Operational Modeling of Soil Moisture at Local and Regional Scales

Christa Peters-Lidard, Yihua Wu, Mike Tischler, Peggy O'Neill

Abstract

Soil moisture is one of the basic links between the water and energy cycles of land surfaces through its regulation of infiltration, runoff, transpiration and thermal capacity. In this study, an operational modeling system of soil moisture at hillslope (local) to watershed (regional) scales has been developed using the community Noah land-surface model (LSM). This system simulates profiles of soil moisture (both liquid and frozen) and soil temperature, skin temperature, snowpack depth, snowpack water equivalent (and hence snowpack density), canopy water content, and surface water and energy fluxes, including runoff, infiltration, and evapotranspiration. The system was tested using soil moisture data from the Monsoon '90 experiment, carried out at the Walnut Gulch Experimental Watershed (WGEW), near Tombstone, Arizona. The results show that the system has the potential for operational soil moisture modeling.

Keywords: soil moisture, land-surface model, Monsoon '90, soil-vegetation-atmosphere transfer

Introduction

Routine, or operational, estimates of hillslope-to-watershed scale soil moisture have potential applications in regional resource management, including flood and water resource forecasting, irrigation scheduling and determining mobility with lightweight vehicles. Hillslope scales may be defined as 10 to 100 m and watershed scales range from 1,000 to 25,000 km^2. Watershed management applications generally require daily soil moisture information to depths ranging from the sub-surface (15 cm) to the entire root zone (>1 m), while remote sensing-based products provide only surface soil moisture at depths ranging from 1-5 cm over bi-weekly to monthly intervals. Therefore, we are developing a combined approach using Soil Vegetation Atmosphere Transfer (SVAT) models and remotely sensed observations to provide routine daily estimates of profile soil moisture.

SVAT models have generally been developed for weather and climate modeling applications, and typically include solution of a form of the Richards' equation, including representation of parameters and processes controlling the evolution of soil moisture such as infiltration, evapotranspiration, percolation and drainage (see also Moran et al., in review). In this work, we apply a publicly available SVAT model known as the community Noah LSM (Chen et al. 1996), which has been validated at the point and watershed scale with respect to its water and energy balance predictions. In the following sections, we describe the application of the model to the Monsoon '90 field program conducted in WGEW, and assess the suitability of the SVAT model for operationally predicting hillslope-to-watershed scale soil moisture.

Monsoon '90

In the summer of 1990, the Monsoon'90 large-scale interdisciplinary field experiment was conducted in the 148 km^2 WGEW (Figure 1). During Monsoon'90, daily gravimetric soil moisture data were collected at eight micrometeorological-energy flux (Metflux) sites, in addition to standard

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meteorological variables and surface fluxes. In addition, an airborne L-band Push Broom Microwave Radiometer (PBMR) mounted on a National Aeronautics and Space Administration (NASA) C-130 aircraft was flown at an altitude of 600m above the ground to yield soil moisture products derived from measured microwave brightness temperature Tb (Schmugge et al. 1994). Tb data were collected over an approximately 8 x 20 km area with a 40 m horizontal resolution for six days: 212 (Jul. 31), 214 (Aug. 2), 216 (Aug. 4), 217 (Aug. 5), 220 (Aug. 8), and 221 (Aug. 9), as shown in Figure 2.

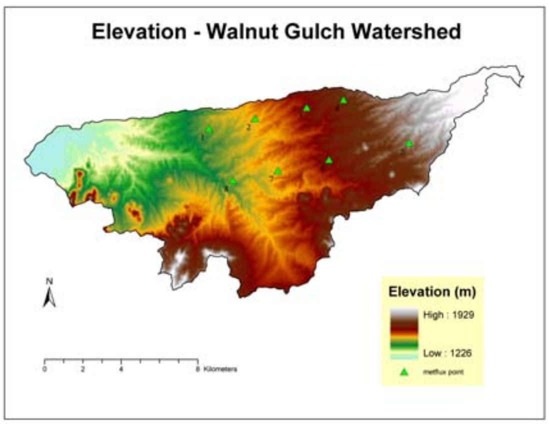

Figure 1. Walnut Gulch Experimental Watershed, showing location of 8 Metflux sites (Kustas and Goodrich, 1994).

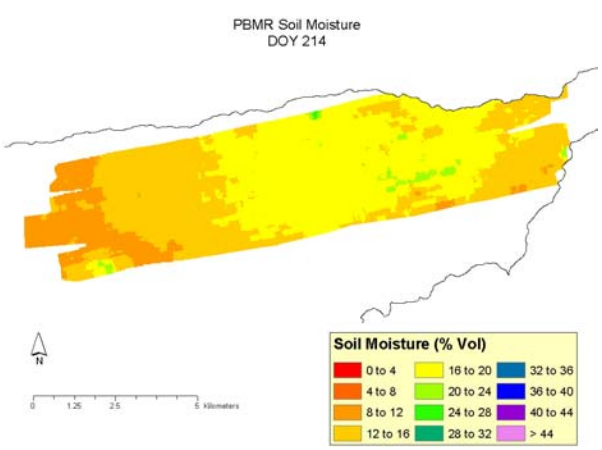

Figure 2. PBMR soil moisture product over WGEW for DOY 214 (Aug. 2) 1990.

We have assessed the overall error of the PBMR product versus the gravimetric observations collected to a depth of 5 cm, and found the expected compound error to be 4.5% ± 1.9%. Figure 3 illustrates the ability of the PBMR data to capture the hillslope-scale 5-cm soil moisture over time during Monsoon '90, as measured by gravimetric methods and converted to volumetric units. As the figure shows, the PBMR data is able to capture the dynamic range of the soil moisture observations.

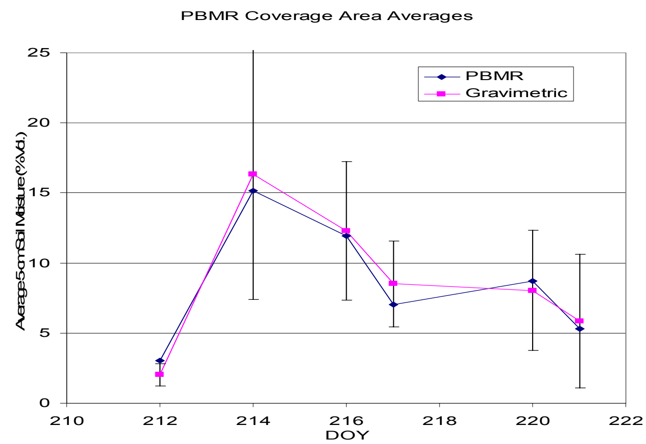

Figure 3. Time series of 5-cm soil moisture measured at the 8 Metflux sites by PBMR and gravimetric sampling. Error bars indicate the standard deviations of gravimetric observations, based on 3 samples per metflux site, or 24 samples total.

Modeling Approach

The publicly available community Noah LSM (Chen et al. 1996), is applied to the WGEW for Monsoon '90 by configuring the model to execute over a 660 by 333 grid domain with a horizontal resolution of 40m. There are four vertical soil layers, with thicknesses of 5, 25 60 and 75 cm. To provide time for "spin-up", simulations commenced at 0000 GMT, DOY 204 and ended at 2300 GMT, DOY 227. Initial soil moisture and temperature at the four depths are interpolated from observations at the eight Metflux sites. Input parameters and near-surface atmospheric forcing data are required as described below.

Forcing data

The NOAH LSM requires input forcing data that includes precipitation, solar radiation, long wave radiation, temperature, relative humidity, wind speed and surface pressure. The dynamic meteorological forcing data were obtained from Houser (1996), who applied a state-of-the-science interpolation algorithm to precipitation data collected at 88 rain gauges deployed over the watershed. All other meteorological forcings were assumed to be spatially constant, given that they were available only at some of the Metflux sites.

Parameters

Soil texture and land cover data are required to specify hydraulic, thermal and radiative parameters required by the LSM. Soil texture data sets considered for operational use include, from finest to coarsest resolution, Soil Survey Geographic (SSURGO), Soil Dataset, State Soil Geographic (STATSGO) Soil Dataset, and Soil texture from Food and Agricultural Organization of United Nations (FAO). Interestingly, there is only one soil type in the Walnut Gulch watershed in both STATSGO and FAO soil classifications: loamy sand for STATSGO and Sandy loam for FAO. All soil texture data were mapped to the texture classes of Cosby et al. (1984), as shown in Figure 4 for SSURGO data, since Noah uses their lookup tables to determine soil hydraulic parameters. In addition to the soil texture data sets, Saturated Hydraulic Conductivity and Porosity were derived directly from the SSURGO data as an optional input to the LSM.

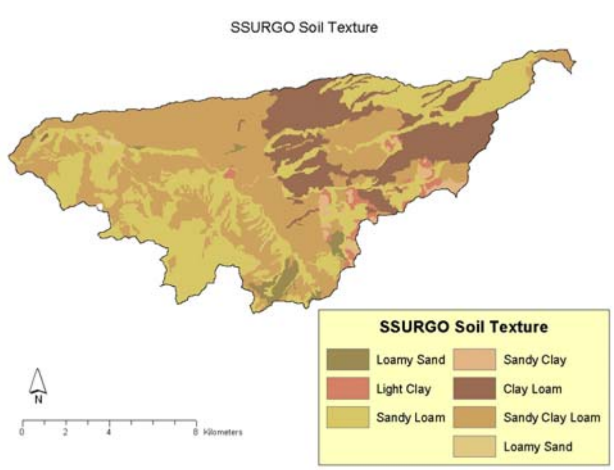

Figure 4. SSURGO soil texture data reclassified according to Cosby et al., 1984.

Three land cover data sets were also considered for use in operational soil moisture modeling. They include the 1992 NALC land cover data set (NALC92), the Environmental Protection Agency (EPA) and United States Geological Survey (USGS) land cover data set (GIRAS), and Moderate Resolution Imaging Spectroradiometer (MODIS) land cover. Given that the Noah model has adopted parameter lookup tables according to the classification of Dorman and Sellers (1989), these land cover data sets were remapped to their 13 land cover types, as shown in Figure 5 for NALC, in order to utilize the parameter lookup tables within Noah. In addition, LAI, greenness fraction and albedo data were obtained from Houser (1996) as optional inputs to the model.

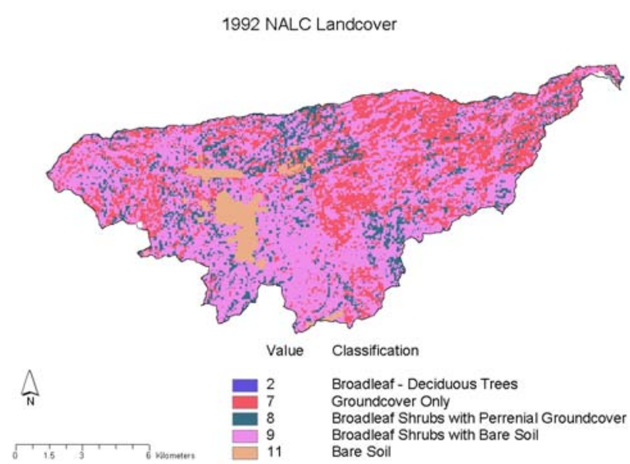

Figure 5. NALC land cover data reclassified according to Dorman and Sellers (1989).

Input degradation experiments

In addition to a control run, in which the highest resolution soil texture and land cover data sets were used along with image inputs of key soils and vegetation parameters, three sets of parameter degradation experiments were conducted. This first set of experiments explores the impact of soil parameter inputs (lookup table vs. images) as well as the impact of coarser resolution soils data on operational soil moisture prediction. The second set of degradation experiments focuses on degrading land cover inputs (tables vs. images) as well as land cover source data sets from finest to coarsest. The third set of experiments explores the impact of degrading precipitation data, by applying averaging windows to the data to simulate rainfall radar inputs as well as watershed average rainfall. The results of these experiments will be compared to that from the control in the next section.

Results

Overall, the results from the control run suggest that the Noah model is skillful in predicting watershed-scale soil moisture, as shown in Table 1. Figures 6 and 7 further illustrate the time series of watershed-scale RMS error and bias, respectively. These results suggest that the model error is close to the observed error, but that there is a persistent high bias in the model. The cause for the high bias has been further explored at the hillslope scale, as discussed below.

Table 1. Results of the control run.

RUN	MODEL	PBMR	RMS	BIAS
SSURGO + Ksat +Porosity Input	0.14	0.09	0.08	0.05

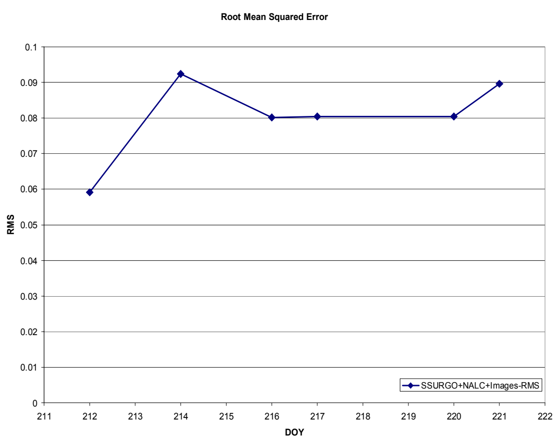

Figure 6. Time series of watershed-scale RMS error for the control run.

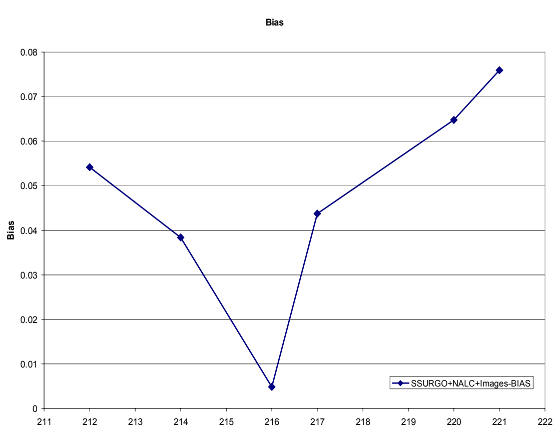

Figure 7. Time series of watershed-scale bias for the control run.

Comparisons between model predictions at the hillslope scale are made by extracting the model and PBMR 40 x 40 m pixels in the vicinity of the gravimetric sampling sites (as shown in Figure 1). This analysis suggests that the model physics is generally consistent with the observed, but that there is a persistent high bias at certain Metflux sites, as shown in Figure 8 for Metflux site 7.

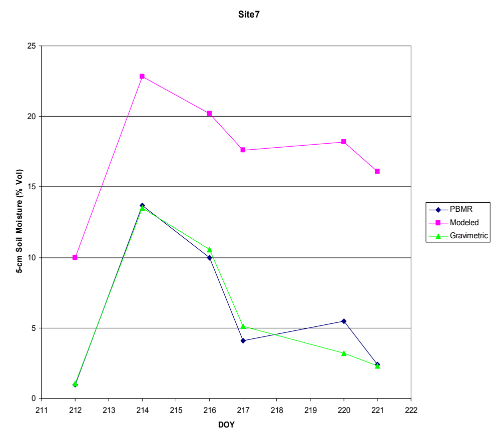

Figure 8. Time series of modeled and measured soil moisture for Metflux site 7 illustrating high bias in the initial conditions for the model.

This bias is likely the result of a poor initial condition, and the fact that the model was initialized only 8 days prior to the experiment. Further analysis suggests that bias is a strong function of soils and land cover parameters (not shown), with sites classified as “bare soil” exhibiting high bias during the wettest period, and sites classified as “loam” or “sandy clay loam” exhibiting the highest bias throughout the period.

Following the assessment of the model at the watershed and hillslope scales, an assessment of the models sensitivity to data sets was conducted in order to determine the level of effort required for operational implementation.

Soils degradation experiments

Soil data sets were degraded from SSURGO to STATSGO to FAO, in addition to replacing the SSURGO-derived images of hydraulic parameters with those using Cosby et al. (1984) lookup tables. The results of these experiments are summarized in Table 2.

Table 2. Results of the soils degradation experiments. First experiment denotes the control run, with the finest available parameter inputs.

RUN	MODEL	PBMR	RMS	BIAS
SSURGO + Ksat +Porosity Input	0.14	0.09	0.08	0.05
SSURGO + Lookup Table	0.18	0.09	0.10	0.10
STATSGO + Lookup Table	0.13	0.09	0.06	0.04
FAO + Lookup Table	0.15	0.09	0.07	0.06

As illustrated by the table, RMS errors are lower for STATSGO and FAO soils than for SSURGO, although this is likely due to the fact that the STATSGO and FAO soil classifications reclassify soils with the highest errors to those with the lowest errors. An important result is that the soil parameter lookup table clearly degrades results, as shown by comparing the control run in line 1 with the lookup table run in line 2. Given the PBMR product errors of approximately 4.5% $\pm$ 1.9%, the differences among SSURGO, STATSGO and FAO may not be statistically significant.

Land cover degradation experiments

Land cover data sets were degraded from NALC, to EPA/USGS to MODIS, in addition to replacing the Houser (1996) images of land cover parameters with those using default Noah lookup tables. The results of these experiments are summarized in Table 3.

Table 3. Results of the land cover degradation experiments. First experiment denotes the control run, with the finest available parameter inputs.

RUN	MODEL	PBMR	RMS	BIAS
NALC+Greenness+Albedo Images	0.14	0.09	0.08	0.05
NALC+Lookup Table	0.13	0.09	0.08	0.04
EPA+Lookup Table	0.18	0.09	0.10	0.09
MODIS+Lookup Table	0.17	0.09	0.09	0.08

As illustrated by the table, the soil moisture bias is slightly lower for lookup tables as compared to the control run image input, although as with the soils degradation experiments, the differences are likely not statistically significant. However, the soil moisture bias is clearly increased with EPA and MODIS land cover, suggesting that the higher resolution NALC land cover is important for operational soil moisture modeling.

Rainfall degradation experiments

Finally, a set of rainfall degradation experiments was conducted to assess the importance of high resolution rainfall input for soil moisture modeling. These experiments consisted of degrading the original interpolated rain gauge data by taking first 10x9 pixel averages, then 30x37 pixel averages, then watershed average rainfall, as illustrated in Figure 9.

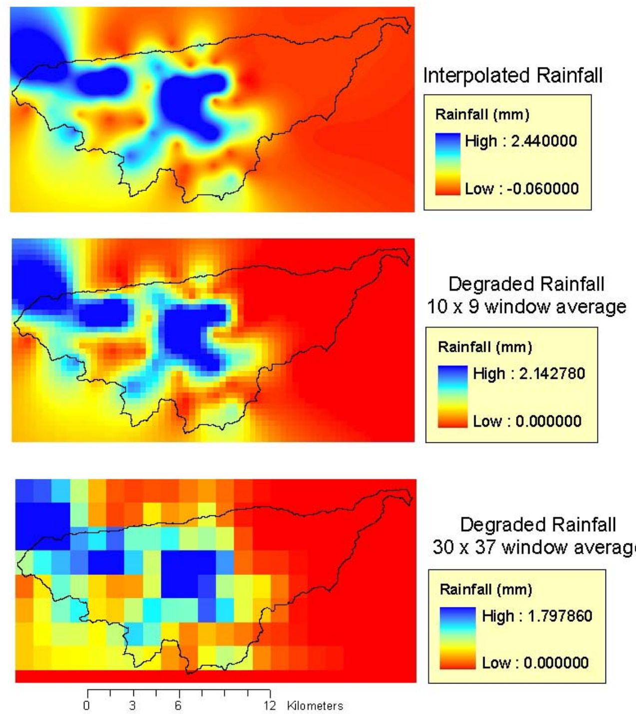

Figure 9. Original and degraded rainfall for DOY 204.

The results of these degradation experiments are summarized in Table 4, which indicates the counterintuitive result that the domain average rainfall produces the best results. This can be explained by noting the consistent wet bias caused by improper spin-up, which is counteracted by the domain average rainfall, as it tends to underestimate local rainfall rates. This leads to an overall reduction in RMS as well, since most of the error in the model is bias.

Table 4. Results of the rainfall degradation experiments. First experiment denotes the control run, with the finest available parameter inputs.

RUN	MODEL	PBMR	RMS	BIAS
Interpolated Gauge Rainfall	0.14	0.09	0.08	0.05
400m Average	0.12	0.09	0.07	0.03
1200m Average	0.12	0.09	0.07	0.03
Domain Average Rainfall	0.08	0.09	0.05	-0.01

Conclusions

In summary, a publicly available LSM has been applied to the problem of operational soil moisture prediction using data sets collected during the Monsoon ’90 field program. The PBMR soil moisture products for Monsoon ’90 were derived from regressions at 8 gravimetric sampling locations, with an expected compound error of 4.5%±1.9%V/V, although locally the error may be in excess of 8%.

The Noah LSM has a positive (wet) bias, which persists throughout the Monsoon ’90 period. Causes of error include a poor initial condition, with high bias caused by inadequate spinup, an underestimation of losses such as evapotranspiration, likely caused by underestimates of greenness and high stomatal resistance parameters. Overall, the model is shown to adequately predict soil moisture at the watershed scale, with errors in predicted soil moisture at about 8%V/V for the “best” input data. The parameter degradation experiments indicate that using lookup tables for soil hydraulic parameters clearly degrades results, and that the results are highly sensitive to rainfall data input. Given that degraded rainfall offsets the high bias in the initial conditions, it is likely that given proper initial conditions, degraded rainfall would result in a dry bias. This suggests that spatially distributed rainfall input is critical to accurate operational soil moisture prediction.

Current and future work with this modeling system is focusing on integrating the LSM with a geographic information systems (GIS) interface in order to facilitate use of the system for applications, including regional resource management, flood and water resource forecasting, irrigation scheduling and determining mobility with lightweight vehicles. As part of this process, we are developing tools to facilitate the substantial data preprocessing activities involved, including interpolation and downscaling of coarse resolution or point-scale data sets to the hillslope scales required for these applications.

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