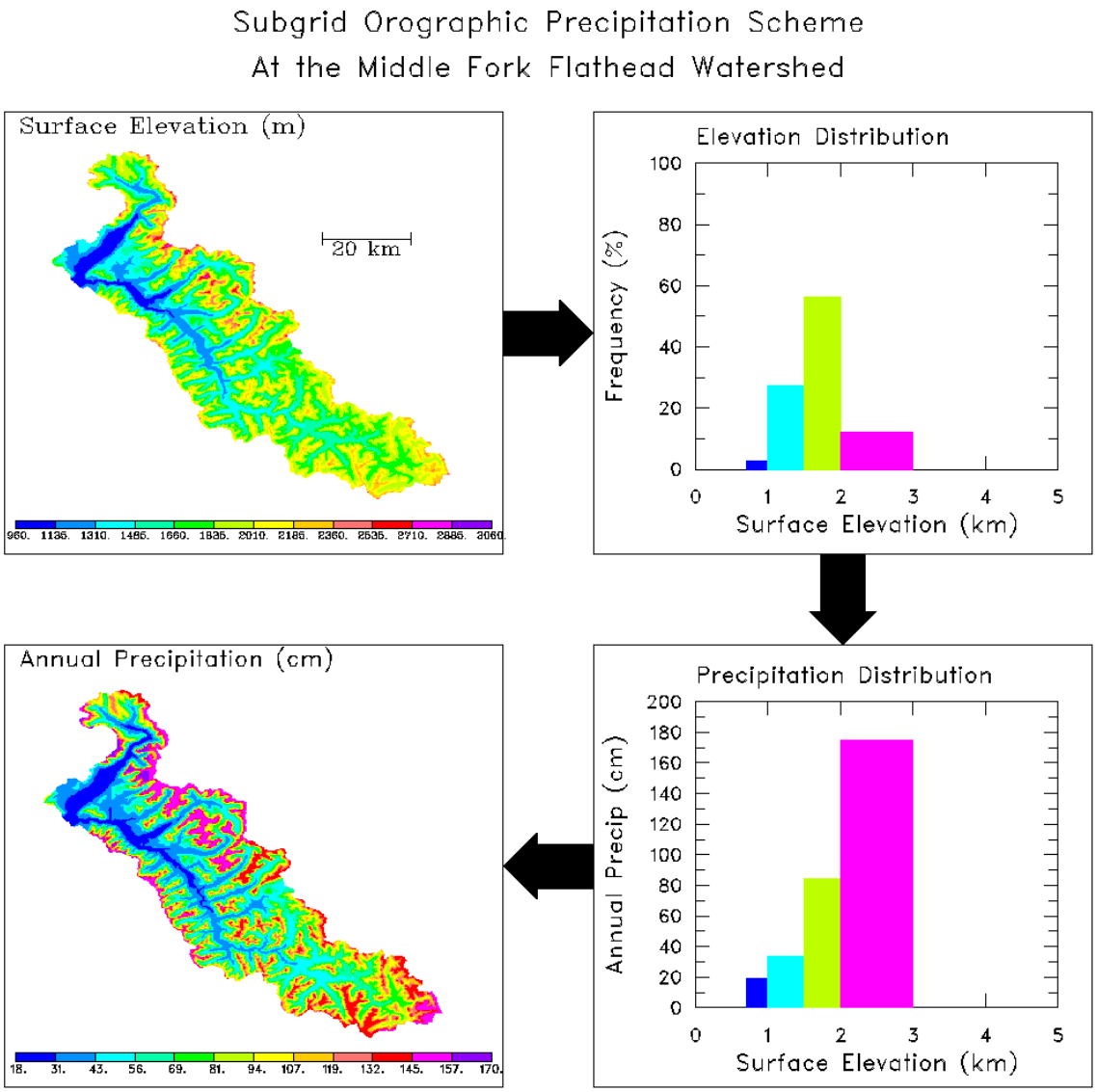

Figure 2. A schematic illustration of the subgrid parameterization of orographic precipitation applied to the Middle Fork Flathead watershed. Upper left: surface topography of the watershed at 1 km spatial resolution. Upper right: subgrid elevation classification. Lower right: simulations of precipitation at each subgrid elevation class. Lower left: mapping of precipitation to the watershed geographical area based on elevation to yield high spatial resolution distribution of climate conditions for driving hydrology models.

Three-Layer Variable Infiltration Capacity (VIC-3L) Model

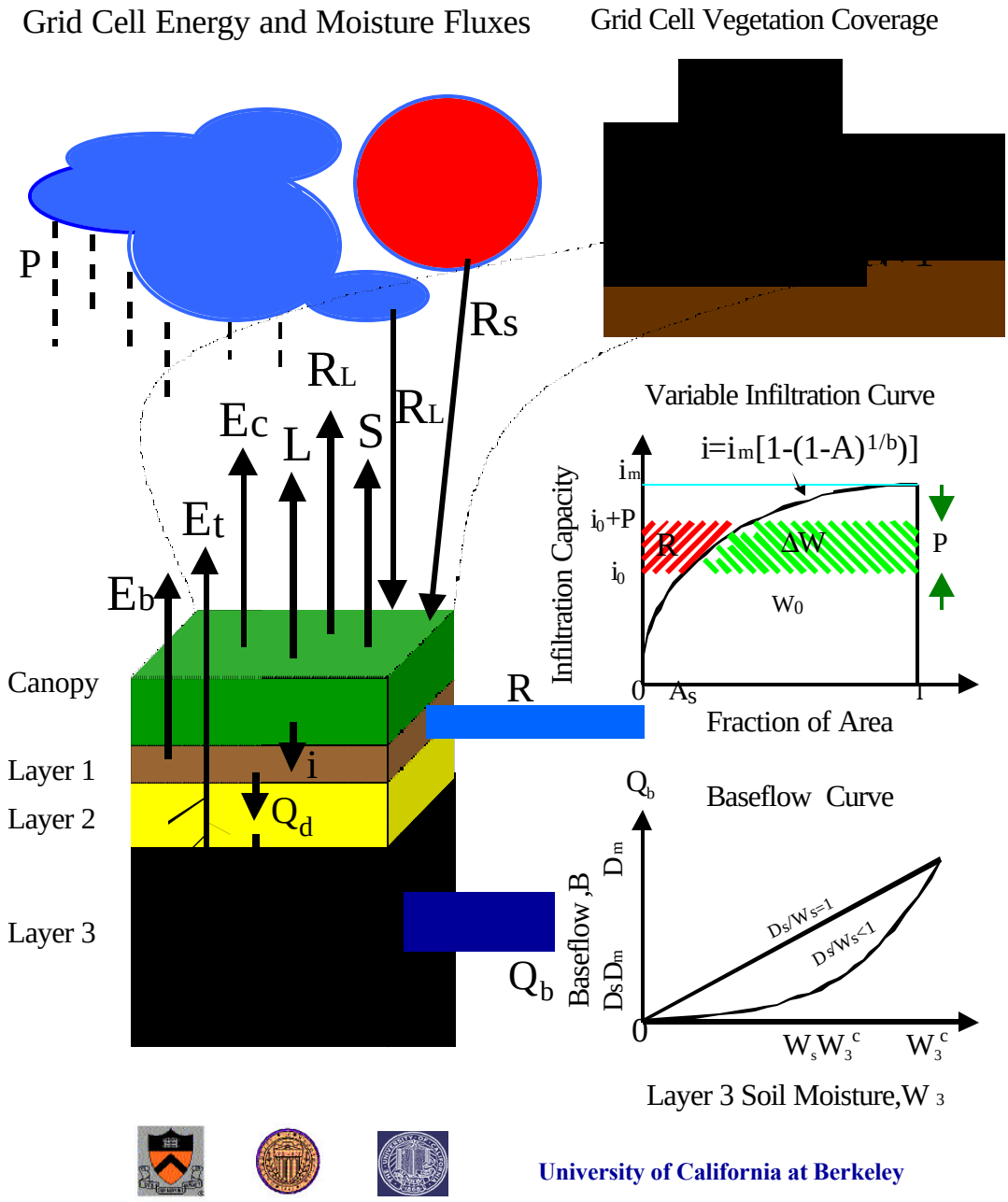

Figure 3. Schematic description of the Three-Layer Variable Infiltration Capacity (VIC-3L) Model.

Model Coupling Strategy

Leung and Wigmosta used RCM and DHSVM to examine strategies to fully couple atmosphere and land surface models. Two model setups were used with DHSVM applied over the American River watershed which covers 206 km^2 in the Pacific Northwest using observed meteorological forcings.

Simulation I: Apply DHSVM at 100 m spatial resolution to a two-dimensional domain covering the watershed. DEM was used to define the surface elevation of each grid cell.

Simulation II: 100 m resolution surface elevation data was aggregated to 13 surface elevation classes at 100 m intervals. Land surface processes were calculated for each elevation class based on meteorology that were also aggregated by elevation. The runoff simulated for each elevation band is area-weighted to calculate the total runoff for the watershed without the effects of channel routing.

Simulation III: Same model setup as in Simulation II, except precipitation, surface temperature, humidity, and solar radiation simulated at the RCM subgrid elevation bands (Leung and Ghan, 1998b) were used as forcings instead of the observations.

Results:

- Figure 4a: Over topographically diverse watersheds, hydrological modeling using elevation classification driven by atmospheric forcings aggregated likewise may provide an adequate framework to represent the impacts of the complex terrain on land surface processes.

- Figure 4b: Subgrid parameterization of Leung and Ghan can provide reasonable climate information for driving a hydrology model linked through elevation bands to simulate surface hydrology.

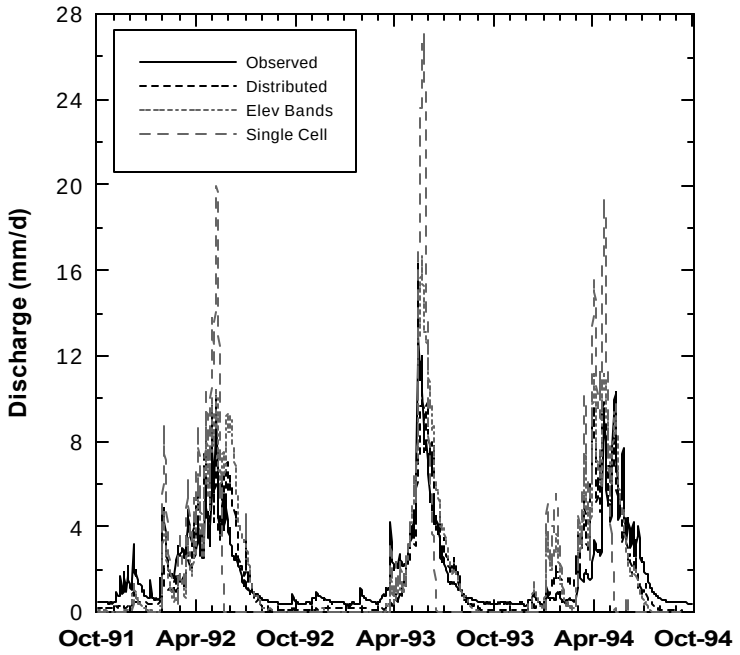

Figure 4a: Comparison of observed discharge (Observed) with discharge from Simulation I (Distributed) and Simulations II (Elev Bands). Simulated discharge for a single grid cell representation of the watershed (Single Cell) is also shown for comparison.

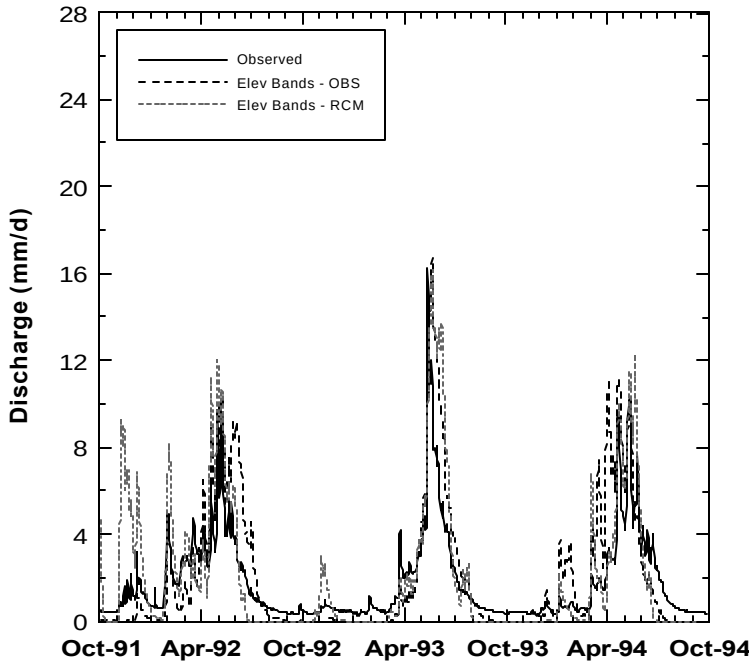

Figure 4b: Comparison of observed discharge (Observed) with discharge from Simulation II (Elev Bands – OBS) and Simulation III (Elev Bands – RCM).

Generalization of a Subgrid Parameterization of Land Surface Heterogeneity

- Based on the above findings, we will use the basic framework of the subgrid elevation classification to couple RCM and VIC-3L; that is, land surface processes will be calculated at each subgrid elevation class using simulated atmospheric forcings for each subgrid class.

- 1-km resolution topography DEM data will be used to define the subgrid elevation classes for each RCM grid cell. To account for spatial variability at the hillslope scale, VIC-3L will further divide each subgrid elevation class into a number of land cover types using the NOAA/NASA Pathfinder AVHRR Land cover data (DeFries et al., 1995) at 1 km resolution.

- Two aspects of the subgrid parameterization will be further developed.

Subgrid Precipitation

- Combine the subgrid orographic precipitation scheme with the statistical dynamic subgrid precipitation scheme developed in VIC-3L. The goal is to use the subgrid orographic precipitation scheme (Figure 2) to represent subgrid processes affected by airflow and cloud formation over complex terrain, and to use the statistical dynamic subgrid scheme (Figure 5) within the subgrid elevation classes to account for variations in precipitation and its interactions with soil properties and vegetation variations to generate heteorogeneity in soil moisture, surface fluxes, and runoff within an elevation band.

- Fan et al. (1996) analyzed hourly NEXRAD data and developed an empirical equation based on two years of data over three different locations at spatial scales ranging from 40 km to 500 km to estimate the FC. The equation uses one parameter that has spatial scale dependency. Figure 6 shows the general performance of this FC parameterization at the Red-Arkansas Basin. Clearly improvements are possible.

- We will use this method as a starting point to represent precipitation heterogeneity within subgrid elevation classes. We propose to use the TRMM data and the NEXRAD data to test the empirical equation extensively in the Appalachians and the Huaihe River basin, and to develop the dependency of the parameter on various atmospheric properties.

- Subdaily precipitation estimates from radars (e.g., 37 NEXRAD radars over the LSA-E and 3 doppler radars over the HUBEX) and the various networks of precipitation gauges (e.g., Automated Weather Observing System (AWOS), Surface Airways Observations (SAO), and Automated Surface Observing System (ASOS) in the LSA-E; and Automatic Raingauge Observations over 59 stations in the HUBEX region) will also be used.

Subgrid Soil Properties and Hillslope Flow

- VIC-3L uses a Beta distribution function to represent subgrid spatial heterogeneity in the infiltration capacity. The shape of the distribution function is determined by a single coefficient that has no physical analog and is determined through calibration.

- We will modify the quasi-dynamic wetness index of Barling et al. (1994) and Iida (1984) to estimate the variable infiltration capacity function directly for each subgrid elevation/vegetation class from readily available data such as DEM and the STATSGO soil information. This approach provides a physically based method for specifying the function by accounting for topography, soil properties, and the time taken for subsurface soil moisture redistribution.

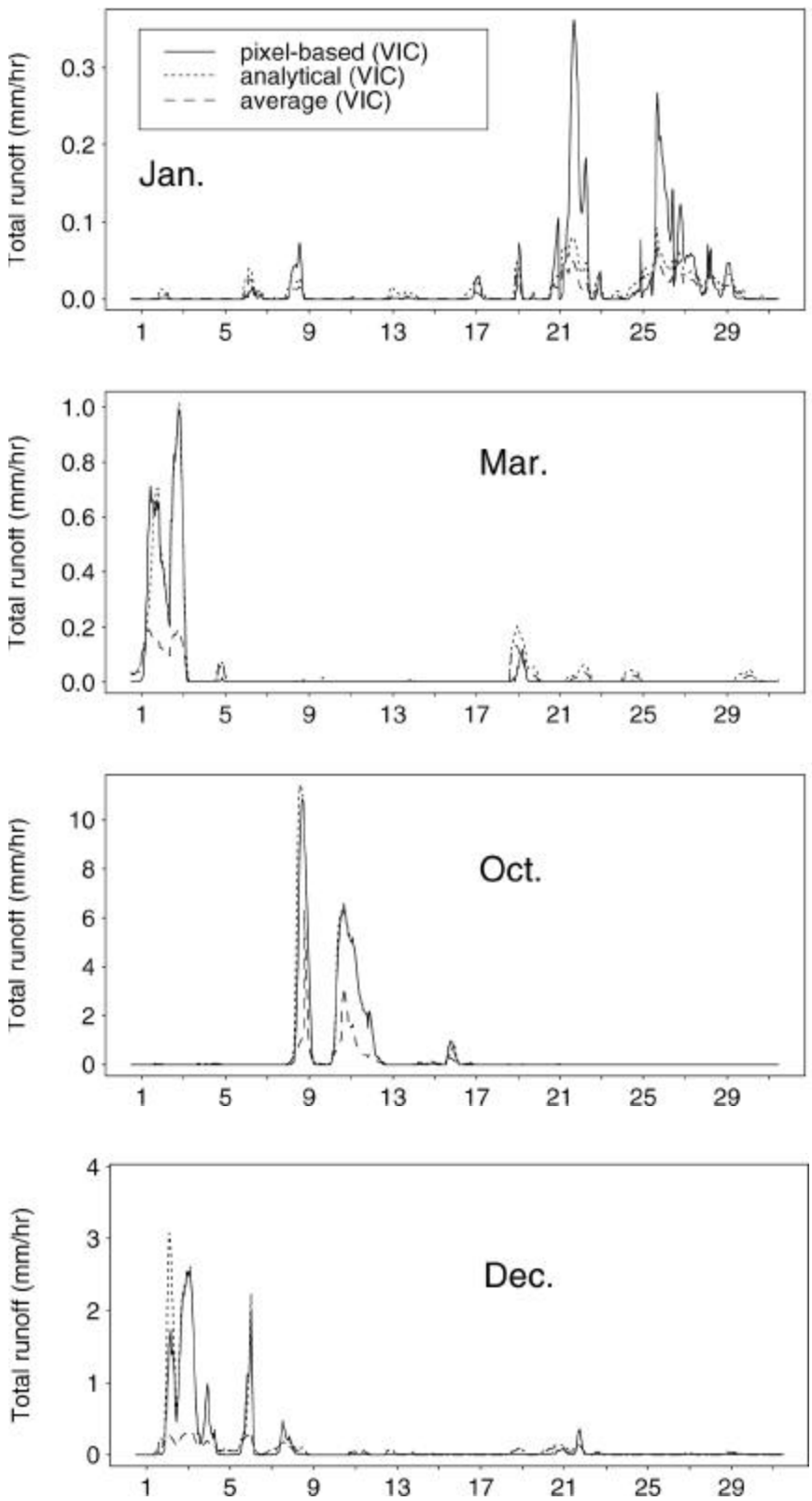

Figure 5. Comparison of runoff simulated by VIC-3L using pixel-based ('truth'), analytical (VIC subgrid estimate), and averaged precipitation at the PILPS forest. All three estimates of precipitation have the same total precipitation.

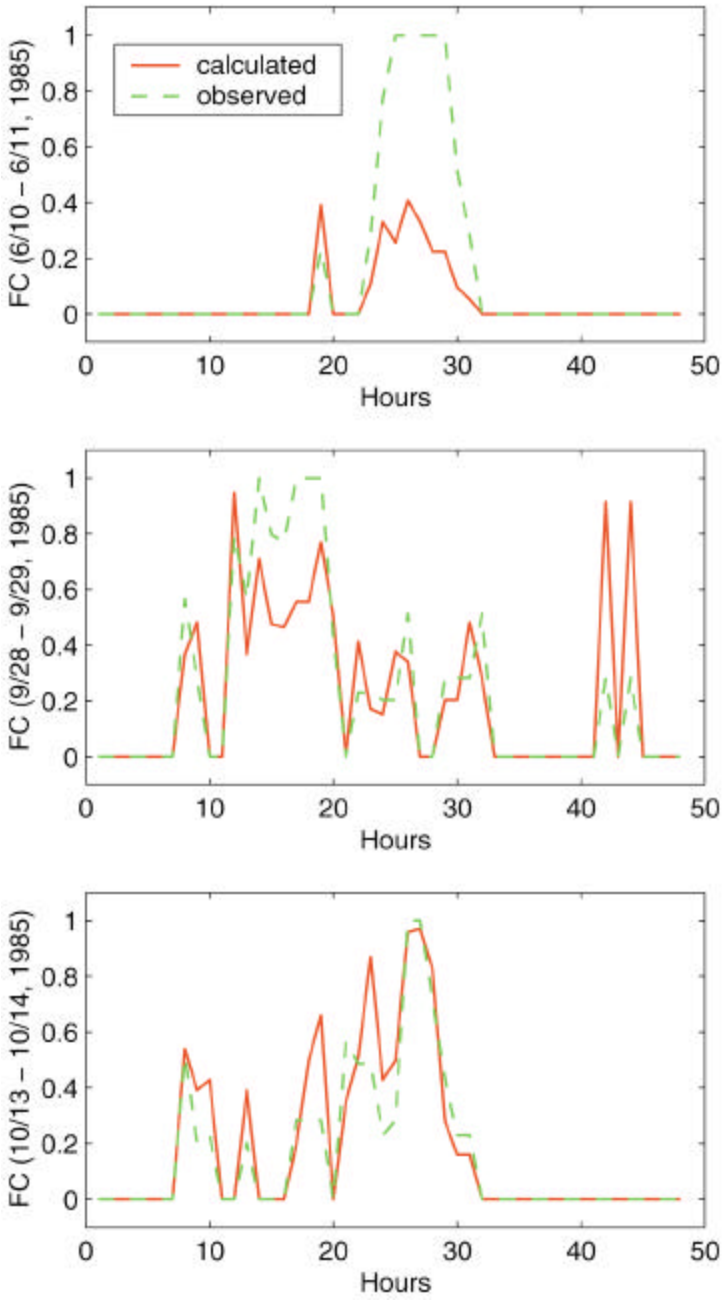

Figure 6. Comparison of fractional coverage (FC) of precipitation at a grid cell (34.5N, 99.5W) in the Red-Arkansas Basin based on the parameterization by Fan et al. (1996) (calculated) and manually digitized radar (MDR) data (observed).

Subgrid Soil Properties and Hillslope Flow (Cont'd)

- The grid-based representation of the watershed/channel system currently used in VIC-3L will be replaced by a topographically based method (Figure 7). During the model run, surface and subsurface runoff simulated for each elevation/vegetation class will be mapped into segments of the channel network contained defined by DEM. Flows are then routed through the channel network using the 1-D model employed by DHSVM (Perkins and Wigmosta, 1996), which allows simulated discharge to be output at any location(s) in the channel system. This watershed-based approach of river routing represents a significant advancement over the grid-based approach commonly used by macroscale hydrology models.

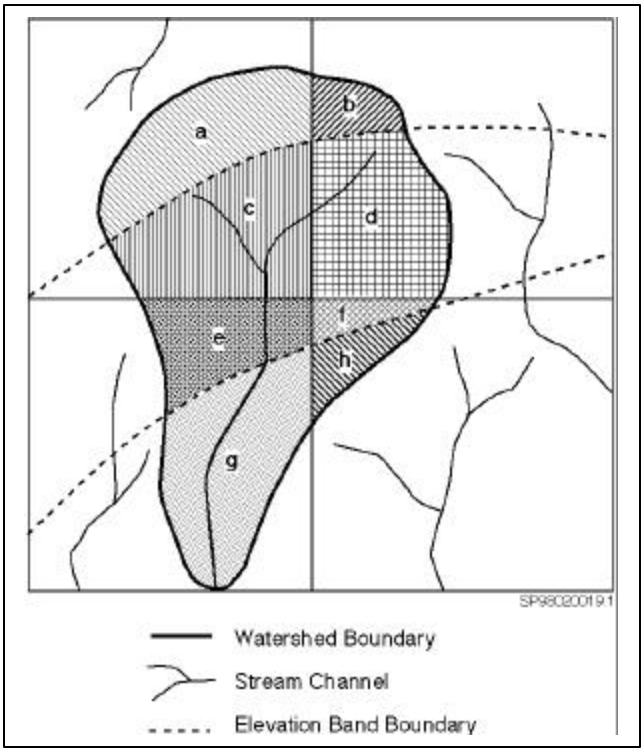

Figure 7. Relationship between climate model grid cells (rectangles), subgrid elevation and vegetation classes (Labeled a-h), and the natural watershed/channel system (a single watershed is highlighted for clarity). In the proposed routing scheme, the DEM is used to map runoff (per unit area) from elevation and vegetation classes to appropriate channels in a one-dimensional model of the river network.

Sensitivity Experiments

- For the GCIP LSA-E region, several simulations will be performed for winter-spring to study the cold season precipitation and land surface processes. The winters of 1997-98 and 1998-99 are good candidate years because they represent rather different conditions of the warm and cold phase of the ENSO event.

- Over East Asia, simulations will be performed for several summers including that of 1998 which coincides with the HUBEX Intensive Observing Period. Precipitation will be an important focus for analysis because during the Meiyu, organized precipitation is often found at multiple spatial scales that could be related to heterogeneity in the land surface conditions.

- All simulations will be driven by the observed large scale circulation such as the NCEP/NCAR reanalyses. They will be performed at first at explicit spatial resolutions of about 30 km, 60 km, and 90 km without the subgrid parameterization. Different components of the subgrid land surface parameterization will be added, one at a time, and simulations will be repeated. Detailed budget analyses will be performed to determine the effects of subgrid scale land surface heterogeneity on land-atmosphere interactions.

4. SUMMARY

- A research project has been proposed to determine the roles of multi-scale land surface heterogeneity in land-atmosphere interactions. The proposal focuses on three aspects of this problem – subgrid representation of land surface heterogeneity, subgrid representation of precipitation, and land-atmosphere interaction.

- In-situ and remote sensing data from the GCIP LSA-E and GAME HUBEX experiments will be used for numerical modeling and analysis of data.

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