Multi-scale dynamics of soil moisture variability observed during SGP'97

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Abstract. Data sets produced by the 1997 Southern Great Plains Field Experiment (SGP'97) provide information about surface soil moisture dynamics across a range of scales. A multi-scale analysis of the data reveals a qualitatively different relationship between soil moisture means and soil moisture spatial variances when variability is sampled at fine (<1 km) versus coarse (>10 km) spatial scales.

Introduction

The inability to resolve or predict subgrid scale variability in soil moisture fields leads to grid scale errors in predicted water and energy fluxes due to nonlinear relationships among soil moisture, transpiration, infiltration and gravity drainage [*Entekhabi and Eagleson* 1989; *Wood* 1997; *Famiglietti and Wood* 1995]. Understanding the dynamics of soil moisture variability over a range of hydrologic conditions is a first step in developing a closure approach for these errors. Unfortunately, insights about the general relationship between soil moisture spatial variability and mean levels of soil moisture often appear contradictory. For instance, *Sellers et al.* [1995], *Bell et al.* [1980], and *Famiglietti et al.* [1998] suggest that the dynamics of soil drying acts to progressively reduce the spatial variance of both relative and gravimetric soil moisture fields, while *Rodriguez-Iturbe et al.* [1995] and *Famiglietti et al.* [1999] present observational arguments that suggest drying acts to increase small scale relative and volumetric soil moisture variability.

The apparent contradiction may be resolvable if each statement is taken in the context of specific spatial scales. The description of *Sellers et al.* [1995] is applicable to relatively coarse scale spatial heterogeneity introduced by rainfall and removed through dry-down dynamics. While *Rodriguez-Iturbe et al.* [1995] is referring to the introduction of fine scale stochastic variability during a dry-down in a spatial region that has been uniformly wetted during the previous rainfall event. This line of reasoning suggests a transitional scale that separates fine scale soil moisture dynamics, where changes in soil moisture spatial variance are negatively correlated with changes in mean soil moisture, from coarse scale dynamics, where changes in soil moisture spatial variance are positively correlated with changes in mean soil moisture.

Data collected during the Southern Great Plains 1997 field experiment (SGP'97) provides an excellent opportunity to evaluate the existence of such a transition. The purpose of this analysis is to use data sets collected during SGP'97 to examine the temporal dynamics of volumetric soil moisture spatial variances at a variety of scales in an attempt to resolve previously contradictory descriptions of the relationship between soil moisture spatial variances and soil moisture means.

Description and analysis of SGP'97 data sets

The SGP'97 experiment was a NASA funded field campaign run between June 16 to July 17, 1997 within a region of central Oklahoma. During the campaign a number of different techniques were used to measure surface (0-5 cm) volumetric soil moisture. The three of interest here are: Time Domain Reflectivity (TDR) probe measurements, gravimetric soil sampling, and remotely sensed estimates based on Electronically Scanned Thinned Array Radiometer (ESTAR) imaging. Airborne ESTAR imaging occurred within a transect running southwest to northeast within central Oklahoma. Gravimetric and TDR probe sampling occurred at three experimental sites within the ESTAR transect: El Reno, the Little Washita Basin, and the Central Facility. See Figure 1 for site and transect

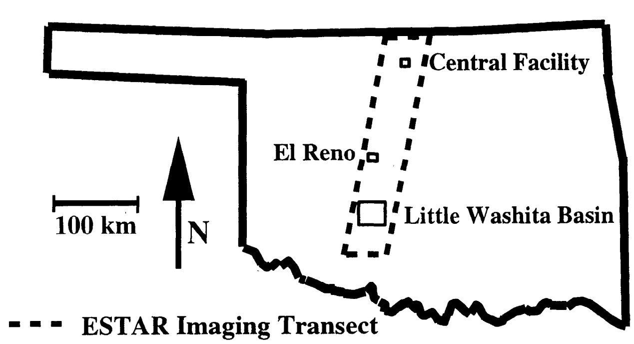

Figure 1. Location of individual study sites within the ESTAR imaging transect. Approximate dimensions of study sites are as follows: the Central Facility (6.5 x 5 km), El Reno (8 x 5 km), and the Little Washita Basin (32 x 24 km).

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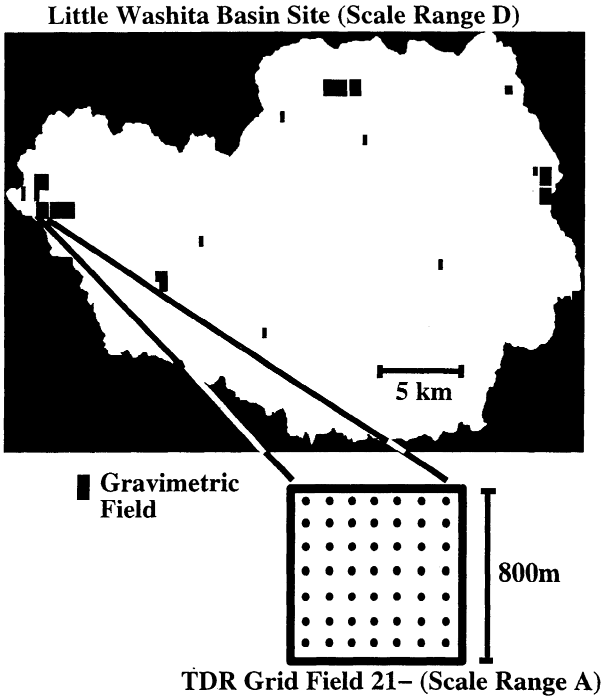

Figure 2. Location of fields within the Little Washita Basin study site that were gravimetrically sampled for surface soil moisture during SGP'97. Also shown is an enlargement of a single field containing a 7 x 7 TDR grid.

locations. Figure 2 shows a detailed view of the Little Washita Basin site, including a TDR grid located within one field. Further details can be found in the SGP'97 experimental plan [*Jackson* 1997]. All data sets collected during SGP'97 are available on-line at: http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/SGP97.

Data sets based on gravimetric, TDR, and ESTAR derived soil moisture measurements provided information about soil moisture dynamics at five different scale ranges. Descriptions of these ranges, labeled A to E, are given in the following sections.

TDR Measurements

The portable TDR probes relied on a physical relationship between electromagnetic impedance and the water content of soil to estimate volumetric soil moisture. Measurements were made at three fields within the Little Washita Basin site, two fields at the El Reno site, and one field at the Central Facility site. The sampling configuration for each field consisted of 49 nodal locations spaced 100 m apart in a square 7 by 7 grid. Daily TDR measurements were taken at each node in the grid. Collection and processing techniques for the TDR data set are described in *Famiglietti et al.* [1999]. Day to day differences in both field scale (~800 m) means and sub-field scale (~1 m) variances were calculated for each of the six TDR fields and will be referred to as Scale Range A. A minimum of half the TDR nodes in a grid had to be sampled on a given day for that particular field to be included in the analysis.

Gravimetric Sampling

Gravimetric soil moisture sampling was carried out for twenty-three fields at the Little Washita Basin site, seventeen fields at the El Reno site, and nine fields at the Central Facility site. Fourteen surface soil samples were taken in each field on a daily basis. Conversions from gravimetric to volumetric soil moisture values were made using measured values of soil bulk density. Field size was generally on the order of 800 m. For each site, day to day differences in site scale (~10 km) means and sub-site (i.e. field) scale (~800 m) variances were calculated. The dimensions of the Little Washita Basin site were significantly larger than the dimensions of the El Reno and Central Facility sites - see Figure 1. To accommodate this difference, gravimetric sampling done at the El Reno and Central Facility sites was lumped into a single scale range (Scale Range B), while gravimetric sampling done at the Little Washita Basin site was separated (Scale Range D). Sampling uncertainty within field scale means was corrected for by assuming independence of the 14 sub-field measurements. For each site, gravimetric data had to be available for a minimum of 5 separate fields before a given site was included on a given day

ESTAR Images

Sixteen images of surface brightness temperature were obtained from ESTAR overflights during the study period. The ESTAR radiometer is a synthetic aperture passive microwave sensor, operating at a center frequency of 1.413 GHz, flown aboard a NASA P-3 aircraft. Microwave brightness temperature was then processed into 800 m estimates of volumetric surface soil moisture. See *Jackson et al.* [1999] for a description of processing. Because the imaged ESTAR domain changed slightly during the course of the experiment, daily differences in the ESTAR fields were calculated using only the spatial union of successive images. All other areas were masked out. Day to day differences within Scale Range C were calculated by sampling the mean and variance of 800 m soil moisture pixels within 12.8 km portions of the ESTAR imagery. Daily differences within Scale Range E were examined by aggregating the original 800 m resolution image up to a resolution of 12.8 km and sampling a mean and variance within the entire ESTAR transect. Only 12.8 km pixels that contained a perfect set of 256 unmasked 800 m pixels were included in the analysis.

Figure 3 summarizes the five scale ranges (A to E) over which soil moisture variability was sampled. The left hand side of the line segments shown in Figure 3 refer to the scale at which each measurement technique resolved soil moisture information, and the right hand side refers to the domain size within which soil moisture

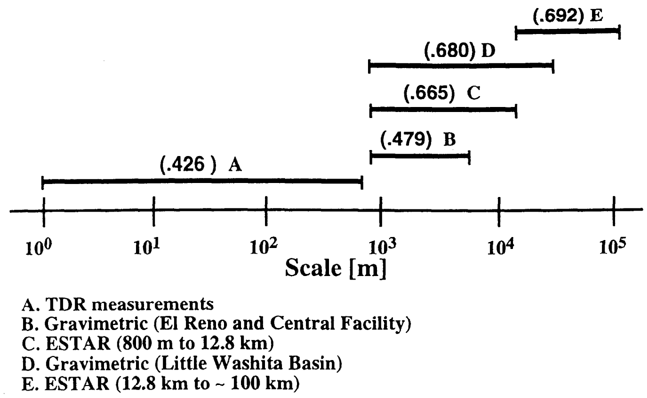

Figure 3. Spatial scale ranges for various soil moisture measurement techniques employed during SGP'97. The left edge of the line segment refers to the scale at which soil moisture measurements were resolved. The right edge indicates the size of the domain in which soil moisture statistics were sampled. Values shown above lines give the fraction of times temporal changes in sampled soil moisture variability had the same sign as temporal changes in sampled soil moisture means.

spatial means and variances were calculated. The segments correspond to the range of spatial scales at which each technique is capable of sampling soil moisture variability. For each of the scale ranges listed in Figure 3, day to day differences in soil moisture means (at the domain scale) and day to day differences in variances (resolved at the resolution scale and sampled within the domain scale) were calculated. Differences were not calculated for successive measurements separated by more than two days.

Results

Figure 4 shows a portion of the data used to calculate results for Scale Range A and Scale Range D. The spatial scales associated with Scale Range A - point scale resolution within field scale domains - and Scale Range D - field scale resolution within site scale domains - are demonstrated in Figure 2. Figure 4 suggests that temporal changes in soil moisture means and variances are negatively correlated within Scale Range A and positively correlated within Scale Range D. Results for all available data are summarized in Figure 3. The values shown refer to the fraction of observations in which daily changes in sampled soil moisture means had the same sign as daily changes in sampled soil moisture variances.

Results in Figure 3 suggest that the probability of daily changes in soil moisture means and variances having similar signs undergoes a transition between 1 and 10 km. Descriptions of the relationship between soil moisture spatial variances and soil moisture means vary when soil moisture variability is sampled at length scales above and below this transitional range. For instance, Scale Range A samples at scales *finer* than this transitional range and has a sampled fraction of less than 0.5. In contrast, Scale Range E samples at scales *coarser* than the transitional range and returns a fraction greater than 0.5. Scale Range B samples *within* the transitional range and consequently has a fraction that is statistically insignificant from 0.5. Finally, Scale Ranges C and D sample at a range of scales *within and coarser than* the transitional range and show results that fall between those of Scale Range E and Scale Range B.

Table 1 lists the fractions shown in Figure 3, as well as the sampled fractions when daily changes dominated by soil moisture wetting and drying were separated and analyzed independently. A transitional range between 1 and 10 km is observed in both the wetting and drying dynamics. The statistical significance of each measurement in terms of its departure from a random walk process is also listed.

Discussion

Figure 3 and Table 1 present results where the dynamics of soil moisture wetting and drying are scale dependent. The effect of precipitation and dry-down events on soil moisture spatial variability was qualitatively different at fine (<1 km) and coarse (>10 km) scales. The threshold between these two scale regimes may represent a transition between organized coarse scale spatial heterogeneity imposed by land surface re-

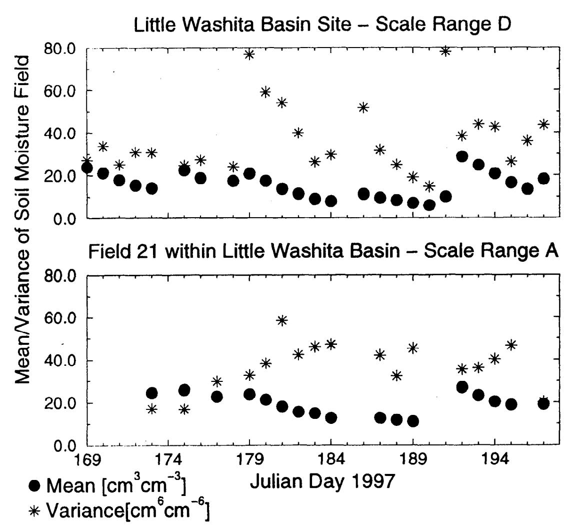

Figure 4. Time series of sampled soil moisture means and variances. The top graph was produced by resolving surface soil moisture at the field scale and sampling soil moisture statistics using all the fields within the Little Washita Basin site (Scale Range D). The bottom graph was produced by resolving soil moisture at the point scale and sampling soil moisture statistics using all 49 TDR nodal values within Little Washita field 21 (Scale Range A).

Table 1. Sampled probability that daily changes in soil moisture spatial variances have the same sign as daily changes in soil moisture means. The given percentages relate the one-tailed statistical significance of each probability in terms of its departure from the value expected in a random walk process (0.5).

	Scale Range A	Scale Range B	Scale Range C	Scale Range D	Scale Range E
All Daily Changes	0.426(6.2%)	0.479(44%)	0.665(<.01%)	0.680(5.5%)	0.692(13%)
Wetting Only	0.389(12%)	0.400(37%)	0.552(11%)	0.667(34%)	0.667(50%)
Drying Only	0.442(17%)	0.500(50%)	0.700(<.01%)	0.684(8.4%)	0.700(17%)

sponse to rainfall and disorganized fine scale variability produced by local variations in topography, soils, and vegetation. A similar transition is seen in data from the Washita'92 Experiment presented by *Rodriguez-Iturbe et al.* [1995]. Their data set, however, contained only three days and was not suitable for the inference of any temporal trend.

The existence of this scale dependency has several implications. It dictates that closure approaches for soil moisture spatial variability based on knowledge of soil moisture spatial means will be dependent on scale. It also suggests natural length scales where statistically homogeneous soil moisture variability can be separated from organized soil moisture structure imposed by antecedent precipitation. Such length scales may represent optimal grid sizes for land-atmosphere modeling of the region. Finally, this scale dependence highlights the limitations of calculating soil moisture spatial statistics from isolated point scale measurements. Sampling strategies that are incapable of resolving a range of scales between the point (~1 m) and the region (~100 km) are likely to miss critical soil moisture dynamics.

The spatial structure of individual rainfall events will clearly have an impact on these results at coarse scales. For instance, three major wetting up events were observed within the ESTAR data set: June 25-26, June 29-30, and July 10-11. Two of these events (June 25-26 and June 29-30) were associated with an increase in spatial variability when soil moisture was sampled within Scale Range E. Rainfall accumulations from these two storms had strong north-south gradients, with heavy precipitation in the northern half of the study area and little to no precipitation in the southern portion of the study area. In contrast, the rainfall event associated with a decrease in soil moisture variability within Scale Range E (July 10-11) had nearly homogeneous accumulations across the entire study region. Agricultural and land management practices employed within the SGP'97 study area also introduce spatial structure into the landscape at length scales near the proposed transitional scale range. It is possible that this human imposed heterogeneity enhanced the appearance of scale dependency within the SGP'97 data sets.

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