J1.12 SIMULATION OF FINE-SCALE SOIL MOISTURE VARIATIONS AT THE WALNUT RIVER WATERSHED IN KANSAS

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1. INTRODUCTION

Soil moisture affects the surface energy balance through the partitioning of net radiation. The resulting sensible heat and latent heat fluxes have a strong influence on planetary boundary layer development. The major surface sources of moisture in the atmosphere above land are transpiration by vegetation, direct evaporation of moisture from soil, and evaporation of water ponded on soil and leaf surfaces. Clearly, variations in soil moisture can influence the hydrological cycle in the atmosphere, and inhomogeneities of land surfaces have an important role in mesoscale circulation.

The effects of soil moisture on mesoscale processes have been studied extensively. For example, the impact of surface moisture variability on shallow convective cumulus clouds and precipitation was studied by Chen and Avissar (1994), who used the CSU RAMS model (Colorado State University Regional Atmospheric Modeling System) (Pielke et al. 1992), and the relationship of land surface conditions and cloud amount during the daytime was studied by Wetzel at el. (1996) for both a FIFE (First ISLSCP Field Experiment) case in Kansas and an Oklahoma case. Recently, the OSU (Oregon State University) land surface model (Pan and Mahrt 1987) and another land surface model described by Xiu and Pleim (2001) were coupled with MM5 (the fifth-generation Mesoscale Model) (Grell et al. 1994), released with MM5 version 3 (Chen and Dudhia 2001). These land surface models greatly improve the ability of MM5 to estimate surface temperature and moisture because of their better description of processes involving land surface vegetation. Research is needed to evaluate the behavior of surface parameters, as well as their interactions with physical processes involving the planetary boundary layer, clouds, and precipitation. This paper presents a study of soil moisture for selected periods during the spring of 1997 at the Walnut River Watershed (WRW) in Kansas (Lemone et al. 2000). Work focuses on microscale, fine-resolution simulations using the OSU land surface model coupled with MM5. Modeled soil moisture contents were compared with observations in the WRW for four typical soil wetness conditions.

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2. DESCRIPTION OF SIMULATIONS

The nonhydrostatic model MM5 version 3 (MM5V3) simulates cloud, radiation, boundary layer, and land surface processes. The land surface model combines a soil thermal and hydrological model with a surface energy balance model; it is coupled with a boundary layer model (Hong and Pan, 1996) to estimate water vapor and heat flux, as well as soil moisture content and temperature. Four layers are simulated in soil: surface-10 cm, 10-30 cm, 30-60 cm and 60-100 cm. Hydraulic conductivity, water diffusivity, thermal diffusivity, and stomatal resistance are tied to the soil moisture content in each layer. This modeling scheme was used to simulate fine-scale soil moisture within a rectangular area, 0.8° long. by 1.0° lat., that enclosed the WRW. This area was nested within coarser modeling domains. In the WRW, the surface vegetation consists mostly of grass and agricultural crops, and the soil texture classes are primarily silt loam and silt clay loam. Four time periods in April and May 1997 were selected to simulate several soil wetness levels. April 29 to May 1 was dry, with initial soil moisture volumetric content of 0.28 m^3/m^3; May 10 to May 12 was moderately dry, with initial soil moisture content of 0.31 m^3/m^3; May 20 to May 22 was wet, with initial soil moisture content of 0.38 m^3/m^3, and May 19 was dry early in the day, with initial soil moisture content of 0.24 m^3/m^3, and near saturation later because of heavy precipitation.

MM5 was initialized with ETA data preprocessed by REGRID and INTERP. The ETA data were provided by the National Weather Service and had a spatial resolution of 40 km. The initial data set contains three-dimensional meteorological fields at vertical pressure layers, as well as two-dimensional surface data including soil moisture content. The soil temperature and texture were processed by the model preprocessor TERRAIN, using U.S. Geological Survey terrestrial, soil, and vegetation data.

Four-dimensional data assimilation (FDDA) was applied in the model simulations to achieve dynamic initialization. Analysis nudging forced three-dimensional fields (wind, temperature, and water vapor mixing ratio) toward the analysis results of observed first-guess fields. FDDA effectively corrected errors, such as exceptionally low moisture at some times, in the simulation results.

3. RESULTS AND DISCUSSION

The simulation of soil moisture content can be dominated by the accuracy of soil moisture initial conditions. Other factors, such as soil physical properties, evapotranspiration, radiation, and wind speed also affect the simulated soil moisture content. Precipitation can become as important as soil moisture initial conditions when the precipitation is heavy. Accurate simulation of soil moisture requires input precipitation data that match the model's spatial and temporal resolution. One approach is to supply observed radiation and precipitation data to the land surface model. This method, however, does not allow the feedback of modeled soil moisture into atmospheric processes. Another approach is to use the numerical simulations to study the interactions between the atmosphere and the land surface. MM5V3 was chosen in the current study to fulfill this purpose.

Soil moisture was simulated for three cases with skies observed to be clear and partially clear. The vegetation type and topography 5-min data were processed by TERRAIN at 3-km resolution. Observational data included soil moisture volumetric content in the top 10 cm of the soil at eight observation stations operated by the National Center for Atmospheric Research (NCAR). For the case of May 20-22, soil moisture simulation involved interaction with modeled radiation and clouds. The soil was initially saturated with water on May 20 because of heavy precipitation on May 19. The modeled soil moisture in the top layer (surface-10 cm) matched the observations very well (Fig. 1, days 140-142). Soil water depletion by evaporation tends to be driven by radiation and other atmospheric variables, which were adequately simulated for this case. For the dry period on days 119-121 and the period with intermediate moisture levels on days 130-132, unrealistic clouds and precipitation were produced by the model. The simulations had generated too much moisture in the boundary layer, and excessive heat flux was subsequently generated because of convective

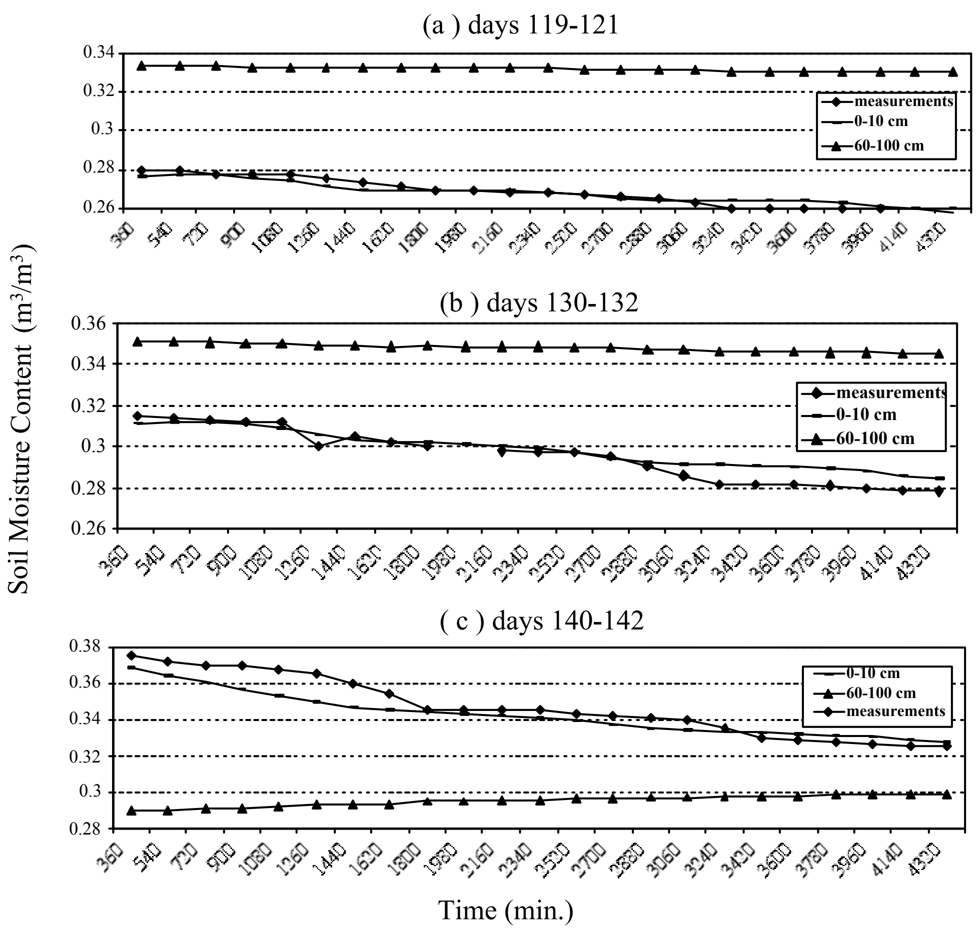


Fig. 1. Modeled domain-averaged soil moisture values for the two layers of soil between 0-10 cm and 60-100 cm, along with a comparison to the average of measurements in the upper layer at eight stations in the Walnut River Watershed during three time periods with mostly cloudless skies.

processes. It became necessary to break the cycle of moisture and heat flux between the atmosphere and the land. To do so, the model was run in the absence of convective and nonconvective clouds. Modeled radiation was corrected on the basis of typical values for clear conditions. The modeled soil moisture in the layer between the surface and 10 cm agreed well with the NCAR observations after these changes were made (Fig. 1, days 119-121 and 130-132).

The initial soil moisture for these three periods in the WRW domain was adjusted by using the average of measurements of soil moisture at the eight NCAR stations. Generally, soil moisture was sensitive to the changes in soil moisture initial condition except when soil was wet; the soil moisture content (0.38 m^3/m^3 for case of May 20-22) was higher than field capacity for silt loam (0.36 m^3/m^3) and was close to the field capacity of clay loam (0.38 m^3/m^3). Uncertainties in soil moisture initial conditions have greater effects for dry and semi-dry conditions.

Simulations of soil moisture during rain were also carried out for May 19. The observed daily precipitation values used here, obtained from the Arkansas-Red Basin River Forecast Center, were based on Nexrad and rain gauge data. The simulation started at 0000 hr GMT. The domain-averaged initial soil moisture (0.22 m^3/m^3) was very close to the averaged measurements (0.23 m^3/m^3). Observations from rain gauges in the WRW indicate that precipitation started in the early morning. Both convective and nonconvective clouds were simulated to generate precipitation. In a preliminary test run, the vegetation type and topography were at 3-km resolution. The simulated soil moisture was substantially smaller than measurements during the rain, suggesting that the spatial distribution and intensity of precipitation were the major source of errors. The deviations became even larger when the simulation started earlier, in part because the less detailed terrain information resulted in a negative feedback in the simulation of precipitation. Results were improved by using the finer grid resolution of 1-km, derived from 2-min data, to describe vegetative and topographical variations. Three simulations were carried out: Run 1 started at 0000 hr GMT on May 19 and continued for one day, Run 2 began on 0000 hr on May 18 proceeded for two days, and Run 3 began on 0000 on May 17 and proceeded for three days. For Run 1, the modeled soil moisture was still much smaller than the observed values during the rain (Fig. 2), probably because simulation time was not sufficient for completion of land-atmosphere-cloud exchange cycles. The simulation time was increased for Run 2 by beginning it 24 hours earlier. The pulse in the observed in the top layer (surface to 10 cm) that occurred near 1200 hr (720 min in Fig. 2) is seen in the modeled values. The modeled soil moisture increased as precipitation progressed. Run 3 began on 0000 hr on 17 May and produced soil moisture estimates that were very similar to those from Run 2. These results show that the heterogeneity of land surface had significant impact on heat and moisture circulation in the WRW. The time scale of the feedback processes was about one day when the model horizontal resolution was reduced to 1 km.

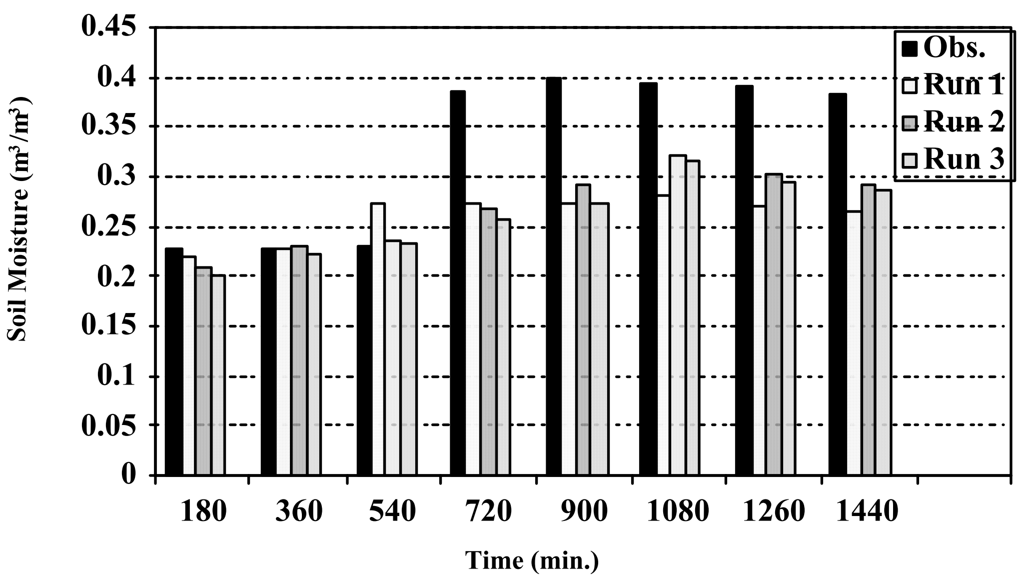
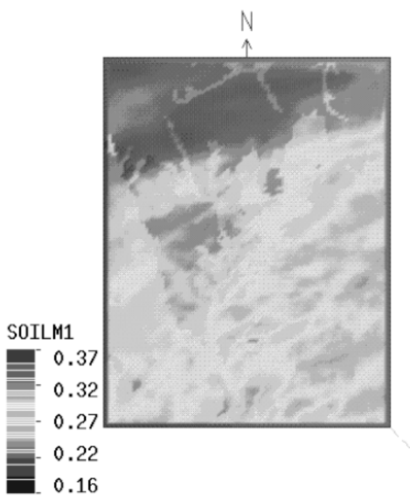


Fig. 2. Domain averages of soil moisture volumetric content in the top layer of soil observed on May 19, 1997, and modeled with MM5 for three different simulation start times.

(a) (b)



(c) (d)

Fig. 3. Simulated spatial distribution of soil moisture volumetric content (m^3/m^3) in the surface layer of soil for May 19, 1997, (a) at 0900 hr , (b) 1200 hr, (c) 1500 hr, and (d) 1800 hr GMT, for the rectangular area enclosing the WRW, over a north-south distance of about 100 km and an east-west distance of about 75 km.

Figure 3 shows examples of the surface soil moisture distribution derived from Run 2 for the WRW. The soil moisture began to increase in the extreme northern part of the domain at 0600 hr GMT, corresponding to the first appearance of convective rain. The change in soil moisture had spread over increasingly large areas by 0900 hr and 1200 hr (Figs. 3a and 3b). The nonconvective rain started in the afternoon (Fig. 3c), and the maximum occurred at 1800 hr (Fig. 3d) with both convective and nonconvective rain. For most of the area, the soil moisture content was greater than 0.35 m^3/m^3. This was less than the observed amount (0.4 m^3/m^3), because the total amount of modeled precipitation was only about one half of the observationally based precipitation estimates, and the model's peak precipitation was located about 0.5° from the peaks in the observed daily precipitation. This problem might be related to uncertainties in the spatial distribution of initial soil moisture because the soil was quite dry (0.22 m^3/m^3) before the rain.

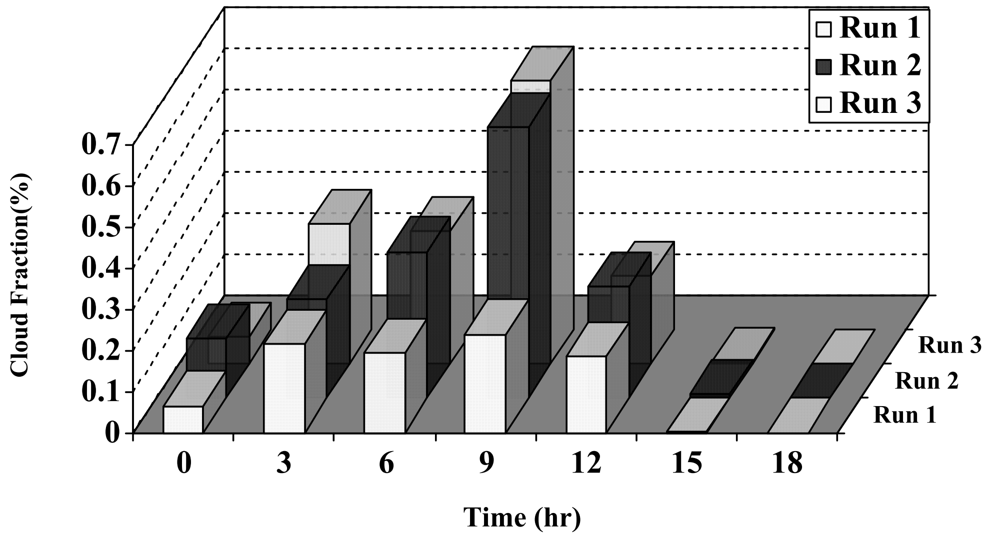


Fig. 4. Cloud fraction during the rain, simulated with MM5 at 1-km grid resolution for May 19, 1997, for three different simulation start times.

Cloud amount was checked for each simulation (Fig. 4). The cloud amounts for Runs 2 and 3 were very similar. For Run 1 the modeled cloud amount was one-third of that in Runs 2 and 3. This difference can be partially associated with the simulation times allowed for cloud formation and interactions involving soil moisture. The smaller cloud amounts produced by Run 1 resulted in a decrease in precipitation rates, and subsequently much less accumulation of soil moisture. Improvement of results will require more studies about the time scale for soil moisture feedback to the atmosphere, as well as detailed treatment of surface characters and processes.

4. SUMMARY

Soil moisture at the WRW was simulated by MM5. For eight NCAR observation stations, the average modeled soil moisture was compared to the averages of measurements in the layer of soil between the surface and a depth of 10 cm. The soil moisture content matched very well with measurements for dry, moderately wet, and wet soil conditions. Findings indicate that soil moisture is sensitive to initial conditions when the soil is dry and insensitive when the soil is relatively wet. Soil moisture during rain events was simulated for May 19. An initial test run with 3-km resolution produced inferior results, probably because of less detailed land surface characters and uncertainties in the initial soil moisture distribution. Simulations with finer 1-km resolution started at (1) 0000 hr GMT on May 19 and continued for one day, (2) 0000 hr on May 18 for 2 days, and (3) 0000 hr on May 17 for 3 days. During the rain, the soil moisture estimates increased more realistically in Runs 2 and 3 than in Run 1 during rain, but the estimates were still smaller than the observed values. These differences can be related to underestimates of rainfall amounts. Cloud amount was strongly underestimated by Run 1, one-third that for Runs 2 and 3 during the rain events. This discrepancy might have been caused by insufficient simulation time for feedback to form clouds.

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