P2.4 REGIONAL VARIABILITY OF SOIL MOISTURE FROM SCAN MEASUREMENTS: IMPLICATION FOR LAND SURFACE MODELING AND ASSIMILATION

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1. INTRODUCTION

Soil moisture (SM) estimates are considered as a valuable input for various environment models, including weather forecasting, water management, agriculture, and forestry applications. In order to better understand the sources of SM error/bias and spatial variability, simulated with Land Surface Models (LSM), observed and simulated SM were compared. This comparison was performed over a spatial domain across the lower Mississippi river valley, *aka* the Mississippi Delta, during Summer/Fall months spanning years 2004 to 2006.

2. SOIL MOISTURE DATA

Soil moisture measurements from seven SCAN sites (SCAN 2007) located over the Lower Mississippi Delta Region and five in the state of Arkansas were used for analysis and comparison with Noah LSM simulations. The geographical distribution of these sites within the study area is depicted in Fig. 1. The SM volumetric fraction is retrieved from the real component of complex water dielectric constant measured at 50 MHz with the Hydra Probe II SM sensor (Stevens 2007). The SM sensing volume represents a cylinder having 4 cm diameter and 5.8 cm height. The nominal SM accuracy provided by the sensor and evaluated as a standard deviation of measurements from the calibration curve is ±3 % (m^3/m^3). Seyfried and coauthors (2005) showed that deviations from the reference calibration were generally related to the clay mineralogy (different clay types) and could exceed the above standard deviation, especially for clayey soils. Depending on the soil texture, represented by 12 USDA classes, four standard calibration curves/options provided by the sensor manufacturer are available for users (Stevens 2007). The SM measurements at SCAN sites are performed using the standard calibration of the Hydra Probe II sensor every hour at the following depths: 5 cm, 10 cm, 20 cm, 51 cm, and 102 cm.

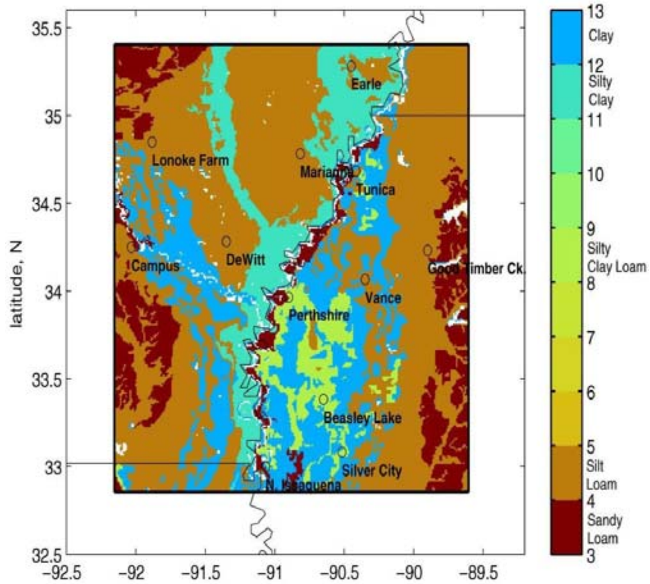

Figure 1. Geographical distribution of USDA soil classes within Noah/LIS integration domain with 1-km resolution. SCAN sites used for soil moisture analysis and validation of Noah/LIS simulations are shown by circles. White color stands for water bodies.

In addition to SM measurements, SCAN network provides site-specific data about physical soil parameters including texture, particle size distribution, water retention, and others. These data represent mean values for soil layers with a different thickness in the range from about 10 cm to 30 cm, which depends on site and depth. Finally, the surface layer meteorological data, such as air temperature and humidity, wind speed, downward solar radiation flux, and precipitation, all hourly-measured at SCAN sites were also used in the present study for comparison/analysis purposes. The current study covers the 3-year period spanning from January 2004 to December 2006.

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3. LAND SURFACE MODEL SETUP

The Noah LSM (Ek et al., 2003) available within the state-of-the-art Land Information System (LIS) developed at NASA Goddard Space Flight Center (Peters-Lidard et al., 2004, Kumar et al., 2006) was configured at 0.01°x0.01° latitude-longitude resolution (about 1x1 km²) over a domain with an approximate latitude-longitude size of 2.5º×2.5º and covering the Lower Mississippi Delta region located mainly in the state of Mississippi (see Fig. 1). The LIS provides a rather flexible tool for unified specification of land topography, soil and vegetation parameters, and running various LSMs either regionally or globally.

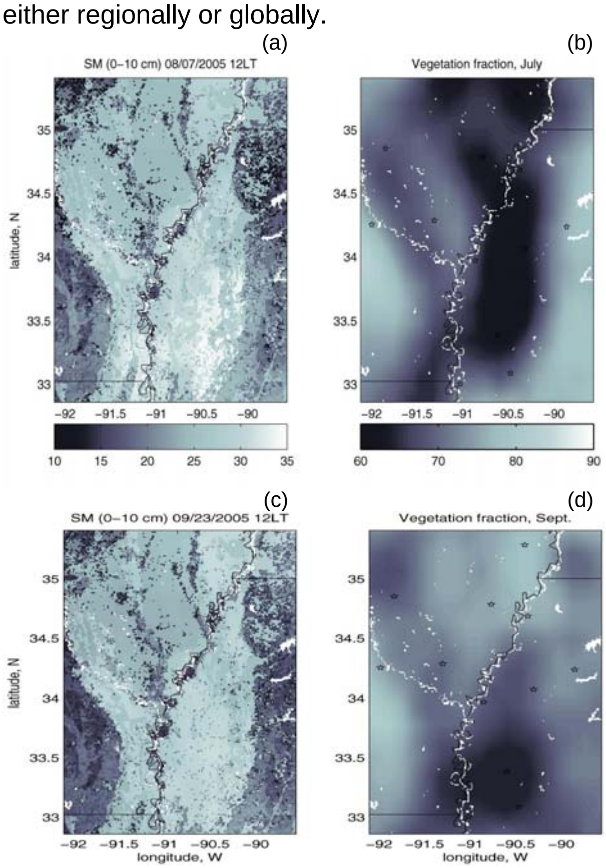

Figure 2. Examples of soil moisture (within top 0-10 cm layer) geographical distribution simulated by the Noah/LIS model for August (a) and September (c) 2006. Right frames illustrate vegetation fraction spatial distribution for July (b) and September (d) used for soil moisture simulations. Note close association between soil moisture patterns and those of soil types shown in Fig. 1.

The Noah LSM (version 2.7.1) was used for moisture simulations with 4 standard layers in the soil shown in Fig. 2a. The soil texture was represented by CONUS-SOIL (Miller and White, 1998) data based on USDA STATSGO database. The geographical distribution of STATSGO soil classes within the Noah/LIS integration domain is shown in Fig. 1. Only five texture classes (sandy loam, silt loam, silty clay loam, silty clay, and clay) are observed over the model domain, as shown in Fig. 1. Clay soils (silty clay loam, silt clay, and clay) depicted in blue-green colors are dominant over the Delta with a small quantity of sandy soils observed mainly along the Mississippi River (see Fig. 1). Sandy soils (sandy loam and silt loam) prevails to the east and west from the Delta, so there is a clear contrast of the soil texture exists between the Delta and adjacent territories. The vegetation/land use description was based on 13 land cover classification types developed at the University of Maryland.

For retrospective simulations the LIS framework supports various atmospheric data sets such as GLDAS, GOES, NLDAS, ECMWF, and others with different levels of spatial and temporal resolution. The atmospheric input (forcing) into the LIS involves the following surface variables: air temperature and water vapor content, pressure, components of the wind, downward fluxes of solar and longwave radiation, and rain- snowfall rates. In the present study North American Land Data Assimilation System (NLDAS) atmospheric data were used to force the Noah LSM model. The NLDAS forcing project was described in detail by Cosgrove et al. (2003). NLDAS hourly fields cover the CONUS region and some adjacent regions of Canada and Mexico with 0.128º latitude-longitude resolution (approximately 15 km grid spacing). They are available online from the end of 1996 until the present. The Noah/LIS runs were performed using NLDAS forcing spanning the period from January 2004 to the end of the year 2006.

Quality of NLDAS fields was amply validated against point observations and has proven a rather high. Luo and coauthors (2003) performed an evaluation study of the NLDAS forcing over the southern Great Plains, spanning almost a two-year long period and showed that typical standard deviations between NLDAS and observed at surface stations atmospheric variables are 2.3 ºC (for the air temperature), 1.1 g/kg (for the water vapor specific humidity), 1.5 m/s (for the wind speed), 120 W/m² (for the downward solar radiation flux), and 0.65 mm/hr and 0.15 mm/hr (for the hourly and daily precipitation rates, respectively). The hourly precipitation forcing in NLDAS is based on daily precipitation reanalysis, which produced from gauge reports at NCEP Climate Prediction Center (CPC) with 0.25º latitude-longitude resolution and *aka* the unified CPC precipitation analysis. Within the NLDAS processing routine, these daily gridded precipitation are interpolated to the 0.125º NLDAS grid and then disaggregated into hourly rates using Doppler radar precipitation estimates, which are based on real-time hourly analysis data having 4 km resolution (stage 2 data). Details of this procedure and all sources of the involved data were described by Cosgrove and coauthors (2003). The NLDAS downward solar radiation flux at the surface is retrieved from NOAA's GOES satellite measurements. The other NLDAS forcing fields are interpolated both temporally and horizontally from analysis fields produced by the NCEP Eta Data Assimilation System at 40 km resolution every 3 hr.

4. RESULTS

4.1 *Dependence on soil texture*

Typical spatial patterns of the top 10 cm SM after precipitation and in the end of a drying period simulated with the Noah model are shown in Figures 3a and 3c, respectively. These Figures reveal a rather close association between spatial patterns of the soil texture depicted in Fig. 1 and those of the SM due to the SM response to the hydraulic properties (e.g. Robock et al. 2003; Richter et al. 2004). Quite similar examples of the SM geographical distribution over the part of the same region were published by Mostovoy et al. (2007). Close correlation between simulated SM and soil type's spatial patterns shown in Fig. 1 is quite apparent. Areas of relatively low SM content coincide well with corresponding areas of sandy loam soil depicted by the brown color in Fig. 1. Indeed, marked footprints of the sandy loam are clearly observed in the SM fields along east/west boundaries of the model domain within a latitudinal zone bounded by 33ºN and 34ºN (see Fig. 3). Conversely, areas of relatively high SM correspond to those of clay soils, which are dominant over the Delta and shown in Fig. 1 by blue and green colors. Using a one week of intensive field and remote sensing observations over the SW Oklahoma in 1997, the similar strong control of the SM spatial distribution by the soil texture was recently described by Mohr and coauthors (2000).

This association between soil texture and SM is well established and supported by previous empirical studies of SM spatial organization. Performing analysis of multi-year SM time series sampled biweekly during growing season over the state of Illinois at 15 grass-covered sites, Hollinger and Isard (1994) reported soil texture and structure as the major factors controlling water storage within 1 m top soil layer. These authors showed that fine-grained and well-structured, silty-clayey soils with high porosity have twice as much water stored within the 1 m top layer than coarse-grained and poorly-structured sandy soils with relatively low porosity. Some studies showed that SM spatial organization is controlled by the soil porosity, which depends on the soil texture (e.g. Rodríguez-Iturbe et al. 1995; Yoo et al. 1998). Using SM of the top 5 cm layer and field porosity data with 200 m resolution available from the Washita'92 experiment, Yoo and coauthors (1998) demonstrated that spatial correlation scales/lengths are about the same (around 2000 m, on average) for both SM and porosity fields. Results of the above study suggested that soil texture/porosity is more important as a factor controlling spatial distribution of SM during drying out periods than rainfall and various landscape factors, such as a terrain's slope and orientation and vegetation patterns.

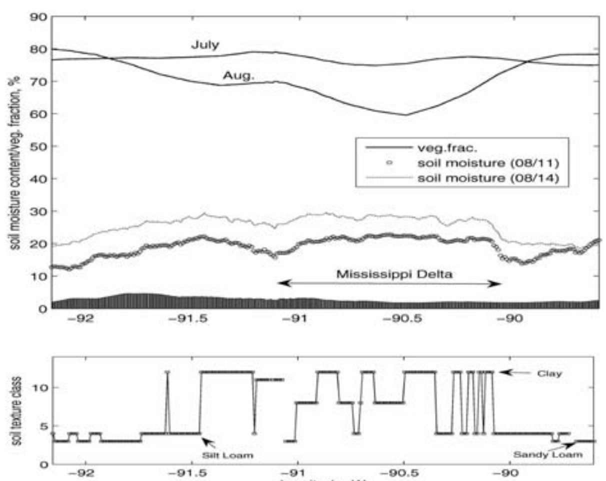

Figure 3. Longitudinal variations of soil moisture simulated within top 0-10 cm layer by the Noah model, vegetation fraction, and NLDAS precipitation (all averaged within 1-degree latitude belt confined between 33º N and 34º N) and soil texture dominant (lower frame) within the same latitudinal zone across the Lower Mississippi Delta during July-Aug. 2006. Two soil moisture curves are depicted: one (the lower line) corresponds to the end of drying period and the other (the upper line) represents soil moisture distribution after subsequent rainfall events. Precipitations were converted to daily mean amounts (in mm) between dates related to lower and upper lines.

In a good qualitative agreement with the above mentioned results, Fig. 3 shows that 0-10 cm SM simulated with the Noah model has distinctly elevated values within the Delta region where soils with relatively high clay content prevail and, conversely, lower SM values over the regions to the east and west from the Delta where silt-loam-sandy soils are dominant. In addition to these marked changes of the soil texture between the Delta and adjacent territories, there is a green vegetation contrast between the Delta with the relatively low values of *f* and surrounding well-forested territories to the east and west having a high level of *f*. Examples of *f* geographical distribution with the Noah model simulation domain representing the multiyear mean monthly data of vegetation fraction (Gutman and Ignatov 1998) are depicted in Fig. 2 (b, d) for July and September. To assess how close the changes in soil texture and vegetation fraction are related to simulated spatial distribution of 0-10 cm SM, these variables are averaged within one-degree latitudinal range (from 33º N to 34º N) except for the soil texture, which was aggregated within the same range and plotted in Fig. 4 as a function of the longitude for the year 2006. As can be expected, a good direct agreement illustrated by Fig. 3 is observed between SM and texture distributions with longitude. Both during July and October (data not shown) the SM perfectly respond to soil texture changes demonstrating elevated level of SM over the Lower Mississippi Delta where clayey soil types are dominate (they are shown in Fig. 3 as numbers representing the USDA soil texture classes ranging from 8 /Silty Clay Loam / to 11 /Silty Clay/ and 12 /Clay/) as compared with regions of lower SM to the east and west where sandy soil types (corresponding numbers ranging from 3 /Sandy Loam/ to 4 /Silt Loam/) prevail. Note that the SM responds to changes in soil texture in the same way at the end of drying periods and after precipitation events (see corresponding SM lines in Fig. 3). Similar features of SM response were observed during other years (2004 and 2005) having marked differences in precipitation amounts (plots not shown). Note that the SM changes most sharply along the eastern boundary of the Delta where almost discontinuous decrease in the SM of about 10 % is observed. These facts suggest the importance of the soil texture in maintaining spatial SM gradients both during relatively dry and wet conditions.

Finally, a formal stratification of simulated SM (averaged within one-degree latitudinal range) according to the soil texture classes gives additional evidence of the soil texture control on spatial SM patterns. Symbolic distributions (represented by box-plots showing the data range, upper and lower quartiles, and the median) of the SM values within a particular soil texture class are plotted in Fig. 4 for a three-year period spanning from 2004 to 2006, showing a rather gradual increase in the median SM when the soil texture class changes from 3 (Sandy Loam) to 12 (Clay). Because the texture class 11 (Silty Clay) contains a relatively small number of sample points (twelve), its distribution cannot be considered as a statistically indicative. The SM difference between soil texture classes as illustrated by Fig. 4 is related to the choice of hydraulic properties (Richter et al. 2004). Overall, these plots support a general notion of soil texture importance in maintaining a particular SM level within top 0-10 cm layer.

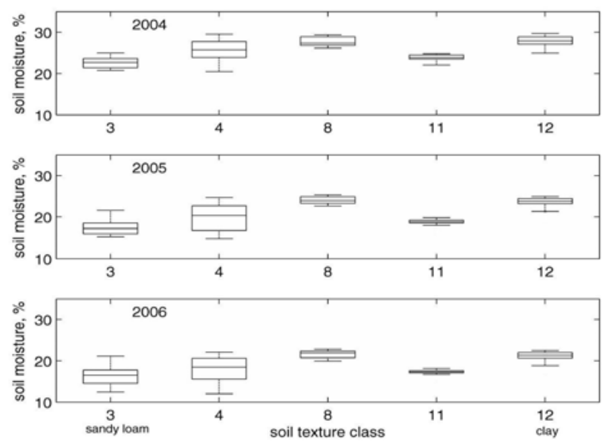

Figure 4. Symbolic box-plots of soil moisture (values were averaged within 33º N – 34º N latitude range) distributions stratified by soil texture type for years 2004 to 2006 (July-August period). Median, upper and lower quartiles, and data range are shown.

4.2 *Observed variability of soil moisture*

The correlation between soil texture and simulated 0-10 cm SM patterns observed over the Lower Mississippi Delta region and described in a previous section is fairly well confirmed by point SM measurements available over the same region. Fig. 5 shows examples of SM dynamics within 1 m top layer at five SCAN sites having different soil texture during years 2005 and 2006. For plotting purposes the SM, which is measured at five levels, is linearly interpolated between these levels. Daily mean values of SM are depicted in Fig. 5, and periods of missing measurements are shown by white bars as well. Local soil texture distribution with depth sampled at SCAN sites and corresponding soil texture classes derived from STATSGO data are also shown in Fig. 5.

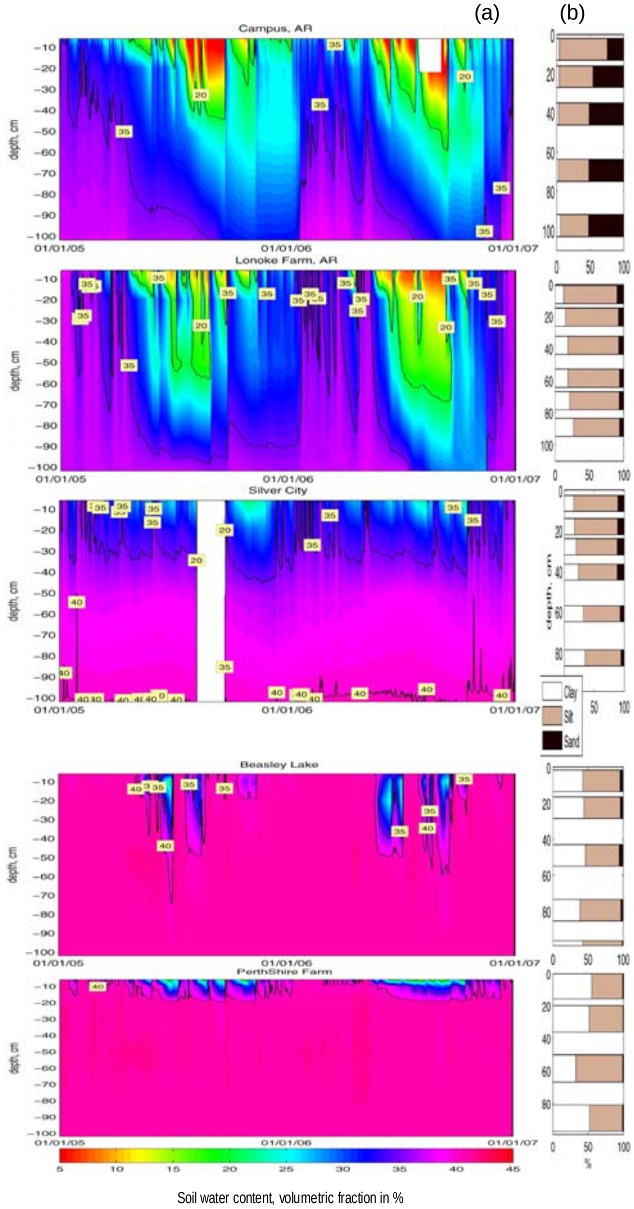

Figure 5. Time-depth plots showing soil moisture dynamics (a) from Jan. 2005 to Dec. 2006 and local soil texture (b) at five selected SCAN sites. Note close association between clay content increase and changes (overall increase) of observed soil moisture.

Two upper frames in Fig. 5 illustrate SM dynamics for Campus, AR and Lonoke Farm, AR SCAN sites having silt loam soils and located to the NW of the Delta. Three lower frames depict SM dynamics observed at SCAN sites within the Delta region; they are Silver City, MS (silt loam, 4), Beasley Lake, MS (silty clay, 11), and Perthshire Farm, MS (silty clay, 11). Locally sampled texture classes are indicated in parenthesis. Figure 5 clearly depicts typical changes in SM dynamics caused by a transition in the soil texture from sandy to clayey soils. Comparison between upper frames representing sandy soils and lower ones relating to clayey soils supports the importance of soil texture in maintaining a specific level of SM, particularly during the drying out stages of soils. Indeed, increase in clay content up to 50% (as shown in two lower frames) leads to a very shallow layer having about 20 to 40 cm in thickness affected by the surface evaporation and, as a consequence, relatively high SM. Conversely, relatively low clay content (as illustrated by three upper frames in Fig. 5) produces a rather deep (up to 1 m) soil evaporation layer and low SM.

Rather high correlation or association between both observed and simulated SM and soil texture suggests that accurate specification of soil texture classes, provided that they correctly describe and control soil hydraulic properties, is of major importance for quality improvement of simulated SM. This inference is especially important for the drying out periods of soil matter. It should be noted that a relatively small region covering approximately area of 2.5º×2.5º in latitude-longitude, as compared with a typical size of large-scale weather systems (atmospheric high, lows, and fronts), was considered in this study. Therefore, it would be reasonable to accept almost horizontally homogeneous atmospheric conditions (related to precipitation and evaporation levels) over this area**.** Their horizontal variability is rather small. It is also obvious that in addition to the soil texture, horizontal variations of other local factors, such as water table depth, soil cracks, and macro- and mini terrain features favoring standing water and ponding, and others can affect locally observed SM dynamics. These factors are neglected in this study.

Because all SCAN sites are covered by the short grass with a relatively small locally-observed *f*, a vegetation influence on SM is assumed not to be essential in this study. Use of vegetation parameterizations has proven to be critical for simulations, especially long-term, of surface fluxes although an impact of these parameterizations on the SM is not well established and understood

(Bosilovich and Sun 1998). Using the ECMWF LSM for multi-years runs over Australia, Richter et al. (2004) demonstrated a little sensitivity of modeled SM to variations of vegetation parameters, such as *f* and *LAI*, in comparison to a relatively large response to changes of soil hydraulic parameters. Results of our sensitivity tests with the Noah model showed that activation of the short grass vegetation cover with $f = 0.5$ resulted in a soil water sink having approximately constant rate, which mimics a water extraction by plant roots, and located within three top model layers. In most test cases, adding of the vegetation parameterization produced a little impact on the top 0-10 cm SM.

5. SUMMARY

Observed and simulated with the Noah model, values of soil moisture (offline simulations were used with approximately 1x1 km^2 horizontal resolution) were compared on a daily basis over the Lower Mississippi Delta region during summer/fall months spanning years 2004 to 2006. Hourly soil moisture measurements and other data including local meteorological and soil physical properties data from twelve SCAN were used for these comparisons. For comparison purposes, the SCAN soil moisture data available at 5 levels spanning from 5 cm to 102 cm were aggregated to match to a vertical size of three top Noah model layers having total thickness of 100 cm. The Noah simulations covered $2.5^{o} \times 2.5^{o}$ latitude-longitude domain and were forced by the NLDAS atmospheric forcing. It was shown that both observed and simulated levels of soil moisture depend critically on specified/sampled soil texture. Soil types with high content of clay matter (more than 50% of weight) contain more water due to reduced rate of drying in comparison with silty/sandy soils having 20% or less of clay, provided that other conditions are the same. This fact is in agreement with previous studies (Mohr et al. 2000; Robock et al. 2003) and implies an importance of soil texture right specification in order to simulate and assimilate soil moisture accurately.

This preliminary study suggests that there is still enough room for quality improvement of soil moisture maps simulated by NOAH/LIS retrospective runs. It is clear that better agreement of simulated data with point soil moisture measurements can be achieved by using site-specific soil texture instead of that derived from STATSGO data.

6. ACKNOWLEDGMENTS

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