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Improvements to the Terrestrial Hydrologic Scheme in a Soil-Vegetation-Atmosphere Transfer Model

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Abstract

Climate models, both global and regional, have increased in sophistication and are being run at increasingly higher resolutions. The Land Surface Models (LSMs) coupled to these climate models have evolved from simple bucket models to sophisticated Soil-Vegetation-Atmosphere Transfer (SVAT) schemes needed to support complex linkages and processes. However, some underpinnings of terrestrial hydrologic parameterizations so crucial in the predictions of surface water and energy fluxes cause model errors that often manifest as non-linear drifts in the dynamic response of land surface processes. This requires the improved parameterizations of key processes for the terrestrial hydrologic scheme to improve the model predictability in surface water and energy fluxes.

The Common Land Model (CLM), one of state-of-the-art LSMs, is the land component of the Community Climate System Model (CCSM). However, CLM also has energy and water biases resulting from deficiencies in some parameterizations related to hydrological processes. This research presents the implementation of a selected set of parameterizations and their effects on the runoff prediction. The modifications consist of new parameterizations for soil hydraulic conductivity, water table depth, frozen soil, soil water availability, and topographically controlled baseflow. The results from a set of offline simulations are compared with observed data to assess the performance of the new model. It is expected that the advanced terrestrial hydrologic scheme coupled to the current CLM can improve model predictability for better prediction of runoff that has a large impact on the surface water and energy balance crucial to climate variability and change studies.

Key words: Land Surface Model, Soil-Vegetation-Atmosphere Transfer Model, Runoff, Soil-moisture

1. Introduction

The Land Surface Models (LSMs) coupled to these climate models have also evolved from simple bucket models to sophisticated assimilation schemes utilizing high resolution satellite data. As the resolution increases, the LSM component needs to incorporate more sophisticated

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linkages and process interactions that require the improved parameterizations of key land surface processes, especially for terrestrial hydrologic schemes. Runoff is one of the important components for the terrestrial hydrologic cycle. It plays a significant role in the soil moisture dynamics and evapotranspiration, which has a large impact on the surface energy balance as well. Although land surface parameterizations in Common Land Model (CLM), a state-of-the-art LSM, has been developed with a detailed representation of the hydrologic cycle, the prediction of runoff in CLM has been problematic due to crude parameterizations for the existing terrestrial hydrologic scheme. In this study, the modifications of CLM consist of new parameterizations for soil hydraulic conductivity, water table depth, frozen soil, soil water availability, and topographically controlled baseflow.

The performance of the improved terrestrial hydrologic scheme in predicting runoff is evaluated at a small spatial and temporal scale for a study catchment around the Ohio Valley. The predicted runoff results from both the new developed scheme and the baseline runoff scheme in CLM are compared with the weekly runoff observations. Both models are run in the off-line mode using the consistent North American Regional Reanalysis (NARR) meteorological forcing dataset and realistic surface boundary conditions (Liang et al., 2005).

2. Basin-scale application

2.1 Study basin

To evaluate the performance of terrestrial hydrologic schemes in CLM at a basin scale, I have chosen a study domain in which the observed stream flow discharges are available from the United States Geological Survey (USGS) National Water Information System. A USGS gauge station, namely Kentucky River at Lock 4 at Frankfort, KY (Sta. 03287500) is located near the drainage outlet of the study basin. The drainage area of the Kentucky River basin (13,706 km^2) is modeled by fifteen grid-meshes with a 30-km cell size, which is a part of the computational domain for the U.S. regional climate simulations (Liang et al. 2004).

2.2 Meteorological forcing data

The NARR data are used in this study for the forcing data from the atmosphere to drive the models. The NARR data is a long term set of consistent climate data on a regional scale for the North America domain. The NARR data values at the first simulation time step (January 1, 1995 00:00) are used to initially drive the models.

3. Descriptions and Modifications

3.1 Bedrock profile

The one of key properties in hydrologic modeling is the bedrock profile, which is generally neglected or roughly assumed to be the lowest model layer in most LSMs. The bedrock acts as a bottom lid that effectively prevents downward water flux and affects the sub-surface moisture dynamics. Although water may rarely penetrate the fresh bedrocks, the moisture flux can occur through fractures, fissures, and cracks in the rocks. However, it is neither easy to model the fracture flow mechanism through bedrocks, nor sufficient to use the bedrock information and property data for it. Therefore, a drainage parameter D_f is used to estimate drainage through bedrocks. The saturated hydraulic conductivity of bedrocks is 1% of that at the lowest soil layer right above the bedrock layer.

3.2 Water table depth

The water table depth has considerable influence on both surface and subsurface runoff generation and the partitioning of the two, crucial to terrestrial water and energy balances. One of recent methods for the water table depth calculation is available in equilibrium with the soil moisture in the soil column. Although this method was intended to produce a smooth change of the water table depth with time in the discretized soil model layers, it may generate an unrealistic shallower water table depth for the dynamic case with the soil moisture flux. Therefore, the groundwater recharge and discharge processes are utilized to solve the dynamic water table depth. The recharge rate Q_r is computed by Darcy's law, and then the temporal change of the water in the soil column below the water table is given as

$$\frac{dW_s}{dt} = Q_r - R_{sb} \quad (1)$$

where W_s is the total soil water below the water table, R_{sb} is the groundwater discharge.

The water table at the next time level will be present in the jth layer where the summation of the pore space of layers from the bottom is greater than the total soil water W_s, and the water table depth is then updated as

$$Z_\nabla = Z_{j-1} + \frac{\sum_{k=j}^{nl} 10^3 \Delta Z_k \theta_s(k) - W_s}{10^3 \theta_s(j)} \quad (2)$$

3.3 Soil hydraulic conductivity

The hydraulic conductivity K and matric potential ψ are expressed as a function of soil wetness w. Brooks and Corey(1964) suggested their relations as $K(w) = K_s w^{2b+3}$ and $\psi(w) = \psi_s w^{-b}$, where K_s and ψ_s are the compacted hydraulic conductivity and the suction head at saturation, respectively. The exponent b is the pore size distribution index. The baseline runoff scheme in CLM uses the constant soil hydraulic conductivity for each soil layer, while the new scheme uses the assumption of exponential decay of the saturated hydraulic conductivity with depth proposed from Beven and Kirby (1979):

$$K_{s_z} = K_s e^{-f(z-Z_c)} \qquad (3)$$

where K_{s_z} is the vertical saturated hydraulic conductivity, Z_c is the compacted depth representing macroporoes effect near the soil surface, assumed to be the plant root depth of 1 m (Stieglitz et al. 1997; Chen and Kumar 2001). f is the decay factor of K_{s_z}.

3.4 Surface runoff

The total available water supply rate Q_w on the surface is computed as

$$Q_w = Q_{rain} + Q_{dew} + Q_{melt} \qquad (4)$$

where Q_{rain}, Q_{dew}, and Q_{melt} are rainfall, dewfall, and snowmelt rate at the surface. Surface runoff is generated by both Hortonian and Dunnian mechanism:

$$R_s = \underbrace{(1-F_{imp})\max[0, Q_w - I_{\max}]}_{Hortonian} + \underbrace{F_{imp}Q_w}_{Dunnian} \qquad (5)$$

where $I_{\max}$ is the maximum rate of the potential infiltration, and F_{imp} is the impermeable area fraction consisting of the fractional saturated area and frozen area.

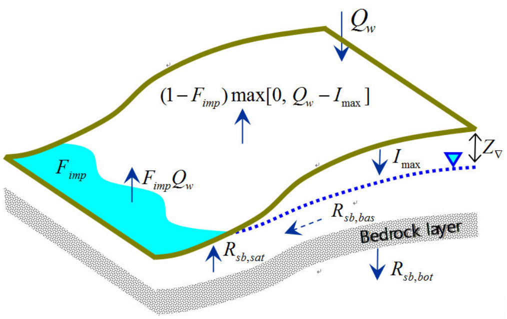
3.5 Subsurface Runoff

The current CLM takes bottom drainage and saturation excess runoff into account for subsurface runoff. In the recent studies, subsurface lateral flow controlled by topography is explicitly incorporated in the subsurface runoff scheme.

$$R_{sb} = R_{sb,lat} + R_{sb,dra} + R_{sb,sat} \qquad (6)$$

where $R_{sb,lat}$, $R_{sb,dra}$, and $R_{sb,sat}$ denote subsurface lateral, drainage, and saturation excess runoff, respectively, as shown in Fig 1.

Figure 2 shows the comparison of weekly time series of specific discharges simulated from the baseline runoff formulation and modified runoff scheme in CLM along with the USGS observations.



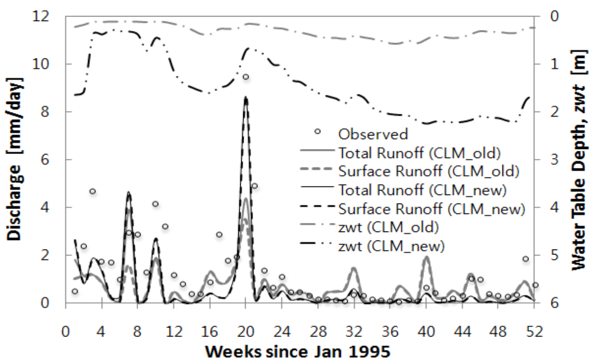


Fig 1. Schematic diagram for surface and subsurface runoff components in CLM

Fig 2. Comparison of simulation results from the baseline and modified schemes in CLM

4. Conclusion

Owing to the model deficiencies resulting from unrealistic assumptions and crude parameterizations in LSMs, several land surface processes have limited predictability. Often these model deficiencies affect estimates of other variables related to fluxes such as surface runoff and surface energy.

The implementation of a selected set of parameterizations affecting on the simulated hydrograph consists of bedrock drainage flux, dynamic water table depth changes, exponential profile of saturated hydraulic conductivity, moisture flux stability in frozen soil, soil water availability preventing supersaturation, and topographically controlled baseflow. These modified parameterizations associated with the terrestrial hydrologic scheme in CLM have the runoff predictions matched with the observations more closely rather than in the baseline runoff model. The crude parameterization can cause significant model errors and consequential unrealistic model parameters for calibration. The new CLM coupled to the improved terrestrial hydrologic scheme can provide a full suite of modeling capability to characterize surface water and energy fluxes for regional, continental, and global hydrologic studies.

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