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# A catchment-based land surface model for GCMs and the framework for its evaluation

A. Ducharne[1,2], R. D. Koster[2], M. J. Suarez[3], and P. Kumar[4]

[1]Universities Space Research Association
[2]Laboratory for Hydrospheric Processes, Hydrological Sciences Branch, NASA/GSFC, Greenbelt, MD 20771, USA
[3]Laboratory for Atmospheres, Climate and Radiation Branch, NASA/GSFC, Greenbelt, MD 20771, USA
[4]Department of Civil Engineering, Univ. of Illinois, Illinois 61801, USA

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**Offset requests to:**
A. Ducharne
USRA
Laboratory for Hydrospheric Processes, Hydrological Sciences Branch
NASA/GSFC, Code 974
Greenbelt, MD 20771, USA

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## Statement of Significance

*QUESTION:* Most land surface models (LSMs) currently used with general circulation models (GCMs) do not include adequate treatments of the lateral redistribution of subsurface moisture. This severely limits their production of realistic surface fluxes. How can this fundamental deficiency be addressed?

*APPROACH:* Our paper summarizes a new strategy for modeling land surface processes. The hydrological catchment is defined as the basic land surface element, and within each catchment, the spatial heterogeneity of soil moisture is diagnosed from bulk moisture variables and the catchment's topography. This spatial heterogeneity is an important control of evaporation and surface runoff. The paper alse describes the numerical framework to test the validity of this approach.

*SIGNIFICANCE AND IMPLICATIONS OF FINDINGS:* The explicit consideration of subgrid-scale soil moisture heterogeneity and its effects on the surface energy and water budgets should lead to an improved simulation of land surface processes. This should in turn lead to more reliable simulations of climate and its sensitivity.

## RELATIONSHIP TO MTPE SCIENCE PLAN

The improved simulation of land surface processes should benefit numerical climate studies. The strategy described in the paper thus has direct relevance to MTPE emphases on (1) seasonal-to-interannual climate prediction, (2) changes in long term climate, and (3) landcover and land use change.

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[1]Universities Space Research Association
[2]Laboratory for Hydrospheric Processes, Hydrological Sciences Branch, NASA/GSFC, Greenbelt, MD 20771, USA
[3]Laboratory for Atmospheres, Climate and Radiation Branch, NASA/GSFC, Greenbelt, MD 20771, USA
[4]Department of Civil Engineering, Univ. of Illinois, Illinois 61801, USA

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**Abstract.** A new GCM-scale land surface modeling strategy that explicitly accounts for subgrid soil moisture variability and its effects on evaporation and runoff is now being explored. In a break from traditional modeling strategies, the continental surface is disaggregated into a mosaic of hydrological catchments, with boundaries that are not dictated by a regular grid but by topography. Within each catchment, the variability of soil moisture is deduced from TOPMODEL equations with a special treatment of the unsaturated zone. This paper gives an overview of this new approach and presents the general framework for its off-line evaluation over North-America.

## 1 Introduction

The realistic representation of land surface processes is critical for the realistic simulation of the global hydrologic cycle and climate, as indicated by numerous sensitivity studies using general circulation models (GCMs) (e.g. Garratt, 1993; Mintz, 1984). Land surface models (LSMs) have therefore increased in sophistication and realism over the last decade. An important effort has focused on the modeling of evaporation, which controls both the surface energy and water budgets. In doing so, the vertical dimension of evaporation processes was largely emphasized, with detailed treatments, for instance of canopy structure and environmental stresses on surface conductances.

The Mosaic model (Koster and Suarez, 1992) is representative of the type of LSM that emphasizes evaporation processes. It includes a canopy interception reservoir and a 3-layer soil reservoir. Interception loss, bare soil evaporation and transpiration occur in parallel and are controlled by resistances that increase with environmental stresses, according to SiB formulations (Sellers et al., 1986). A distinct feature of the Mosaic model is its treatment of subgrid scale heterogeneity in surface characteristics, which motivated its name. The grid cells are subdivided into homogeneous sub-regions (the "tiles" of the mosaic), each containing a single vegetation or bare soil type. A separate energy balance is calculated for each tile, and each tile maintains its own prognostic soil moisture and temperatures. But the Mosaic model, like most of the state-of-the-art LSMs, features overly crude parameterizations of runoff and baseflow processes relative to the sophistication of evapotranspiration, albedo, and other energy balance formulations (Koster and Milly, 1997). In particular, the critical effects of horizontal soil moisture variability are rarely accounted for in current LSMs, and soil moisture is assumed to be uniform at the GCM scale. This is overwhelmingly unrealistic given the actual spatial scales of soil moisture variability, which are largely imposed by topography and precipitation heterogeneity.

Most of the few attempts to describe soil moisture variability at the GCM scale made use of statistical distributions, either of precipitation rate or of soil properties (e.g. Ducharne et al., 1998; Entekhabi and Eagleson, 1989). Following recent advances in catchment models for the large scale (Famiglietti and Wood, 1994; Stieglitz et al., 1997), we are examining a new approach to the modeling of land-surface processes in GCMs. This approach recognizes the hydrological catchment as the fundamental land-surface unit, and calls for the disaggregation of the land-surface into a mosaic of hydrological catchments, with boundaries that are not dictated by a regular atmospheric grid but by topography. The second step of the new approach consists in the use within each catchment of a model that relates soil moisture variability to topography. A first incarnation of this catchment model is briefly outlined in section 2 and the construction of the catchment coverage is outlined in section 3. Section 4 describes the framework for the validation of the new approach, which is discussed in section 5.

## 2 Description of the catchment model

It is widely recognized that a major control on soil moisture heterogeneity is topography (e.g. Beven and Kirkby, 1979;

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*Correspondence to:* A. Ducharne

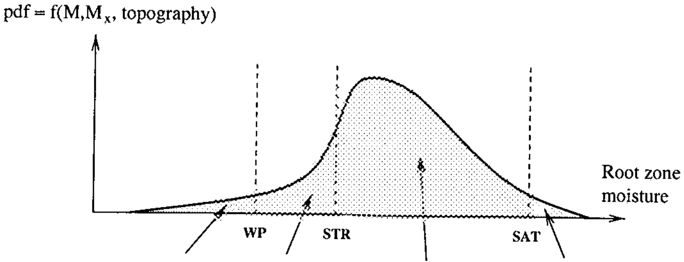
Western and Grayson, 1998; Yeh and Eltahir, 1998). Regions of local concavity tend to be zones of convergent flow, with a shallow water table and a high soil moisture content. Those regions are therefore characterized by high runoff (overland and baseflow) and by evaporation rates close to potential. In comparison, upland soils tend to be progressively drier, with a small contribution to saturation excess runoff (or Dunne runoff), and evapotranspiration rates significantly less than potential because of water stress.

Beven and Kirkby (1979) developed the simple physically-based TOPMODEL to describe the effect of topography on runoff generation and catchment hydrology. This model has two fundamental assumptions. The first one is that the water table shape is related to topography, and the second one states that at any point in the catchment, the water table depth results from quasi-steady state conditions. TOPMODEL can then produce the spatial distribution of the water table depth across the catchment, given the mean water table depth, the topography of the catchment and the vertical distribution of soil hydraulic conductivity. The latter is usually assumed to decrease exponentially with depth, following Beven (1984), but recent developments on TOPMODEL allow to use different transmissivity profiles (Ambroise et al., 1996; Duan and Miller, 1997).

Although TOPMODEL was first proposed for small to medium sized catchments in humid areas, it has been since adapted to a broader range of scales and hydro-climatic conditions (e.g. Sivapalan et al., 1987). The catchment model examined in this paper is based on some ideas from Famiglietti and Wood (1991, 1994) to extend TOPMODEL concepts to the macroscale.

Our modeling strategy will be described in detail in an upcoming publication. Briefly, we characterize the moisture state in the catchment with two bulk moisture variables. The first variable is the "catchment deficit", which is defined as the average amount of water, per $m^2$, that must be added to the catchment's soil to bring the entire catchment to saturation. The calculation of this deficit is based on the distribution of water table depths derived from the TOPMODEL equations and on an assumption of equilibrium soil moisture profiles in the unsaturated zone. The second bulk variable, termed the "root zone excess", represents the average amount of water, per $m^2$, by which the root zone moisture is different from the value implied by the equilibrium profiles. This second variable is important for two reasons: (1) it allows the root zone moisture to respond quickly to storm events and evaporation, and (2) it essentially makes the catchment model equivalent to a more traditional LSM with vertical soil layers in regions of little topography, where TOPMODEL is known to be invalid. Transfers between the root zone excess and the equilibrium state proceed according to timescales that vary with the magnitudes of the variables.

The bulk moisture variables are combined with characteristics of the topography to derive a distribution of root zone soil moisture, which in turn is used to separate the catchment into hydrologic regimes. This is illustrated in Figure 1. As shown in the figure, the transpiration, bare soil evaporation, infiltration, and baseflow calculations are different for the different regimes. We thus treat explicitly the effects of subgrid soil moisture variability on the surface energy and water balances.



| Integrate | A1 | A2 | A3 | A4 |
|---|---|---|---|---|
| Transpiration | No | Stressed | Unstressed | Unstressed |
| BSE | Low | Low | Medium | High |
| Infiltration | Yes | Yes | Yes | No |
| Baseflow | Yes | Yes | Yes | Yes |

**Fig. 1.** Fractioning of the catchment into four hydrological regimes. WP designates the wilting point, STR a vegetation-dependent threshold between stressed and unstressed transpiration; SAT designates saturation, BSE bare soil evaporation, M the catchment deficit and $M_x$ the root zone excess and pdf stands for probability density function.

## 3 Construction of the catchement coverage

The US Geological Survey has developed a global digital elevation model (DEM) at 30-arc-second resolution (approximately 1 kilometer). This DEM was treated over North-America with a geographical information system to compute local slopes, and drainage directions were then extracted according to a "steepest descent" algorithm (Jenson and Domingue, 1988). This allowed the construction of the North-American drainage network. Catchments have been delineated according to ordering rules based on network topology and drainage areas (Verdin and Jenson, 1996). The ordering rules are associated with a catchment coding system (Pfafstetter, 1989). One of the appeals of this system arises from the simple way to assess upstream-downstream relationships between the catchments from their code alone.

This procedure resulted in a coverage of 5020 catchments over North-America, with an average catchment size of 3,640 $km^2$. Figure 2 displays a fraction of that coverage in the South-western part of North America, with overlain 1° × 1° and 4° × 5° grids, the latter being representative of GCM grids. The figure shows the mismatch between the catchment coverage and the grids, as well as the difference in resolution. Most of the 1° × 1° grid cells hold several catchments, and the 4° × 5° grid hold many of them. Using the catchments as the fundamental hydrological units therefore allows us to account for a first level of GCM subgrid scale variability.

Topography in TOPOMODEL, and in the new model, is described in terms of a topographic index, the distribution of which can be idealized by a three-parameter gamma distribution (Sivapalan et al., 1987). The three parameters are

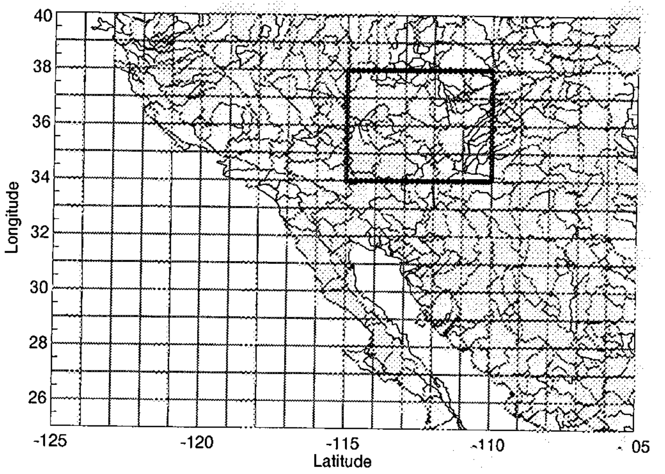


**Fig. 2.** Comparison of the catchment coverage with 1° × 1° and 4° × 5° grids.

a function of the first three moments (mean, variance and skew), minimum and maximum of the actual distribution of topographic indices in the catchment.

The computed slopes and drainage areas have been used to compute the topographic index at every GTOPO30 gridpoint in North-America. These values are used to determine the distribution of the topographic index in every catchment and the statistics of those distributions (mean, variance, skew, minimum and maximum) are currently being converted for each catchment into topography-related parameters used by the catchment model.

## 4 Validation strategy

### 4.1 Off-line Method

The accuracy of a LSM can only be determined through a detailed comparison of its products with observations. However, the validation of a LSM coupled to an atmospheric model can be very difficult if the forcing by the atmospheric model is in error. For instance, simulated precipitation rates are notoriously inaccurate, and these errors may dominate the behavior of the LSM. This explains the widespread use of "off-line" simulations, for which the atmospheric forcing is derived from observations, in validation studies (e.g. Dirmeyer and Dolman, 1998; Henderson-Sellers et al., 1996; Shao et al., 1994).

The ISLSCP Initiative I data set for 1987-88 (Sellers et al., 1996) contains all of the atmospheric and boundary conditions data sets needed to drive a LSM off-line at the 1° × 1° resolution across the globe. Global fields of precipitation, incoming long-wave and short-wave radiation at the surface, and near-surface temperature, humidity, pressure and wind speed, have various observational sources. They are processed with a data assimilation system in order to extrapolate them spatially across the globe and to interpolate them to the 6-hour timescale. The ISLSCP Initiative I data set also provides with data sets of vegetation characteristics at the 1° × 1° resolution, as derived from satellite observations. The data include vegetation type as well as monthly varying fields of leaf area index, roughness length and snow-free albedo.

The general framework for the off-line integration of the new model with the ISLSCP Initiative I data set for 1987-88 is based on the recommendations for the Global Soil Wetness Project (Dirmeyer and Dolman, 1998). In particular, to avoid non-equilibrated spin-up signal, the forcing corresponding to 1987 is repeated until every modeled catchment has converged to an equilibrium state. All the needed forcing fields have been interpolated from the 1° × 1° grid to the catchment space. The difficulty was to determine the intersection between the catchments (defined as polygons) and the grid cells, in order to compute the forcing in one catchment as the weighted average of the forcing from all overlying grid-cells. This has been achieved with a triangulation algorithm, which can also be used to transform data from the catchment space to the grid space. Those transformations in the two directions are of critical importance given our eventual goal of coupling of the new model with a GCM.

### 4.2 Validation of annual runoff rates

The off-line framework limits the number of available variables for validation, since many of commonly measured variables are prescribed. Three potential variables for validation are runoff, evaporation, and soil moisture. Runoff is a choice variable for validation purposes because it can be easily estimated from river discharge measurements, which have been collected for many decades in many areas. Also, river discharge naturally integrates runoff across large distances, which makes its measurement more valuable at the large scale than point measurements of evaporation or soil moisture.

#### 4.2.1 Runoff observations

The original observations consist of annual discharge at a collection of stations scattered across the globe. These data were processed in the manner described by Koster et al. (1998). The suitability for validation purposes of a river basin (defined as the direct contributing area for one station if two or more stations lie on the same river network) is assessed according to two criteria: (1) discharge was accurately measured during 1987-88, and (2) at least 30 rain-gauges per $10^6$ km$^2$ were present is the basin at that period. The latter criterion is necessary because the accuracy of simulated runoff is conditioned by the accuracy of the prescribed precipitation. Those criteria lead to the selection of 14 river basins in North-America. Figure 3 shows their location derived from the catchment coverage (as explained in the next paragraph). For instance, the biggest basin is part of the Missisipi river basin, and three sub-basins are found along both Saint-Lawrence River.

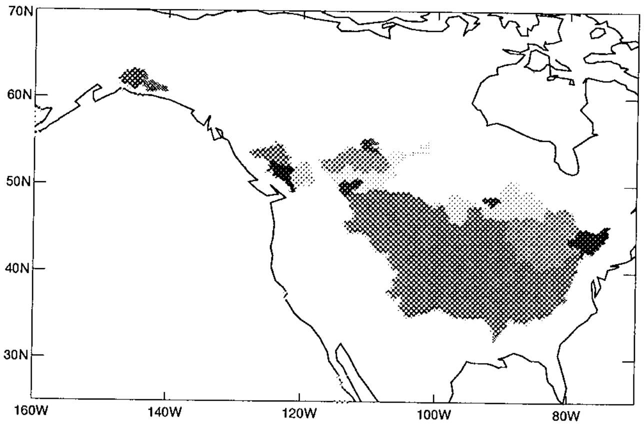


**Fig. 3.** Location of the selected 14 river basins as derived from the catchment coverage.

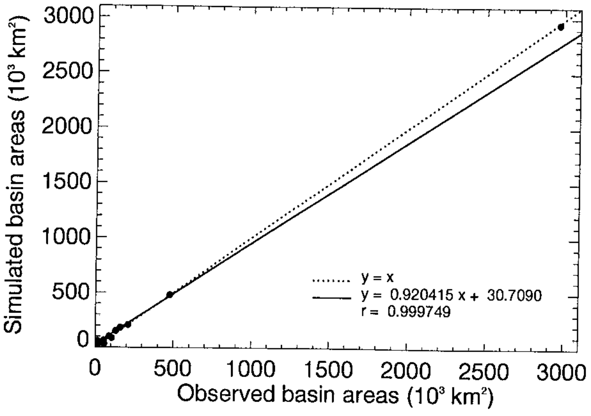


**Fig. 4.** Comparison of the area of the 14 selected river basins from observation and from the DEM. The solid line comes from linear regression, and r is the correlation coefficient.

### 4.2.2 Aggregation of simulated runoff

The catchment ordering scheme mentioned in section 3 describes the upstream-downstream relationships between the catchments. It therefore allows us to identify the catchments that contribute to the discharge measured at the 14 selected stations. As mentioned before, Figure 3 shows the resulting location of the 14 selected river basins. The area of each unit catchment being known, it is straightforward to compute the area of each basin, as well as the weighted average of runoff within those basins. Figure 4 plots these area estimates against the corresponding areas from observation. The strong correlation between observed and estimated areas is an evidence of the accuracy of the drainage network extraction from the DEM.

### 4.2.3 An objective criteria for validation

An important limitation of off-line validation is the lack of feed-back between land-surface and the atmospheric forcing. This is the price we pay to eliminate atmospheric modeling errors when validating LSMs, and it can result in an overwhelming influence of the prescribed atmospheric forcing on the simulated land surface fluxes. For instance, even the poorest LSM can produce realistically low evaporation rates if forced with realistically low precipitation rates. A critical problem in off-line validation is thus to quantify the relative control of prescribed atmospheric forcing on the simulated energy and water balances, to assess which part of the LSM response is really due to its own structure.

In order to validate the new LSM in such a objective way, we will apply the simple criteria proposed by Koster et al. (1998). It is based on an equation proposed by Budyko (1974) that relates annual evaporation to annual precipitation and net radiation, without any consideration of the surface physics. In an off-line framework, annual runoff can be approximated by the difference between annual precipitation and annual evaporation, under the assumption that the inter-annual variations of soil moisture are negligible in comparison with the fluxes themselves. The equation then provides with an annual runoff estimate that can be seen as a "yardstick of success": if the formulations of a LSM contribute to the realism of the fluxes, then the LSM's runoff estimates should be better than the estimate from Budyko's equation. This estimate has been computed for the 14 selected basins, using annual precipitation and radiation data interpolated in the catchment space (section 4.1). The runoff simulated with the new LSM will have to be significantly closer to the observed runoff than to that estimate, for the new approach to be validated at the annual timescale.

The above validation strategy favors the annual timescale, but seasonal and diurnal cycles have to be realistically simulated by LSMs for realism in the GCMs short-term dynamics. In many ways, land-surface physics is more important at short timescales (e.g. Chen et al., 1997; Koster et al., 1998). The runoff data presented in section 4.2.1 are available as monthly means, and we plan then to use those data to evaluate the behavior of the new LSM at the seasonal timescale. Care will be taken to minimize problems related to the time lag induced by river routing and regulation.

## 5 Summary and discussion

Many studies have shown the importance of small scale variability of hydrological processes in the average interactions between the land surface and the atmosphere. This importance limits the ability of point-process models to represent large scale hydrological processes realistically. These considerations motivated the development of our new catchment-based land surface model for use in GCMs.

This new model calls for the disaggregation of the land surface into a mosaic of hydrological catchment, determined through the analysis of a high resolution DEM. Within each catchment, a new LSM based on TOPMODEL accounts for topographically-driven soil moisture variability and its effects on evaporation and runoff. The model introduces the root zone excess prognostic variable to ensure that the limitations of TOPMODEL in regions of little to moderate topography are minimized.

Validation is a critical element of model development, and the second part of the paper was devoted to the description of the off-line validation framework for our new modeling approach. The very preliminary results using that framework do not yet show a significant improvement in annual runoff predictions when going from the Mosaic model to the new LSM. One must however keep in mind that this new model is still under development; not all of the model's intended features have yet been included. We plan for instance to devise a sensible scheme for allowing surface runoff to occur from the unsaturated areas of the catchment, and we will include some representations of bedrock to limit the attainable depth of the water table. Both of these features should in particular increase runoff, which is currently biased low. The main point we want to stress is that the new catchment strategy avoids the inherent problems associated with the one-dimensional representation of subsurface soil moisture. Because of this, we expect the model, once fully developed, to produce a more realistic simulation of land surface processes than is achievable with more traditional approaches.

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