A New Approach
to the Treatment of Sub-grid Scale Heterogeneity in Land Surface Models

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Presented below is a brief overview of a new strategy for modeling land surface processes in a general circulation model (GCM). A comprehensive description of the strategy is included in a paper recently submitted to the *Journal of Geophysical Research* [Koster et al., submitted].

Motivation for a New Approach

Koster and Milly [1997] examined how the evaporation and runoff formulations in a land surface model (LSM) interact with each other in a simulation of the annual energy and water cycle. Their analysis shows that a proper runoff formulation is about as important as a proper evaporation formulation for an accurate simulation of annual evaporation rates. If the formulation of runoff is poor, an LSM will produce unrealistic annual evaporation rates regardless of the quality of the evaporation formulation.

The SVAT (soil-vegetation-atmosphere transfer) modeling approach encourages a significant amount of complexity in the formulation of evaporation relative to that of runoff. Perhaps the greatest weakness in the representation of runoff processes in modern LSMs is the neglect of subgrid variability in soil moisture. In most (though not all) LSMs, the soil is represented as a series of vertically-stacked horizontal layers. The transfer of moisture between layers, which has a fundamental effect on computed baseflow and overland flow, is computed with a one-dimensional vertical transport equation that effectively assumes uniform soil moisture contents in the horizontal. Of course, soil moisture contents vary considerably in space due to variations in topography, soil texture, vegetation, and precipitation forcing, and these variations can be tremendously large and complex across the spatial scales considered in GCM applications. These variations, coupled with the strong nonlinearities involved in soil moisture transport, render a one-dimensional representation ineffective.

A Nontraditional Strategy

The above discussion points to a potentially fruitful LSM development path. Our current approach to LSM development emphasizes subsurface soil moisture processes and their dependence on the spatial heterogeneity of soil moisture. Much of our approach is culled from related studies, including those of Famiglietti and Wood [1991], Beven and Kirkby [1979], Sivapalan et al. [1987], Stieglitz et al. [1997], and Liang et al. [1994].

A key innovation in our approach involves the shape of the fundamental land surface element — we define it to be the hydrological catchment, with boundaries defined by topography. For example, for our model development exercises, North America has been partitioned into roughly 5000 irregularly-shaped catchments with an average size of 3640 square kilometers. The mismatch between the regular atmospheric grid and the irregular catchment grid makes necessary an algorithm that disaggregates the atmospheric forcing to the catchment scale and aggregates the catchment "products" (i.e., the surface turbulent, radiative, and momentum fluxes) to the GCM grid scale. Approaches for the realistic disaggregation of grid cell forcing are available in the literature [e.g., Gao and Sorooshian, 1994; Leung and Ghan, 1995] and could be incorporated into the overall approach.

The separation of the continental surface into catchment elements allows for an explicit treatment of subgrid-scale heterogeneity at the land surface — the average size of a catchment is much smaller than, say, a typical GCM grid cell. Our strategy goes much further in this regard, though, because soil moisture is assumed to vary significantly within each catchment element. Within each catchment, we use pre-existing, well-tested models of catchment processes (e.g., TOPMODEL of Beven and Kirkby [1979]) to diagnose soil moisture distributions from the morphology of the catchment and our bulk soil moisture prognostic variables.

The strategy employs at least two nontraditional prognostic variables. The first, termed the "catchment deficit", is defined as the average amount of water, per unit area, that must be added to the catchment's soil to bring the entire catchment to saturation, assuming equilibrium conditions in the unsaturated zone and a water table distribution determined, say, by TOPMODEL. The second, termed the "root zone excess", accounts for the fact that equilibrium conditions in the unsaturated zone are generally not the rule. Soil moisture near the surface (e.g., in the root zone) responds quickly both to the infiltration of precipitation water and to the extraction of water via transpiration and bare soil evaporation. The root zone excess is defined as the average amount of water, per unit area, by which conditions in the root zone across the catchment are out of equilibrium. Moisture transfer between the root zone excess and the catchment deficit is determined with empirical functions that were fit to the results of complex distributed calculations.

The catchment deficit and root zone excess can be combined to compute, diagnostically, the distribution of soil moisture in the root zone, which in turn allows the separation of the catchment into different moisture regimes. We can derive, for example, (i) the fraction of the catchment over which the ground surface is completely saturated (e.g., along riverbeds), (ii) the fraction of the catchment over which the ground surface is not saturated but transpiration nevertheless proceeds, and (iii) the fraction of the catchment over which the soil is too dry to allow transpiration. This separation is, in fact, the catchment strategy's most important advantage. The physical processes controlling runoff and evaporation are very different in these different hydrological regimes (e.g., evaporation from the soil surface is especially large in the saturated fraction). Thus, the explicit partitioning of the catchment into the different areas and the application of different parameterizations in each area should lead to more credible estimates of evaporation and (especially) runoff across the catchment.

In the limiting case of perfectly flat terrain, the LSM described above reduces to a traditional two-layer LSM. The use of the root zone excess variable allows the catchment LSM to function at least as well as traditional LSMs in flatter areas, despite TOPMODEL's limitations there.

Concluding Remarks

The approach described above has a few additional advantages. First, the partitioning of the continental surface into a mosaic of catchment "tiles" allows a straightforward calculation of streamflow from large river basins; all that is needed is an indexing system that points to the catchments lying within the basin of interest. This is important, of course, for model validation and for the coupling of LSM runoff products to an ocean model. Another possible advantage involves the elevation-based disaggregation of the grid-scale atmospheric forcing provided by the GCM.

Also, the use of the catchment as the fundamental land surface element allows a more direct link to basic hydrological science, for which the catchment is a natural unit of study. Our model development can take advantage of watershed studies that span several decades.

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