6.4 EXPLORATION OF SUBGRID ROUTING RESPONSES IN NOAH ROUTER

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ABSTRACT

Grid-based overland flow and saturated subsurface routing schemes have recently been implemented into an offline gridded version of the Noah surface-vegetation-atmosphere transfer (SVAT) model. Overland flow routing is performed via a two-dimensional diffusive wave for overland flow. Saturated subsurface routing is performed via a finite-difference application of the Dupuit-Forchheimer assumptions. One primary motivation for this work was to evaluate the effect of infiltration excess redistribution on land surface fluxes and associated soil moisture heterogeneity. The model is tested using the rich dataset from the Coupled-Atmosphere-Surface-Exchange-Study (CASES). Benefits of this dataset include the availability of high-resolution (4 km) distributed rainfall estimates from polarimetric radar as well as continuous local measurements of soil temperature, streamflow and land surface fluxes. Comparisons of surface energy components and soil moisture with and without the routing routine are made. Results indicate that at over the CASES domain (central Kansas, USA) there is a large redistribution of surface moisture into the top soil layers. Differences in domain integrated soil moisture values decrease with depth. Latent and sensible heat fluxes also show differences though the differences are comparatively small. Scale effects on surface runoff generation are explored using a subgrid aggregation/disaggregation scheme. Ongoing work includes the coupling of the new 'Noah-router' land surface model to the Weather Research and Forecasting (WRF) model.

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1. INTRODUCTION

The Noah land surface model has recently undergone several enhancements in its representation of hydrological processes (See Fig. 1). Key improvements include, methodologies to allow for: 1) the introduction of ponded surface water and associated evaporation and re-infiltration, 2) lateral routing of overland flow, and 3) the lateral routing of saturated subsurface flow.

1.1 Identification of the Problem

Land surface models, such as Noah, run at traditional atmospheric modeling grid scales (> 10 sq. km) typically assume that lateral transfers of surface and subsurface moisture are negligible in local soil water budgets. One factor contributing to this assumption is that terrain slopes at large spatial scales are quite small. At increasingly finer spatial scales terrain slopes between individual grid cells become larger and therefore possess more potential energy for moving water laterally. This is particularly true in regions of complex terrain where actual topographic relief is quite large. Therefore, at progressively finer scales, the lateral movement of surface and subsurface water becomes a significant component in local water budgets and therefore must be accounted for in land surface models run at high resolutions (e.g. < 2 km). The current version of the Noah model also does not account for the re-infiltration of ponded water or exfiltration of column saturated soil water. It should also be stressed that the hydrological enhancements are of significant importance to both longer-term (i.e. 'climate') simulations and to Land Data Assimilation Systems as they permit a more complete accounting of slowly varying hydrological variables such as soil moisture and saturated subsurface flow. Essential details on the implementation of these processes are presented below in the development of a hydrologically-enhanced version of the Noah model called 'Noah-router'. Full details of the new changes to the Noah Land Surface model are presented in Gochis and Chen (2003).

1.2 Scope

This extended abstract pertains to gridded implementation of the Noah land surface model at comparatively small grid sizes (i.e. dx ≤ 2km) when contrasted with typical mesoscale atmospheric model grid scales. Also, this abstract is only intended to describe the hydrological enhancements in the development of 'Noah-router'. For detailed discussions on the Noah land surface model please refer to Ek et al. (2003), Mitchell et al. (2002) and Chen and Dudhia (2001).

2. MODEL ENHANCEMENTS

Routing in Noah-router is 'switch-activated' through the declaration of parameter values in the Noah driver. Several new parameters and variable arrays are implemented in Noah-router. The specific changes to the model code are discussed as they pertain to each hydrological enhancement made to the model. [Note: In the current implementation subgrid aggregation/disaggregation is used to represent overland and subsurface flow processes on grid scales much finer than the native Noah land surface model grid. Hence, only the routing is represented within a subgrid framework. However, it would be equally as feasible to use the same subgrid methodology to run the entire Noah land surface model and routing schemes at finer resolutions than those at which forcing data, either from analyses or numerical models, is provided.]

2.1 Changes to SUBROUTINE SFLX

Two new variables are inserted into the 1-dimensional land surface model subroutine (SFLX): infiltration excess (INFXS) and surface head (SFHEAD), both have units of mm. INFXS is assigned to 0.0 at the beginning of each model time step and SFHEAD is set equal to the amount of ponded water on the land surface. Prior to calling subroutine SFLX these variables are converted from 2-dimensional arrays (SFCHEAD, INFXS1) to a scalar values (SFHEAD, INFXS) for the 1-d calculations in SFLX as are many of the Noah variables. The operations performed on SFHEAD and INFXS in SFLX are sequentially detailed below.

2.2 Direct Evaporation of Ponded Water

Ponded water, represented by SFHEAD, is only active when overland routing is switched on. (This feature imposes an implicit scaling assumption, in which it is assumed that at large grid sizes, where lateral processes are not significant in local water balances, the aerial extent of water ponded on the land surface is likely to be small.) The scalar value, SFHEAD, is used in the calculation of direct evaporation (EDIR) and ponded water evaporation (ETPND) in subroutine DEVAP. Previously in Noah, direct evaporation was calculated solely as the amount of water evaporated from a bare soil surface.

2.3 Ponded Water Re-Infiltration:

Soil water infiltration is calculated in subroutine SRT within the Noah land surface model subroutine SFLX. [Note: Infiltration is calculated after direct evaporation on each model time-step] In the original Noah model, surface runoff (RUNOFF1) is generated when the effective precipitation (PCPDRP) exceeds the calculated maximum infiltration capacity (INFMAX) of the underlying soil column. RUNOFF1 calculated on each model time-step is accumulated and removed from the model hydrological budget. In Noah-router, prior to the calculation of infiltration, SFHEAD is added to PCPDRP. The sum of PCPDRP and SFHEAD is termed surface water (SFCWATR). Surface runoff calculation in Noah-router remains the same as in the original Noah model except that SFCWATR is used instead of PCPDRP. However, instead of accumulating SRFRUN and removing it from the hydrological budget, in Noah-router, SRFRUN calculated on a model time-step is re-assigned as 'infiltration excess' (INFXS) and is passed back to the Noah-router driver from subroutine SRT through SFLX. Hence, at the end of SRT and SFLX, INFXS is passed back to the Noah driver where they are re-assigned to the 2-d model grid.

2.4. Subsurface Routing:

Routing of subsurface water is performed after the 1-d calculations in subroutine SFLX have been executed on the entire simulation grid for each Noah model time-step. Subsurface lateral flow is calculated prior to the routing of overland flow. This is because exfiltration from a supersaturated soil column is added to INFXS from the 1-d Noah model, which, ultimately, updates the value of SFHEAD prior to routing of overland flow. A supersaturated soil column is defined as a soil column that possesses a positive subsurface moisture flux which when added to the existing soil water content is in excess of the total soil water holding capacity of the entire soil column. Figure 2 illustrates the lateral flux and exfiltration processes in Noah-router.

The method used to calculate the lateral flow of saturated soil moisture is that developed and implemented by Wigmosta et al. (1994) and Wigmosta and Lettenmaier (1999) in the Distributed Hydrology Soil Vegetation Model. It calculates a quasi three-dimensional flow, which include the effects of topography, saturated soil depth (in this case layers), and saturated hydraulic conductivity values. Hydraulic gradients are approximated as the slope of the water table between adjacent gridcells in the x- and y-directions. In each cell, the flux of water from one cell to its downgradient neighbor on each time-step is approximated as a steady-state solution. The looping structure through the model grid performs flux calculations separately the x- and y-directions. It should be noted that other routing methods, such as a path of steepest descent, are possible but have not been tested to date in Noah-router.

2.5 Overland Flow Routing

Overland flow in Noah-router is calculated using the methodology originally developed by Julien et al. (1995) and later expanded by Ogden (1997). This method calculates overland flow as a fully-unsteady, explicit, finite-difference, 2-dimensional diffusive wave flowing over the land surface (See: Fig. 3). The diffusive wave equation, while slightly more complicated, is superior to the simpler and more traditionally used kinematic wave equation, because it accounts for backwater effects and allows for flow on adverse slopes (Ogden, 1997). The diffusive wave formulation is, itself, a simplification of the more general St. Venant equations of continuity and momentum (See: Choudhry (1993) for a formal presentation of the dynamic flow equations and common assumptions in their application).

The overland flow formulation developed by Julien et al. (1995) has been used effectively at fine terrain scales ranging from 30-1000 m (Downer et al., 2002). There has not been rigorous testing to date at larger length-scales (> 1 km). This is due to the fact that typical overland flood waves possess length scales much smaller than 1 km. Micro-topography can also influence the behavior of a flood wave. Correspondingly, at larger grid sizes (e.g. > 500 m) there will be poor resolution of the flood wave and the small-scale features that affect it. Also, at coarser resolutions terrain slopes between gridcells are lower due to an effective smoothing of topography as grid size resolution is decreased. Each of these features will degrade the performance of dynamic flood wave models to accurately simulate overland flow processes. Hence, it is generally considered that finer resolutions yield superior results.

2.6 Subgrid Aggregation/Disaggregation

Recent work (e.g. Hahmann and Dickinson et al., 2002, Molders and Ruhaak, 2002) have shown that representing subgrid terrain features can yield marked impacts on area averaged land surface fluxes and states. This is due to the fact that many significant land surface processes are occurring on scales smaller than those represented by conventional global and mesoscale model grid cells. For example, fully explicit overland flow methodologies described in Section 2.5 above are typically restricted to grid sizes less than or equal to approximately 1 km. At larger grid sizes, poor resolution of the overland flow flood wave and the failure to capture realistic terrain slopes and small-scale topographic features results in degraded performance of the routing methodology. This degraded performance presents significant problems when wanting to account for overland flow processes at grid sizes larger than 1 km, which is typical of many current land surface models run either as stand alone models or when coupled to mesoscale or even global scale atmospheric models.

In Noah-router the routing portions of the code have been structured so that it is simple to perform both surface and subsurface routing calculations on gridcells, which differ from the native Noah model gridsizes provided that each Noah gridcell is divided into integer portions for routing. Hence routing calculations can be performed on comparatively high-resolution land surfaces (e.g. a 250 m digital elevation model) while the native land surface model can be run at much larger (e.g. 1 km) grid sizes. (Hence, the integer multiple of disaggregation in this example would be equal to 4) This procedure adds considerable flexibility in the implementation of Noah-router. However, it should be noted that it is well recognized that surface hydrological responses exhibit strongly scale-dependent behavior such that simulations at different scales, run with the same model forcing may yield quite different results.

The disaggregation/aggregation routines are implemented in Noah-router as two separate loops, which are executed after the main Noah land surface model loop. The disaggregation loop is run prior to routing of saturated subsurface and surface water. The main purpose of the disaggregation loop is to divide up the Noah land surface model grid square into integer portions as specified by AGGFACTR. An example disaggregation (where AGGFACTR=4) is given in Figure 4:

3. MODEL EXPERIMENTS

Original and enhanced Noah simulations were run for the over a portion of the Walnut River watershed (south-central Kansas) for the CASES Intensive Observation Period (IOP), which ran from April 16 to May 23, 1997. Forcing data ware interpolated from available measurements to a 1 km grid (71 x 74 km). Gridded rainfall data (at 4 km) was produced from the NCAR S-Pol radar which was located approx. 70 km west of the modeling site. A time series of precipitation from a four stations (1,4,6,9) within the domain (See Fig. 5) shows that several sizable convective events moved across the basin during the IOP. (see: Yates et al. (2001) for a detailed description of the experimental site and forcing data)

4. RESULTS

Analysis of simulations comparing Noah-router against the original Noah model and between various configurations of Noah-router are currently in progress. Below we provide our preliminary results obtained as of submission of this extended abstract (Nov. 3, 2003).

4.1 Comparsion between Noah-router and the original Noah

Offline, 1 km resolution, simulations comparing Noah-router against the old version of Noah revealed many changes in the modeled soil moisture and evaporative flux fields. The principal findings from these simulations are:

- Accounting for the fate of infiltration excess in the Noah land surface model possesses a significant influence on upper layer soil moisture evolution
- Over the relatively flat CASES-97 domain the primary effect was to allow for subsequent but largely local re-infiltration. This is diagnosable by the fact that while the magnitude of the upper layer moisture content increases in the Noah-router simulations, the spatial pattern of soil moisture content remains very similar
- Direct evaporation increases in Noah-router but remained a small component of the total evaporation, which increased only minimally (where total evaporation = direct evaporation + canopy evaporation + plant transpiration)

Figure 6 shows the change in soil moisture content within the top to layers of Noah-router (0-400 mm). The pattern of soil moisture change corresponds better with total precipitation than to the model terrain indicating that most of the water that was previously determined to be surface runoff re-infiltrates locally. This may not be the case in regions of more complex terrain or where infiltration is severely limited (e.g. shallow or impermeable soils). It is interesting to note that this result is qualitatively different from that obtained by Peters-Lidard et al, 2001 who found that, over a similar topographic region, time-evolved soil moisture fields portrayed increased resemblance to the underlying topography.

4.2 Assessing the impacts of subgird aggregation/disaggregation in Noah-router

Scale dependent behavior in Noah-router was explored using the aggregation/disaggregation methodology presented above in Section 2.6. Using the test data set from CASES-97, Noah-router was run using subgrid-topography for the routing of saturated subsurface and overland flow. Two simulations were executed where the fine-resolution topography (DX) was specified at 500 m and 250 m respectively and the corresponding aggregation factors (AGGFACTR) were 2 and 4, respectively. Routing time steps (DTRT were specified to 15 and 30 seconds.. The results shown in Table 1 below indicate that using progressively finer-resolution topography yields progressively more surface runoff in the form of streamflow volume and overland flow leaving the model domain. Routing on the 500 m and 250 m grids yielded a 27% and 58% increase in streamflow volume, respectively. Corresponding decreases in near-surface (i.e. layers 1 and 2) soil moisture also occurred. This feature highlights a scale-dependent behavior of surface runoff production and overland flow that was also found by Molders and Ruhaak (2002).

5. SUMMARY

The community Noah land surface model has recently been coupled to both an explicit overland flow routing scheme and an analytical subsurface flow routing scheme. An aggregation/disaggregation algorithm has also been implemented into the new model called 'Noah-router' which facilitates the representation of subgrid hydrological processes. Offline simulations have shown that the hydrological enhancements in Noah-router produce changes in both local and domain averaged simulated water budgets over a relatively flat domain in south-central Kansas. Simulations performed at three different scales using the aggregation/disaggregation algorithm yielded significantly different hydrological responses. Specifically, more surface runoff is produced when the model was run at a higher resolution. These results are consistent with those of other workers performing similar tasks on different, integrated modeling systems.

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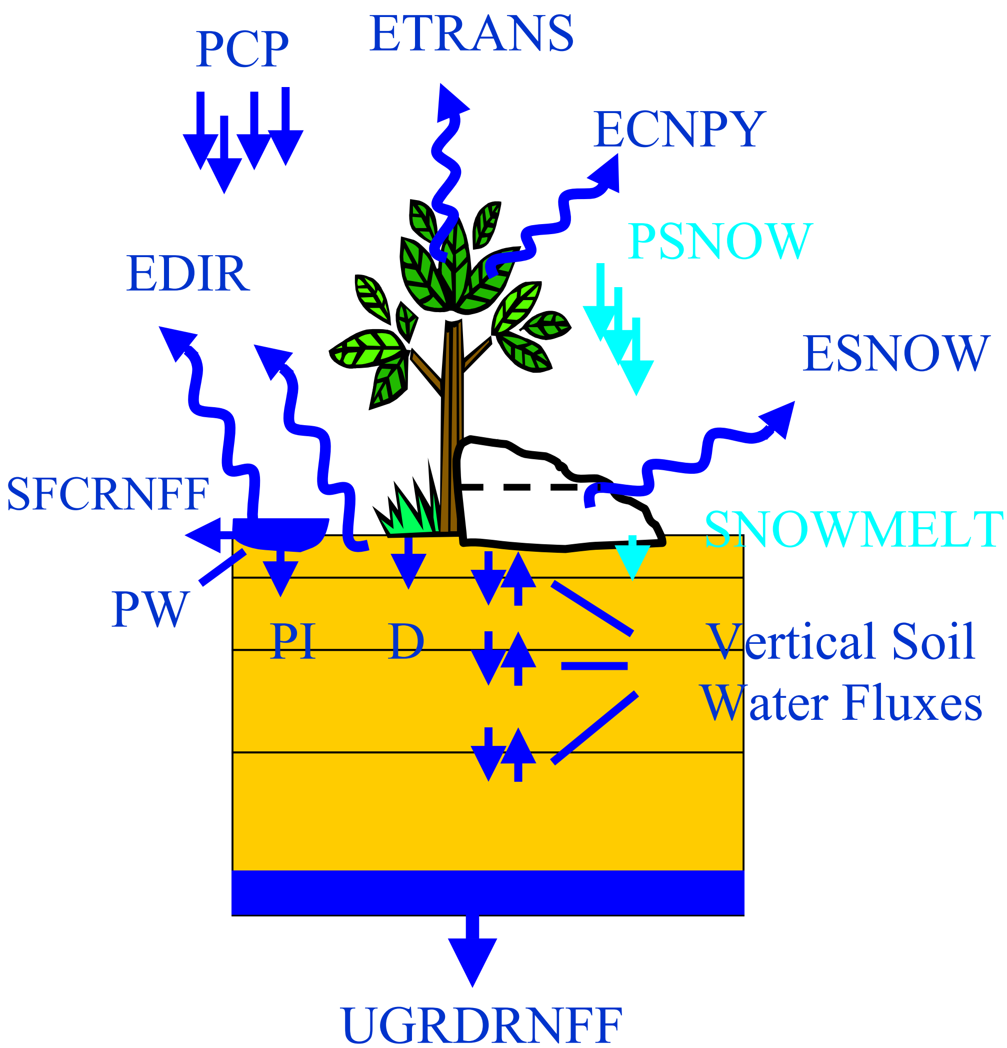
Figure 1: Hydrological Processes in the Noah LSM



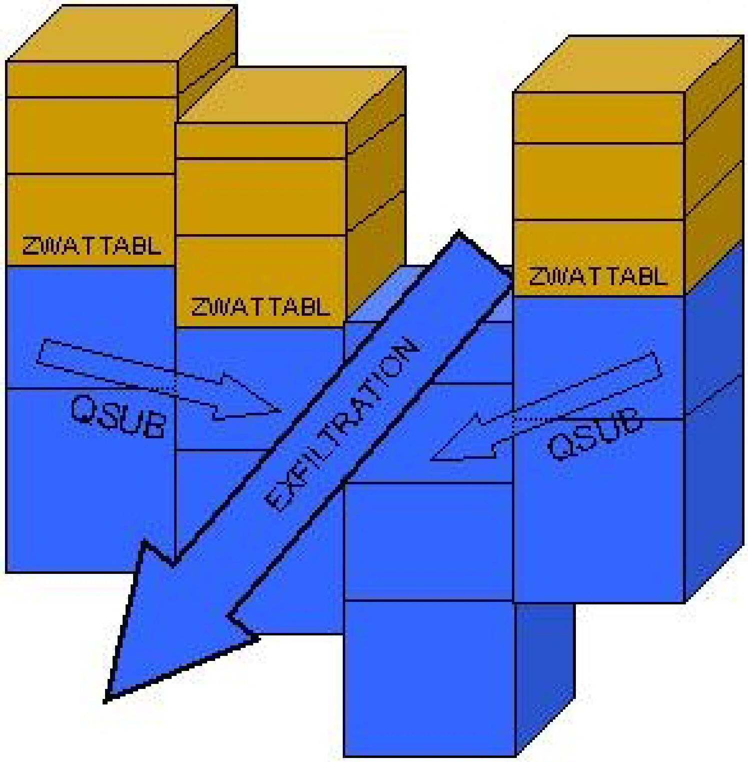


Figure 2: Saturated Subsurface Flow Processes in Noah-router

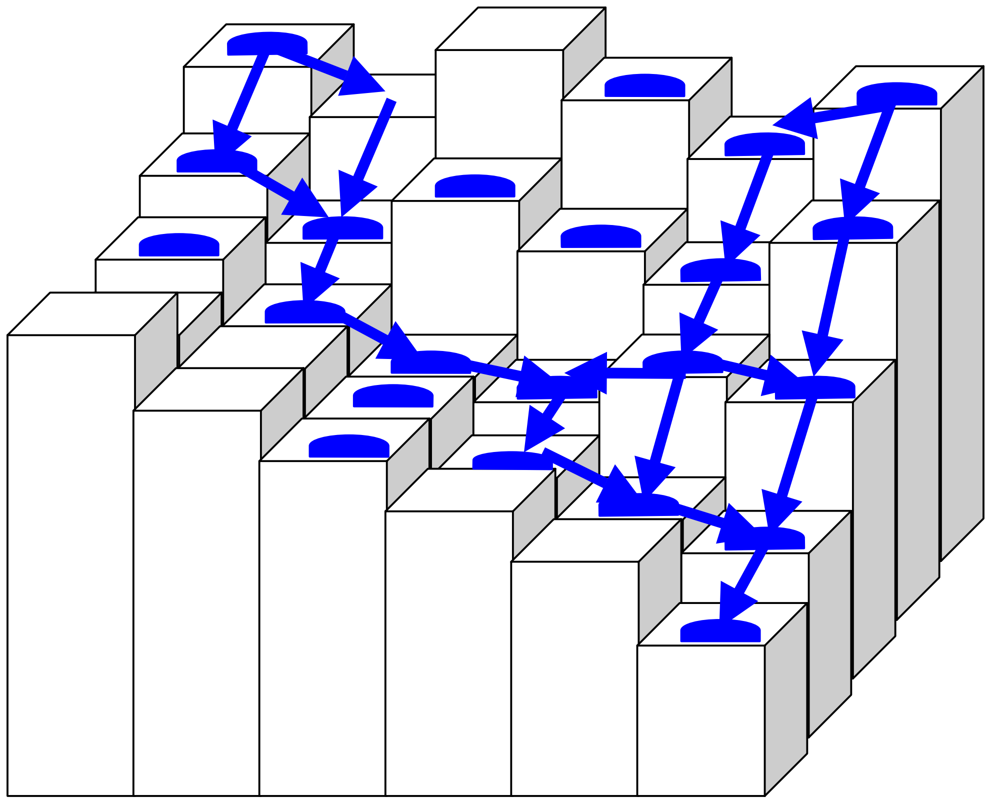


Figure 3: 2-Dimensional Overland Flow Routing
Structure (Adapted from Julien et al., 1995)

Figure 4. Grid Aggregation/Disaggregation

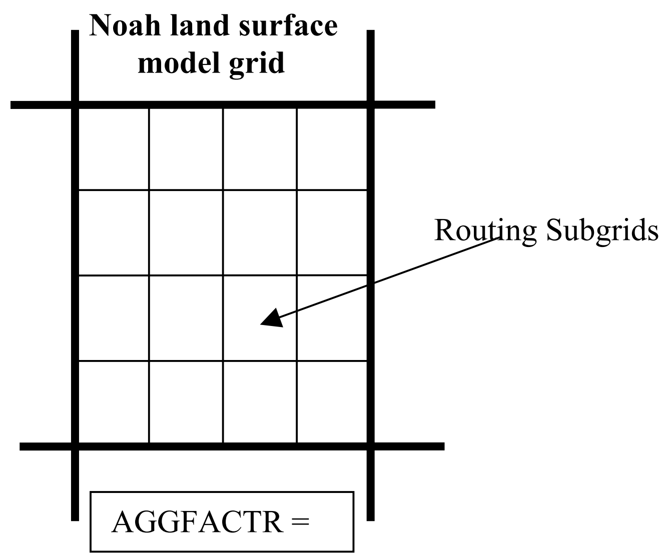


Figure 5. 3-Dimensional Digital Elevation Model and Stream Network from CASES-97
[Note: Terrain elevations range from 313-502 m]

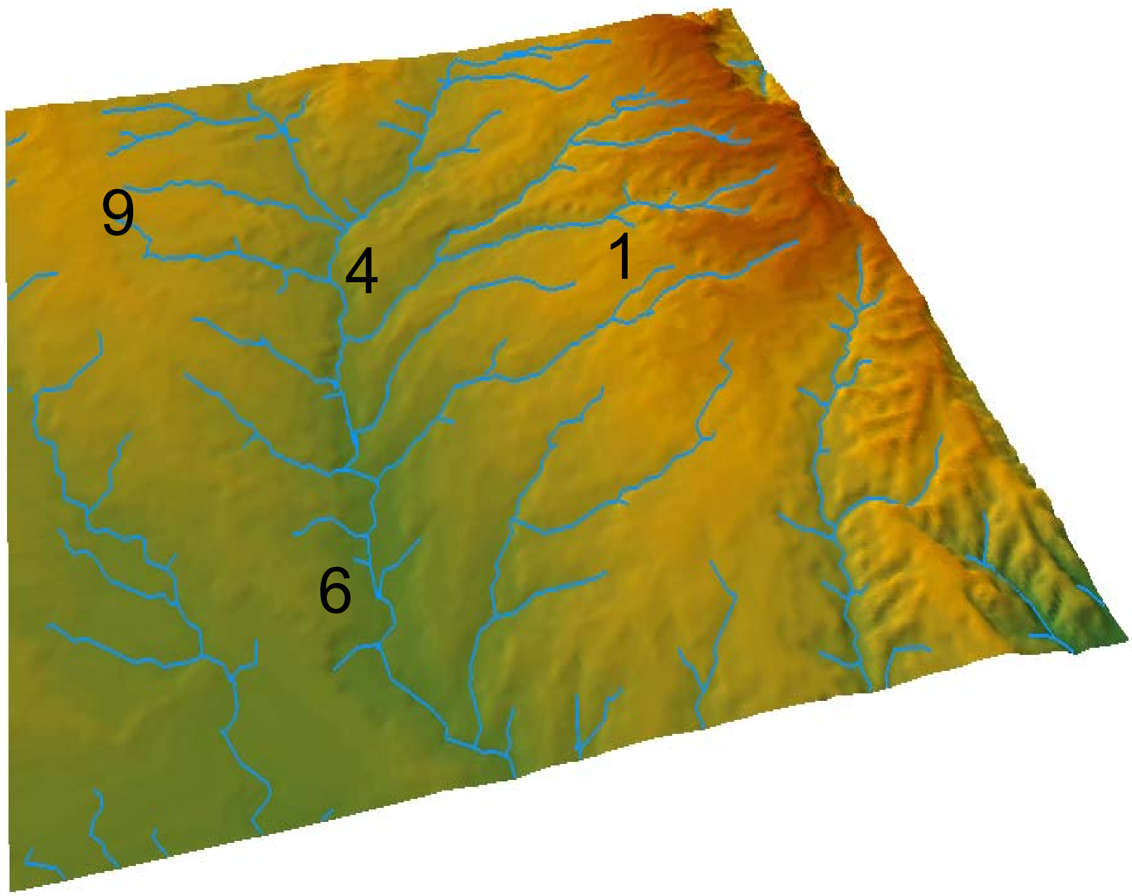


Figure 6 Change in Soil Moisture (mm) in the Top 2 Soil Layers

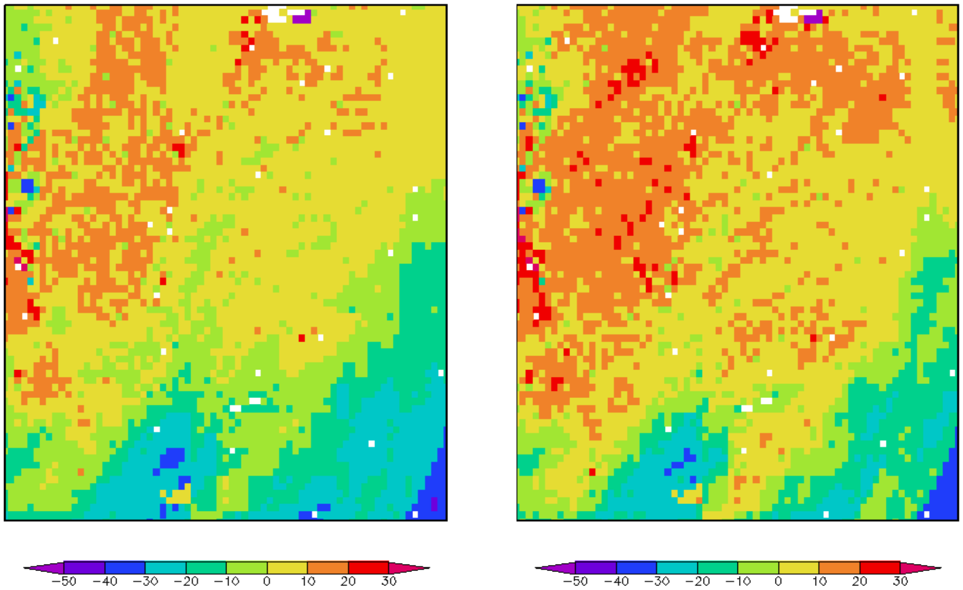


Table 1: Sensitivity of modeled variables to subgrid aggregation

Noah Aggregation Tests Mass Balance			
	Control	% Difference	% Difference
Cum. Terms (mm)	1000m	500m	250m
PRCP	-556151	0.00%	0.00%
DCANOPY WATER	-38.7	0.00%	0.00%
ETA	761169	-0.01%	-0.01%
GRDRUN*	0	n/a	n/a
SRFRUN			
TOTRUN	0	n/a	n/a
DSMC1 (100mm)	-271	-37.02%	-82.25%
DSMC2 (300mm)	-39832	-0.83%	-1.85%
DSMC3 (300mm)	-151787	-0.33%	-0.69%
DSMC4 (300mm)	-6494	-0.29%	-0.59%
DSMC5 (300mm)	-4600	-0.38%	-0.59%
DSMC6 (300mm)	-3136	-0.32%	-0.57%
DSMC7 (300mm)	-2035	-0.16%	-0.68%
DSMC8 (100mm)	-532	-0.11%	-0.56%
TotDSMC	-208687	-0.47%	-1.01%
QSTRMVOL	3787	27.28%	58.12%
QBDRY	149	-2.60%	-3.18%
SUBQBDRY			
SFCHEAD			
Total Residual	228		