ELSEVIER

Journal of Hydrology 255 (2002) 12–24

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Statistical properties of soil moisture images revisited

Anna Oldak*, Yakov Pachepsky, Thomas J. Jackson, Walter J. Rawls

United States Department of Agriculture, Hydrology and Remote Sensing Laboratory, Agriculture Research Service, BARC-West, Building 007, Beltsville, MD 20705, USA

Received 25 September 2000; revised 15 June 2001; accepted 20 July 2001

Abstract

Data from passive microwave remote sensing with an ESTAR L-band radiometer, deployed on an aircraft, were used to produce soil moisture images over the area of the Little Washita watershed in Oklahoma in 1992. This area was revisited during the Southern Great Plains 1997 Hydrology Experiment. This offered an opportunity to evaluate the time-specificity of the conclusions, relating to scaling of the surface soil moisture, that have been reported for 1992. The objective of this work was to compare scaling properties of soil moisture fields observed in 1992 and 1997. We analyzed one 1992 data set and three 1997 data sets, each covering several days of continuous drydown. Different resolutions were introduced by aggregating the pixels of original 200-m resolution into bigger square cells. Scaling in dependencies on resolution was observed for the variance of moisture content, for the within-cell variance, and for the first six moments about zero, the latter indicating multiscaling. Parameters of the scaling equations differed among four drying periods studied. However, once a scaling dependency on resolution was established in the beginning of a drying period, its shape was maintained during the drydown both in 1992 and 1997. Slopes of the dependencies changed only slightly, whereas the intercepts decreased as the drying progressed. Having constant slopes and intercepts dependent on average area water contents gives an opportunity to reduce the volume of observations needed to predict scaling of surface soil moisture during drydowns.

Keywords: Surface soil moisture; Soil moisture scaling; Soil moisture drydown

1. Introduction

Microwave radiometry of the soil surface is an important source of information on soil surface moisture. Moisture content of the soil surface layer can be derived from surface brightness temperature (Jackson, 1993). Knowledge of the spatial distribution of soil moisture is critical when assessing crop yields, surface energy balance, and soil atmosphere gas exchange (Schmugge et al., 1980).

One especially useful feature of microwave remote sensing is that soil moisture variability can be observed across a range of scales (Dubayah et al., 1997) quantified by the resolution. Information about the variability of soil moisture is essential in designing measurement systems and descriptions of the land–atmosphere surface interactions and related hydrologic phenomena (Cosh and Brutsaert, 1999). Examples of its utility include upscaling soil moisture to the resolution level of general circulation models (Hu et al., 1997), downscaling soil moisture from the coarse remote sensor resolution (Crow and Wood, 2000), predicting subgrid variability of soil moisture by combining measurements at different resolutions (Kumar, 1999), analyzing within-pixel variability

* Corresponding author. Fax: +1-301-504-8931.
E-mail address: aoldak@hydrolab.arsusda.gov (A. Oldak).

PII: S0022-1694(01)00507-8

aspects with respect to topography and soil moisture level (Charpentier and Groffman, 1992), and deriving soil hydraulic conductivity (Mattikalli et al., 1998).

Several experiments have been carried out to collect data on spatial variability of soil moisture and factors forming the variability at several resolutions. One such experiment, Washita '92, took place in the Little Washita River watershed in Oklahoma. Maps of the volumetric soil moisture content were generated for eight consecutive days of drying (Jackson et al., 1995).

Data from the Washita '92 experiment were used by several research groups to understand the effect of resolution on soil moisture statistical properties. Pixels of the original 200 m grid of soil moisture images were grouped to change the resolution and the water content was averaged. The areas of the grouped pixels were used as a measure of resolution. Rodriguez-Iturbe et al. (1995) found that the variance of the soil moisture distribution exhibited a power law dependence on resolution across three orders of magnitude of the pixel area. These authors also considered scaling properties of soil moisture spatial clustering, i.e. the probabilistic effect of the moisture level in a pixel on moisture levels in neighboring pixels. Hu et al. (1997) showed that the power law dependence of the soil moisture content variance on resolution holds over the range of resolutions up to 32 km^2 which is larger than the limit of 1 km^2 found by Rodriguez-Iturbe et al. (1995). Hu et al. (1997) interpreted the value of the scaling exponent as an indicator of persistence, or clustering in soil moisture fields. They also computed higher order moments of the distributions, and inferred the presence of multi-scaling in the soil moisture fields with data for moments from second to sixth. Dubayah et al. (1997) applied a procedure similar to that of Hu et al. (1997) and arrived at similar conclusions. Kumar (1999) showed that assuming a multiscaling in soil moisture fields allows the simulation of these fields using the available water content as an auxiliary input. Grouping soil by textural classes was found useful for classifying the moisture fields and their dynamics into groups with different statistical properties (Mattikalli et al., 1998; Cosh and Brutsaert, 1999).

All aforementioned results on soil moisture scaling in Little Washita were obtained with data for a single drying period from 10 to 18 June 1992. Because of the uniqueness of this data set, it was not possible to decide to what extent was the scaling specific to the area of observations and weather conditions of this particular location and time. The Little Washita watershed was revisited in 1997 during the Southern Great Plains (SGP97) Hydrology Experiment (Jackson et al., 1999) and measurements were made that were similar to those of the '92 experiment. These data presented an opportunity to evaluate the time-specificity of the conclusions relating to scaling of the surface soil moisture that have been reported. The objective of this work was to compare scaling properties of soil moisture fields observed in '92 and '97.

2. Materials and methods

2.1. Data source and composition

Two data sets were discussed in this paper: the Washita '92 experiment and the SGP97 experiment. The Washita '92 experiment was described in Jackson et al. (1995) and analyzed by Dubayah et al. (1997), Hu et al. (1997) and Rodriguez-Iturbe et al. (1995). The second data set is the result of SGP97 Hydrology Experiment (Jackson et al., 1999), which evaluated the performance of the soil moisture retrieval algorithm at coarser spatial resolutions. Both during Washita '92 and SGP97 experiments, data were collected using the L band passive microwave mapping instrument — Electronically Scanned Thinned Array Radiometer (ESTAR) (Le Vine et al., 1994). The brightness temperature collected between 18 June–16 July 1997 were used to produce spatial products. These images were then used to create regional soil moisture estimates maps (Jackson et al., 1999). The brightness temperature data, with the near-regular original footprint of about 400 m, were re-gridded to 200 m resolution for the Little Washita area using Surfer software (Golden Software Inc., 1999) in order to match the grid used in the Washita '92 experiment. Finally 228×93 pixel images were created, showing the spatial and temporal distribution of soil moisture for the 848 km^2 Little Washita basin.

Three drying periods following the main rainfall events were observed during the SGP97 experiment — 18–20 June, 1–3 July and 12–15 July. The spatial soil moisture data of these 10 days were the data used in the analysis.

2.2. Scaling models applied to the surface soil moisture imagery

Scaling is a broad term used to quantify the observed similarity in features of natural objects at different scales. Properties of these features, e.g. total number, total length, total mass, average roughness, total surface area, etc., may depend on the scale on which the features are observed. Scaling assumes that, whereas the properties themselves change, the dependence is the same over a range of scales, i.e. it is scale-invariant within this range. Definitions of scale are the subject of discussions in natural sciences (i.e. Blöschl and Sivapalan, 1995). Remotely sensed imagery has the resolution, or pixel size, as a convenient measure of the observation scale. To obtain soil moisture data at different resolutions, the soil moisture data of the original grid are averaged over areas of different sizes that include an increasing number of pixels (i.e. Hu et al., 1997).

Three types of scaling have been observed in the Little Washita data and have been discussed in the literature (Rodriguez-Iturbe et al., 1995; Hu et al., 1997; Dubayah et al., 1997; Kumar, 1999; Crow and Wood, 2000). One type found in soil moisture images is the power law scaling of the variance of moisture contents (Rodriguez-Iturbe et al., 1995; Hu et al., 1997)

$$\mathrm{Var}(w) = \left(\frac{x_0}{x}\right)^m \mathrm{Var}(w_0) \quad (1)$$

Here w and w_0 are the moisture contents measured for two pixel sizes x and x_0, respectively, m the scaling exponent, 'Var' means the variance. Similar scaling was found for soil properties (Mattikalli et al., 1998; Rodriguez-Iturbe et al., 1995; Kumar, 1999).

Multiscaling, defined by the following equation:

$$E[w^q] = \left(\frac{x_0}{x}\right)^{K(q)} E[(w_0)^q] \quad (2)$$

relates the moments of a soil property at a base scale to the comparable moments at a different scale. Here w and w_0 are the moisture contents measured for two pixel sizes x and x_0, respectively, E is the expected value computed as a statistical moment about zero over all pixels for a resolution in question

$$E[w^q] \cong \frac{\sum_{i=1}^{N} w_i^q}{N} \quad (3)$$

where N is the number of pixels at resolution x, q the order of the statistical moment, $q > 1$, $K(q)$ is the scaling exponent. If $K(q)$ is a linear function of the 'scaling moment function' q

$$K = cq \quad (4)$$

where c is a slope, then the scaling is called 'simple scaling' (Hu et al., 1997; Dubayah et al., 1997) or 'monofractal' (Dubayah et al., 1997). If $K(q)$ is a nonlinear function of q, scaling is interpreted as multiscaling or multifractal (Dubayah et al., 1997; Gupta and Waymire, 1993).

The third type of scaling is the dependence of the within-pixel variance on resolution. It has not been examined with the data from the Washita '92. The within-pixel variance can be computed for all pixels larger than the pixels of actual measurements. The variability within pixels is expected to increase as the pixel size increases. Crow and Wood (2000) showed that a piecewise power law scaling was applicable in the Little Washita 1997 area

$$\mathrm{Var}_x(w) = \begin{cases} \mathrm{Var}_1(w)x^{m_1}, & x \le x_* \\ \mathrm{Var}_1(w)x_*^{m_1}\left(\dfrac{x}{x_*}\right)^{m_2}, & x > x_* \end{cases} \quad (5)$$

Here x_* is the cutoff resolution that divides the resolution range into two parts where scaling exponents m_1 and m_2 are different. A fitting procedure allows one to select the value of x_* along with values of m_1 and m_2.

Applicability of scaling laws (1), (2) and (5) was tested in this work.

2.3. Aggregation of moisture contents at various resolutions

In order to generate data at different resolutions, both square and rectangular grids have been used (Rodriguez-Iturbe et al., 1995; Hu et al., 1997; Dubayah et al., 1997). The resolution was defined by the area rather than by the size for rectangular pixels. No overlapping pixels were allowed by the aforementioned authors. Using results of Monte

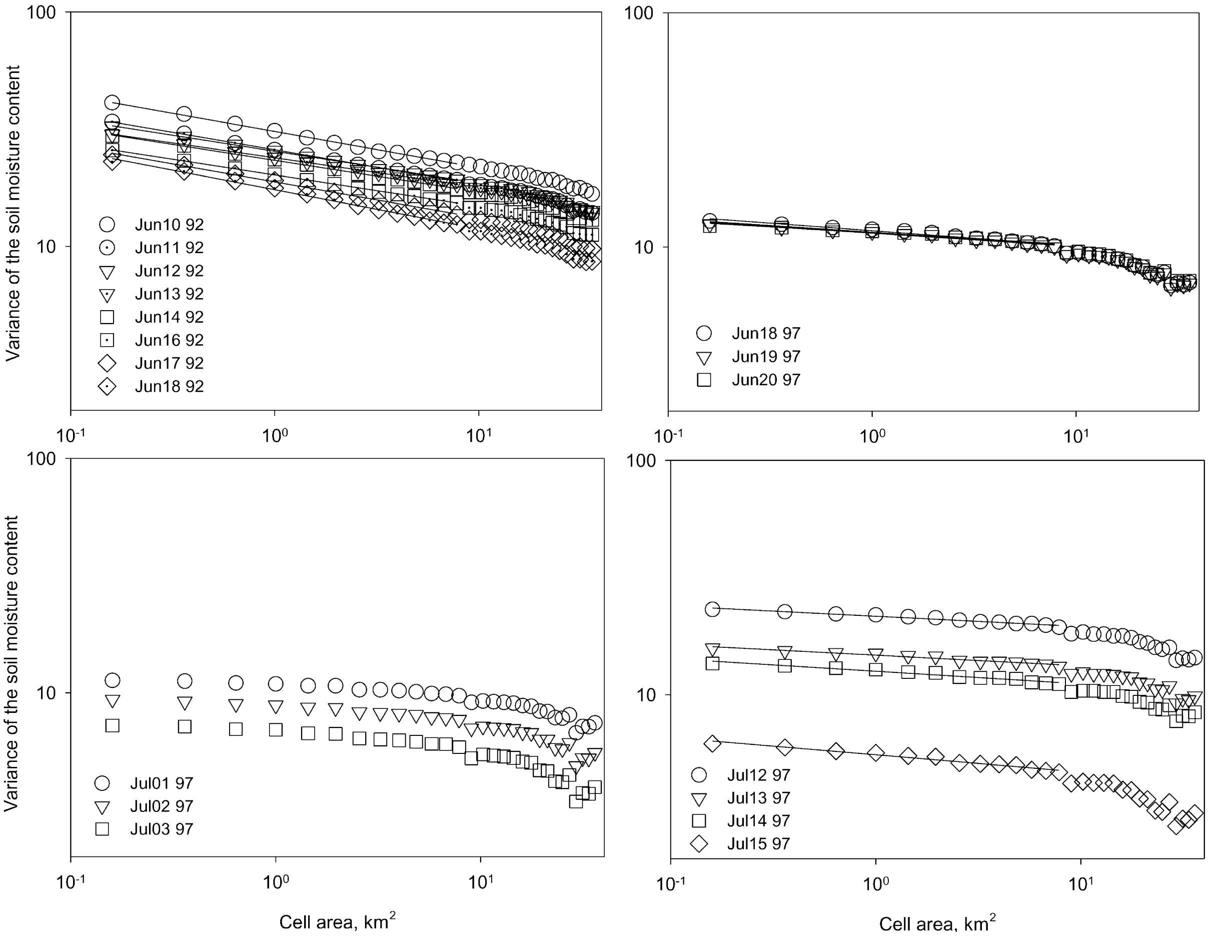

Fig. 1. Dependencies of the variance of soil moisture content on cell area for four drydown periods. Trend lines are shown up to 7.8 km^2.

Carlo simulations of self-affine series, Malinverno (1990) suggested that a 50% overlap between aggregated pixels should be used in spatial scaling studies.

Dubayah et al. (1997) pointed out that the strategy of discarding aggregated pixels containing original pixels with missing data can, in principle, affect results because the effective support of the field will no longer be two-dimensional, i.e. it is not completely plane filling. These authors rejected any aggregated pixel containing at least one original pixel with missing data. Other authors did not report how they treated missing data.

The 200 m grid data from Washita 92 and SGP97 experiment in the Little Washita area were aggregated into 30 different resolutions, creating new, aggregated pixels, or cells, from 2×2 up to 31×31 pixels of the original 200 m grid. For the aggregation purpose, the grid of original pixels was treated as a two-dimensional array with the first and second subscripts increasing towards east and north respectively. For the cells of the resolution $r \times r$, i.e. containing $r \times r$ original pixels, the aggregated water contents, $\theta_{ij}^{(r)}$, were computed as

$$\theta_{ij}^{(r)} = \frac{\sum_{p=i}^{p=i+r-1} \sum_{q=j}^{q=j+r-1} \theta_{pq} G_{pq}}{\sum_{p=i}^{p=i+r-1} \sum_{q=j}^{q=j+r-1} G_{pq}},$$

$$i = 1, 2, \ldots, N_i - r + 1, \qquad j = 1, 2, \ldots, N_j - r + 1 \tag{6}$$

Table 1
Slopes and intercepts of regressions of cell area vs. variance of water content in logarithmic coordinates

Date[a]	Slope	Intercept	Mean volumetric soil moisture
1992			
10 June[a]	−0.1537 ± 0.0021	2.4130 ± 0.0130	23.70
11 June[b]	−0.1493 ± 0.0014	2.3080 ± 0.0089	21.50
12 June[c]	−0.1381 ± 0.0018	2.2340 ± 0.0113	21.20
13 June[d]	−0.1276 ± 0.0012	2.1440 ± 0.0077	19.30
14 June[e]	−0.1367 ± 0.0019	2.1880 ± 0.0120	20.90
16 June[f]	−0.1367 ± 0.0020	2.1250 ± 0.0125	18.00
17 June[g]	−0.1560 ± 0.0025	2.2110 ± 0.0157	15.90
18 June[h]	−0.1698 ± 0.0039	2.2610 ± 0.0246	12.70
1997			
18 June[k]	−0.0698 ± 0.0059	1.4880 ± 0.0375	19.90
19 June[k]	−0.0627 ± 0.0061	1.4350 ± 0.0385	18.56
20 June[k]	−0.0564 ± 0.0058	1.3990 ± 0.0372	15.91
1 July[m]	−0.0456 ± 0.0054	1.3040 ± 0.0342	12.23
2 July[m,n]	−0.0591 ± 0.0066	1.2940 ± 0.0416	9.75
3 July[n]	−0.0659 ± 0.0086	1.2250 ± 0.0544	7.97
12 July[p]	−0.0497 ± 0.0049	1.6330 ± 0.0314	21.05
13 July[p]	−0.0514 ± 0.0055	1.4770 ± 0.0349	16.75
14 July[p]	−0.0607 ± 0.0059	1.4640 ± 0.0378	14.35
15 July[r]	−0.0829 ± 0.0081	1.2410 ± 0.0518	12.47

[a] The same letter in the superscript means that the slopes are not significantly different at the significance level 0.05.

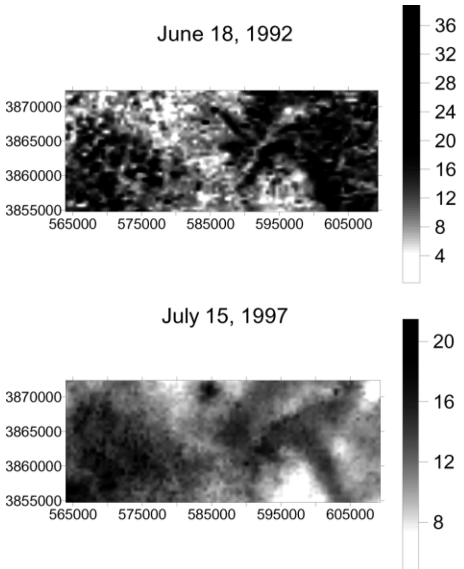

Fig. 2. Soil moisture images for 18 June 1992 and 15 July 1997 having close average soil moisture contents.

where $\theta_{ij}^{(r)}$ is the cell of the resolution of r original pixels that has the original pixels (i,j) in its bottom left corner, θ_{pq} is the water content in the original pixel (p,q) if data are not missing for that pixel, and is equal to zero otherwise, G_{pq} is equal to zero and to one if data are missing and present respectively in the original pixel (p,q), N_i and N_j are the total numbers of columns and rows in the original pixel grid, respectively; $N_i = 228$ and $N_j = 93$ for the grid. About 5% of data were missing in 1992 and less than 0.5% of the data were missing in 1997, except 3 July 1997 when 1.5% of data were missing. Cells were not used in testing scaling laws if all original pixels within them had missing data. To obtain the half-overlapping cells in this work, we selected from the values given by Eq. (6), only those which had subscripts i and j differing by $\{k_i r/2\}$ and $\{k_j r/2\}$, respectively. Here $\{k_i r/2\}$ and $\{k_j r/2\}$ mean integer parts of $k_i r/2$ and $k_j r/2$, respectively, $k_i = 1, 2, \ldots, \{2(N_i - r + 1)/r\}$, $k_j = 1, 2, \ldots, \{2(N_j - r + 1)/r\}$.

We worked only with square cells, used half-overlapping cells to tile the area, and discarded cells if more than half of the original pixels within them had missing data. We tested the effects of the discarding

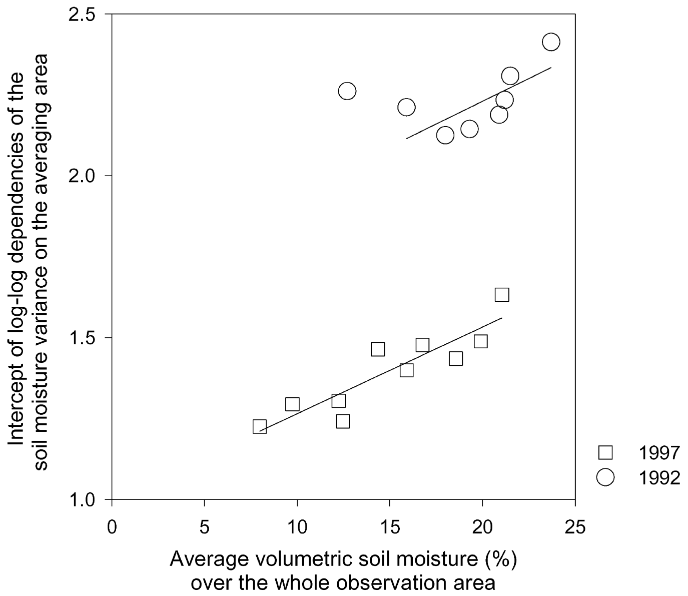

Fig. 3. Effect of the drydown on the intercepts of the 'soil moisture variance — cell area' dependencies. The trend line shown for the 1992 data set does not include the data of 18 June 1992 (the left most circle).

and overlapping strategies by repeating the computations for no overlap of cells and with discarding any cell if at least one observation was missing in the original pixels within it.

2.4. Computing scaling exponents

Scaling exponents m in Eq. (1) and $K(q)$ in Eq. (2) were found as slopes of regression equations 'log x vs. log scaled value' obtained by log-transforming Eqs. (1) and (2), i.e.

$$\log \mathrm{Var}(w) = -m \log x + \log(x_0^m \mathrm{Var}(w_0)) \quad (7)$$

and

$$\log E[w^q] = -K(q) \log x + \log(x_0^{K(q)} E[(w_0)^q]) \quad (8)$$

respectively. Scaling exponents, the cutoff resolution x_* and the intercept variance $Var_{x_1}(w)$ in Eq. (5) were found using nonlinear minimization of the root mean square error of the piecewise-linear regression

$$\log \mathrm{Var}_x(w) = \begin{cases} \log \mathrm{Var}_1(w) + m_1 \log x_*, & x \le x_* \\ \log \mathrm{Var}_1(w) + (m_1 - m_2)\log x_* + m_2 \log x, & x > x_* \end{cases} \quad (9)$$

The Marquardt algorithm was used to obtain average parameter values and to estimate standard errors of parameters. We applied a version of the algorithm described by Daniel and Wood (1973). Availability of the standard errors of the parameters enabled us to test the statistical hypothesis about equality of average parameter values.

The Durbin–Watson test was applied to decide what resolution range could be used to apply linear scaling relationships. This test assesses the randomness in the residuals (Neter and Wasserman, 1974), i.e. randomness of the distribution of the observation points around the regression line; absence of randomness divulges existence of a non-linear pattern in data that is not simulated with the linear regression equation. The hypotheses that regression lines are identical and that the slopes of the regression lines are identical were tested for different observation dates (Neter and Wasserman, 1974). The difference between regression lines means that either slopes or intercepts or both are significantly different. The significance level of 0.05 was used in the statistical testing.

3. Results and discussion

Linearity in the log–log dependency of the variance

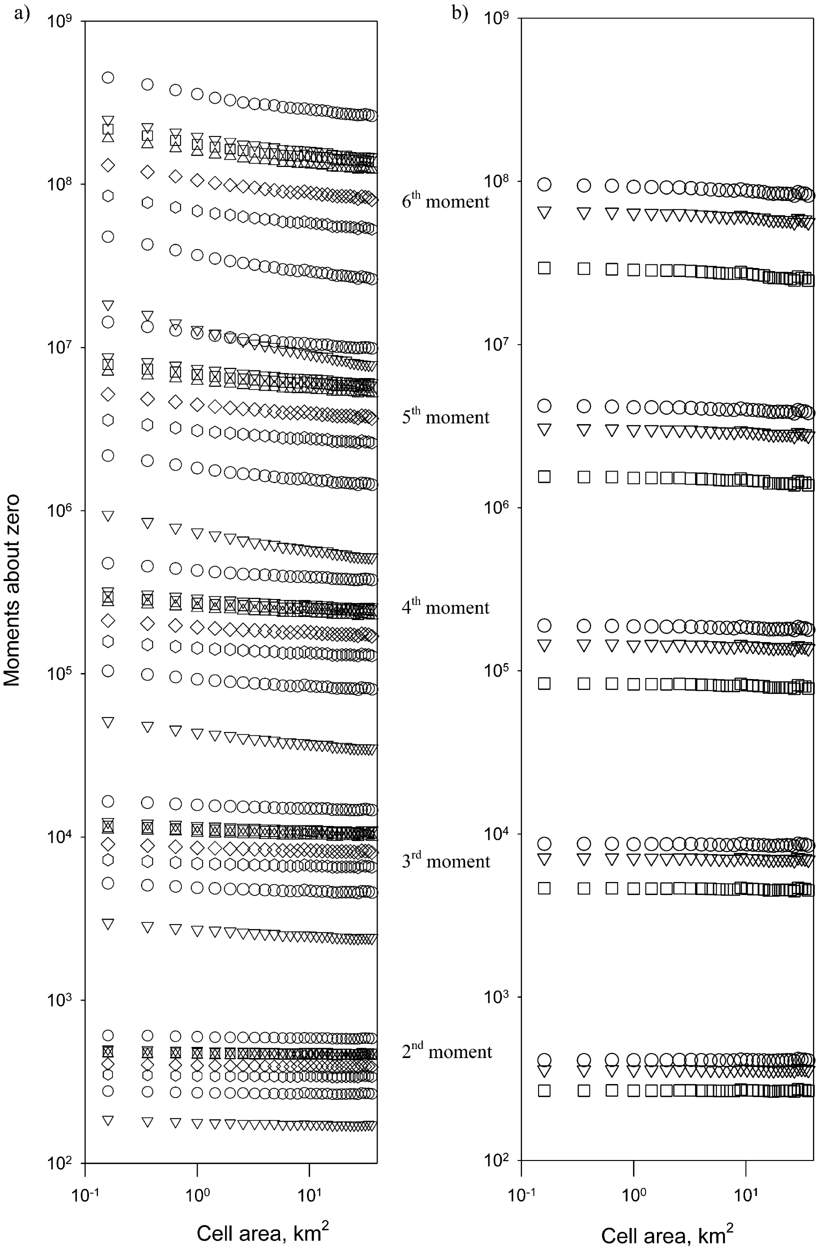

Fig. 4. Effect of the cell area on moments about zero of spatial distributions of soil moisture: (a) — 1992, ○ 10 June, ▽ 11 June, □ 12 June, ◇ 13 June, △ 14 June, ⬡ 16 June, ○ 17 June, ▽ 18 June; (b) — 1997, ○ 18 June, ▽ 19 June, □ 20 June.

on resolution according to Eq. (7) can be observed in the 1997 data sets (Fig. 1). Rodriguez-Iturbe et al. (1995) demonstrated the same type of scaling up to 1 km^2 resolutions with the 1992 data. Hu et al. (1997) suggested that the linearity could be extended up to 32 km^2. In this work, the hypothesis that observation points are distributed randomly around the regression line could not be rejected up to the cell area 7.8 km^2 for all observation dates. The plots in Fig. 1 show linearity only up to this range. At larger

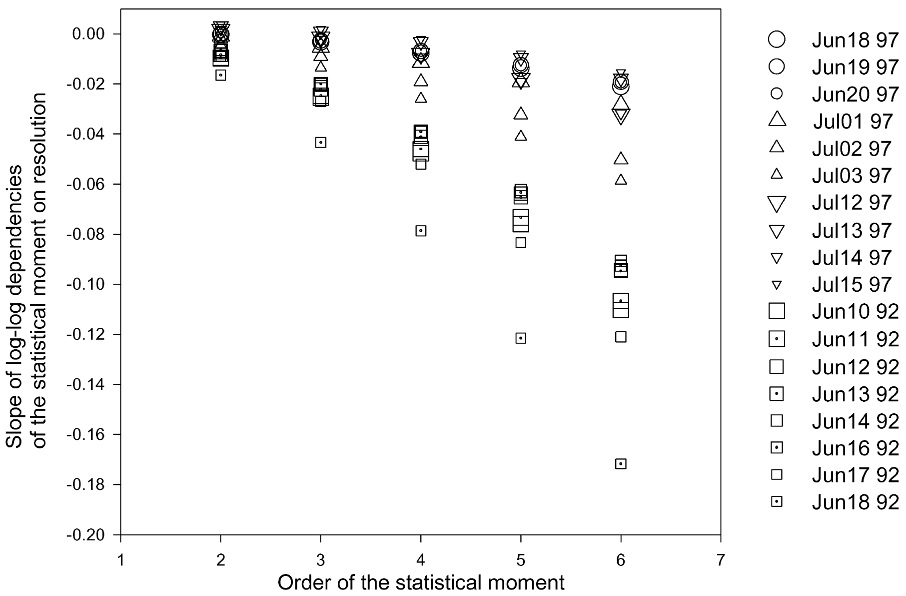

Fig. 5. Evidence of the multifractal scaling in spatial distribution of the soil moisture content.

resolutions, there was a bias in residuals for all observation dates.

Within the linearity intervals, slopes (m) in the relationships described by Eq. (7) were significantly less in the 1997 data sets as compared with the 1992 data set (Table 1). Hu et al. (1997) argued that the larger is the absolute values of the exponent the more clustering is in the image. These authors have indicated that soil moisture images show clustering in soil moisture patches. Slopes observed for the 1997 data sets are much closer to zero than in 1992, indicating that the clustering was less expressed in 1997 than in 1992. Fig. 2 shows the difference in spatial structure for two images from 1992 to 1997 having close mean soil moisture contents (Table 1). These images are constructed from data of the original resolution; both increase in general variability as shown in the color legends and an increase in patchiness is seen in the image from 1992.

The hypothesis that the regression lines (7) are identical during drying periods could be rejected for the 1992 drying period and for the June drying periods in 1997 (data not shown). The intercepts were different in most cases. Slopes were different in most cases in 1992. In 1997, however, the slopes for consecutive days did not differ significantly, 14th and 15th July being the exception (Table 1). Both increases and decreases in the slopes were found during drying periods (Table 1); this can be related to changes in patchiness of images (Hu et al., 1997). Values of the slopes in the log–log dependencies of the variance on resolution (6) changed only moderately as the soil dried both in the 1992 and 1997 data sets (Fig. 1, Table 1) mostly within $\pm 20\%$ of the average value.

Intercepts of the log–log relationships of the variance on resolution decreased during drydowns (Fig. 3, Table 1). The variability at any given resolution became smaller as the drydown progressed (Fig. 1). Because slope changed only slightly, temporal decreases in variability were mostly related to the decreases in intercepts. The average rate of the decrease in intercept values with the drydown was the same in 1997 and 1992 (except 18 June, the left most circle). The intercepts themselves were an order of magnitude less in 1997 than in 1992, which means an order of magnitude smaller variability at any given resolution.

The log–log dependency of the higher statistical moments about zero on the resolution are linear for the 1997 data as had been observed for the 1992 data sets in the analysis of Dubayah et al. (1997) and Hu et al. (1997). This result means that Eq. (7) is applicable.

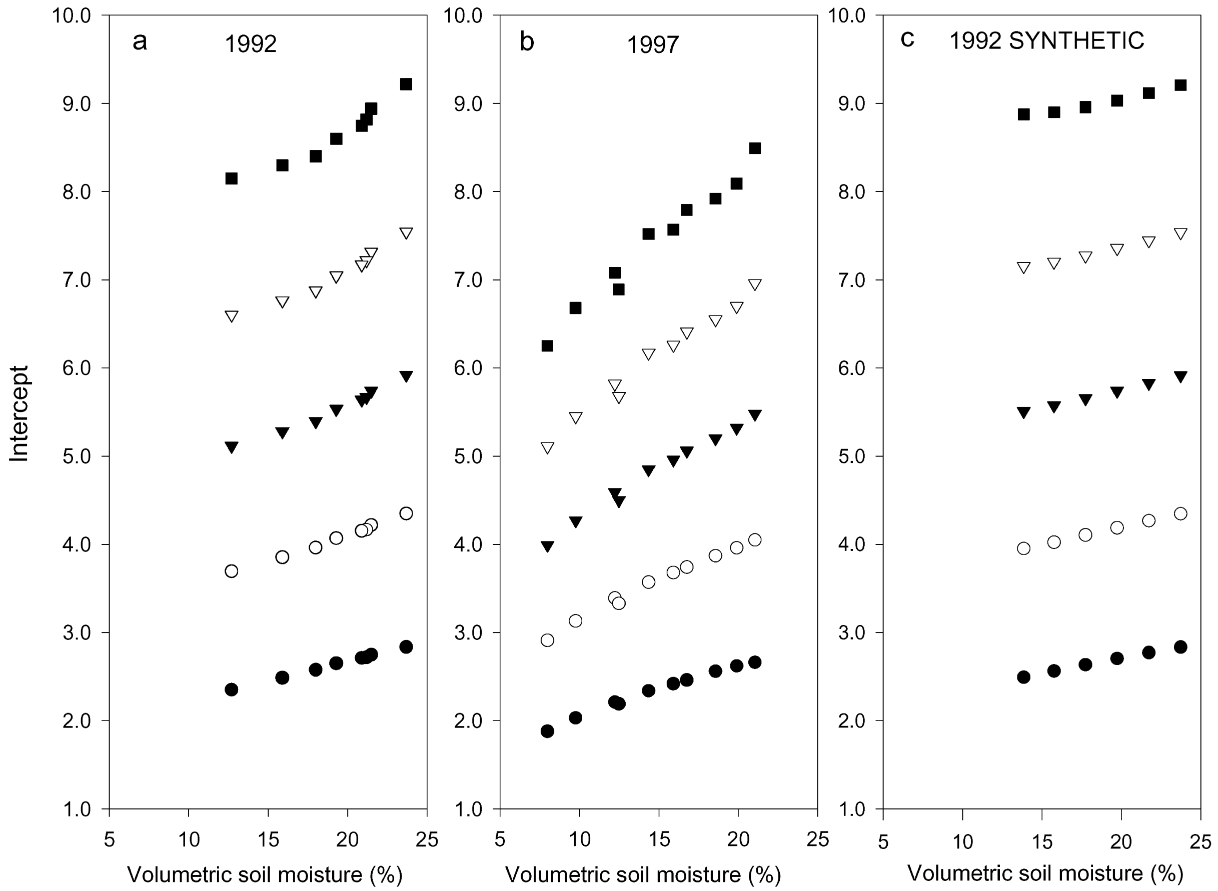

Fig. 6. Effect of the drydown on the intercepts of the 'moment about zero — cell area' dependencies for soil moisture; ● first moment, ○ second moment, ▼ third moment, ▽ fourth moment, ■ fifth moment.

Fig. 4 shows the examples of those dependencies. The hypothesis that observation points are distributed randomly around the regression line could not be rejected up to the cell area 7.8 km^2, the same as for the variance. Fig. 5 shows the dependencies of the slopes on the order of the moment. They are slightly concave. Therefore the 1997 data sets support the conclusion of Dubayah et al. (1997) and Hu et al. (1997) that the multifractal scaling is an appropriate statistical model for soil moisture spatial distributions during drying periods. However, graphs of the scaling moment function $K(q)$ are quite dissimilar in 1992 and 1997. The decrease in values of K as the moment order grows is much larger in 1992. The deviation from the simple scaling was much larger in 1992 than in 1997.

The intercepts of the log–log dependency of statistical moments about zero on the resolution demonstrate close relationships with the average water content in the area (Fig. 6a,b). The values of R^2 are between 0.92 and 0.99. The decrease in intercepts should be expected since the moments about zero must decrease as the value of the random variable decreases across the image. We made a simple computational experiment to illustrate this phenomenon. We took the image of 10 June 1992 that had the largest water content and generated five more images by subtracting 2, 4, 6, 8, and 10 from the values of moisture content in each cell. The multiscaling was observed for each of the synthetic images, and water contents were plotted in Fig. 6c vs. logarithms of intercepts of the regression (8) in the same way that they were plotted for real images in Fig. 6a and b. The logarithms of the intercepts exhibit a linear

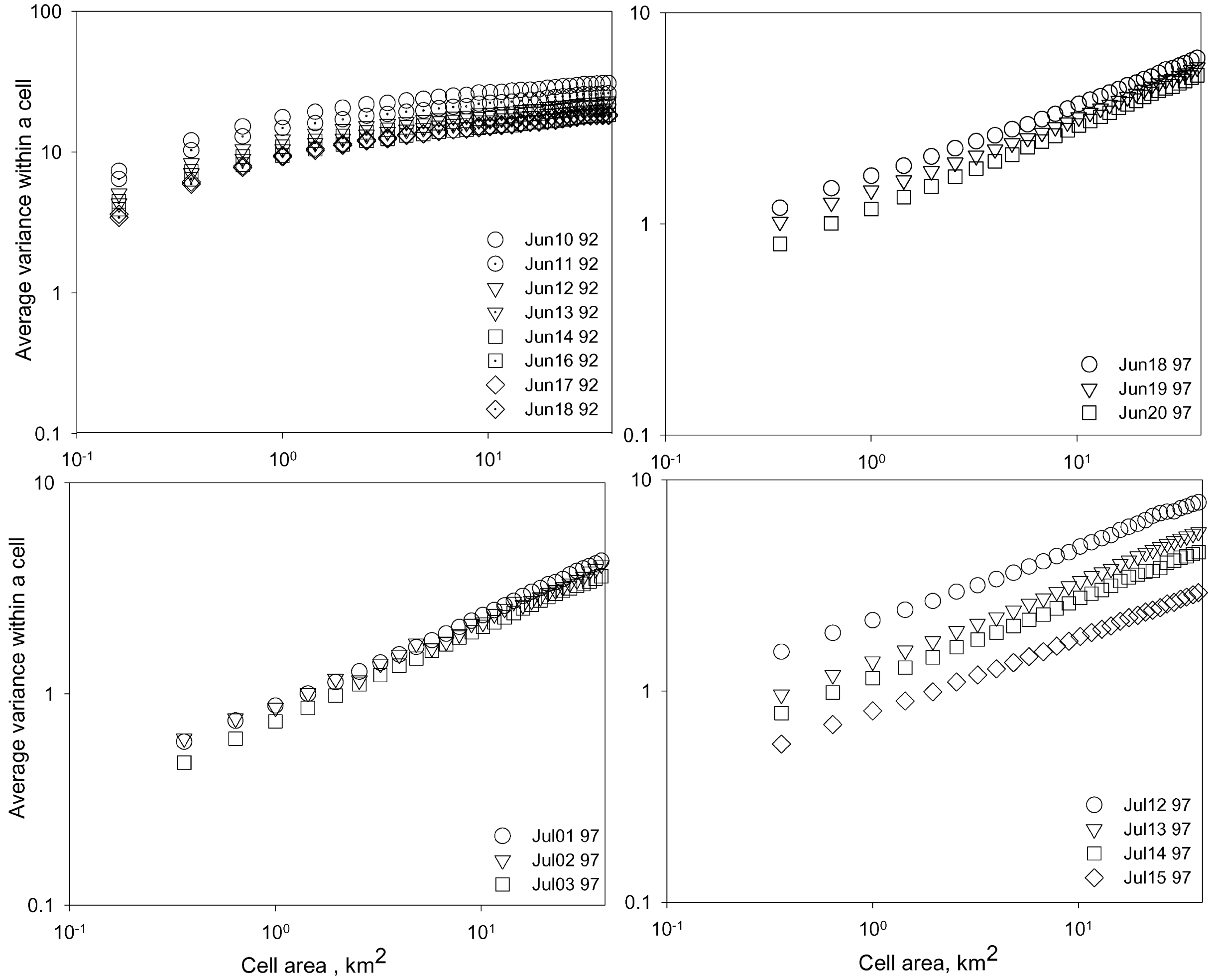

Fig. 7. Dependencies of the variance of soil moisture within cells on cell area for four drydown periods.

dependence on moisture content; the slopes of these dependencies range from 0.035 to 0.042 and are less than the slopes in Fig. 6a that range from 0.04 to 0.1. The synthetic images assume the uniform drying pattern regardless of the variation of soil texture within the investigated area. Different ratio of soil drying depending on the texture might be the explanation for the larger slopes in Fig. 6a.

Dependencies of the within-cell variability on resolution are shown in Fig. 7. These dependencies were linear in the 1997 and piecewise in the 1992. Parameters of the log–log linear and piecewise linear models (9) are shown in Table 2. The intercepts gradually decrease as the drydown progresses and the range of water contents becomes smaller. The piece-wise dependencies keep their shape and creep down as the drying develops. The cutoff resolution x_* in Eqs. (5) and (9) does not change significantly as the drydown progresses (Table 2). The intercellular variability at the same resolution becomes smaller as the drydown progresses. This has to be expected since the water contents do not change much after soils dries to a significant extent.

The hypothesis that regression equations are similar could be rejected for all drying periods. Slopes however did not differ much (Table 2) and were not significantly different in most of pairs of consecutive days. The difference in regression equations stemmed from the difference in intercepts that were decreasing as the drydowns progressed (Fig. 8, Table 2). Unlike

Table 2
Slopes and intercepts of the log–log regressions of cell area vs. variance of soil moisture within cells

Date[a]	First linear segment		Second linear segment	
	Slope	Intercept	Slope	Intercept
1992				
10 June[a]	0.5310 ± 0.0223	−1.8890 ± 0.1231	0.1691 ± 0.0088	5.8960 ± 0.0333
11 June[a]	0.5074 ± 0.0201	−1.8250 ± 0.1113	0.1701 ± 0.0080	5.8800 ± 0.0318
12 June[a]	0.4843 ± 0.0199	−1.7990 ± 0.1126	0.1699 ± 0.0135	6.0120 ± 0.0421
13 June[a]	0.4837 ± 0.0200	−1.8650 ± 0.1128	0.1882 ± 0.0135	6.0160 ± 0.0449
14 June[a]	0.4868 ± 0.0193	−1.8670 ± 0.1089	0.1849 ± 0.0130	6.0180 ± 0.0425
16 June[a]	0.4835 ± 0.0195	−1.9060 ± 0.1103	0.1837 ± 0.0132	6.0150 ± 0.0433
17 June[a]	0.5258 ± 0.0211	−2.1610 ± 0.1192	0.1881 ± 0.0143	6.0250 ± 0.0416
18 June[a]	0.5418 ± 0.0224	−2.2660 ± 0.1265	0.1933 ± 0.0151	6.0220 ± 0.0428
1997				
18 June[b]	0.3453 ± 0.0068	−1.8570 ± 0.0430	nd	nd
19 June[b]	0.3464 ± 0.0061	−1.9300 ± 0.0387	nd	nd
20 June[c]	0.3939 ± 0.0048	−2.2990 ± 0.0307	nd	nd
1 July[d]	0.4156 ± 0.0047	−2.5530 ± 0.0301	nd	nd
2 July[e]	0.3811 ± 0.0096	−2.3390 ± 0.0612	nd	nd
3 July[f]	0.4530 ± 0.0051	−2.8570 ± 0.0323	nd	nd
12 July[g]	0.3510 ± 0.0062	−1.7830 ± 0.0394	nd	nd
13 July[h]	0.3731 ± 0.0053	−2.1070 ± 0.0336	nd	nd
14 July[h]	0.3818 ± 0.0054	−2.2410 ± 0.0345	nd	nd
15 July[g]	0.3578 ± 0.0062	−2.2540 ± 0.0391	nd	nd

[a] The same letter in the superscript means that the slopes are not significantly different at the significance level 0.05.

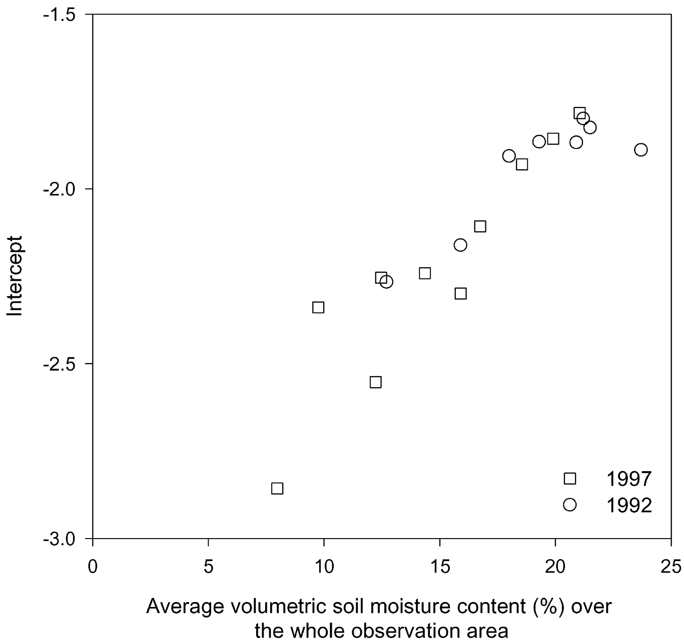

Fig. 8. Effect of the drydown on the intercepts of the 'within-cell variance — cell area' dependencies for soil moisture.

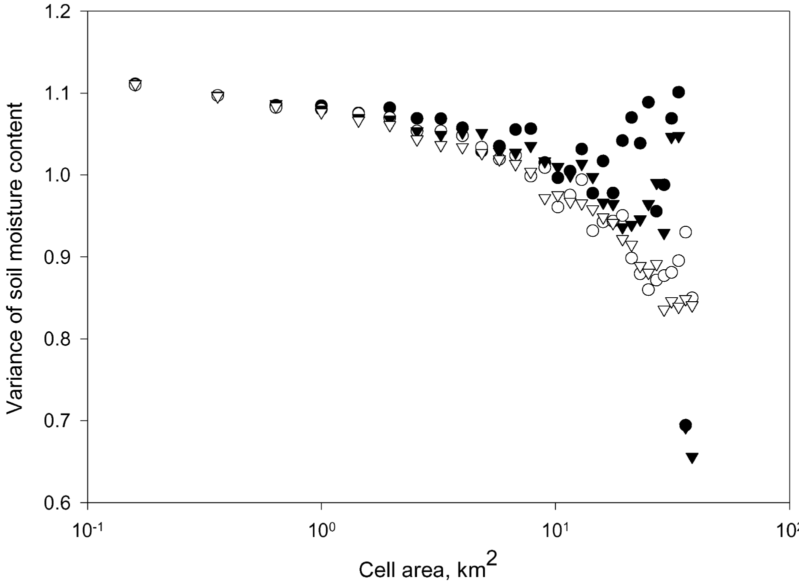

Fig. 9. Effect of the data filtering on the dependencies of the variance of soil moisture content on the cell area; ○, ● — cells do not overlap, ▽, ▼ — cells half-overlap; ●, ▼ — a cell is discarded if at least one original pixel within it has missing data, ○, ▽ — a cell is discarded if at least half of the original pixels within it have missing data.

the intercepts of the intercellular variability shown in Fig. 3, the intercepts of the intracellular variability were comparable in 1992 and 1997 (Fig. 8).

Some effects of the cell-discarding strategy on the scaling relationships are shown in Fig. 9. Discarding cells in which at least half of the original pixels had missing data was compared with discarding cells in which at least one original pixel had missing data (Dubayah et al., 1997). Using the half-overlapping cells was compared with using non-overlapping cells. Fig. 9 shows that the biggest differences develop when the cells are large. The effect of overlapping strategy is not large. Discarding cells with at least one missing data breaks the linearity earlier, and creates an irregular pattern at large cell sizes.

Data of 1992 and 1997 had different original resolution of 200 and 400 m. Aggregating data of 1992 to 400 m resolution resulted in variability that still was much higher than the resolution of 1997. We note that the difference in the original resolution pertains to the soil brightness temperature rather than to soil moisture content. Aggregating soil moisture values derived from the brightness temperature values is equivalent to aggregating soil brightness temperature only if the relationship between brightness temperature and soil moisture is linear. Jackson (2001) indicated that, although the linearity of the 'brightness temperature–soil moisture' is generally acknowledged, this may be not true when the vegetation is present and the land cover is mixed. Analysis in this paper showed, that although effects of the land cover were more apparent at higher resolutions, the same relationship between soil moisture and brightness temperature could be applied at all resolutions studied in this work.

What causes the differences in scaling before the drying period starts — or after the end of rains in the area — remains a challenging question. Although soil texture in the region also exhibits multiscaling behavior (data not shown), this would not change between 1992 and 1997. Therefore, differences in rainfall, vegetation, and initial soil water content should be examined as sources of scaling. Data on the spatial distribution of rainfall data for 1992 presented by Mattikalli et al. (1998) show similarity in amounts of rainfall received in the western and eastern part of the area. We compared data from the two rain gauge stations in 1992 with the data measured by ARS Micronet stations for the 1997 experiment (ftp://164.58.150.49/pub/sgp97/micronet, data not shown). Contrary to 1992, the rainfall distribution was diverse during the SGP97 experiment. The western part of the Little Washita area received substantially more rainfall compared to the eastern section. This difference was especially pronounced during the rainfall event on 10th July. Unfortunately we do not have enough rainfall data to establish spatial properties of the rainfall. Results of Gupta and Waymire (1990, 1993) show that rainfall intensity can be multifractal. It would be interesting to explore how multiscaling patterns in rainfall, soil cover, and, possibly, vegetation may interact to generate a multifractal pattern in surface soil moisture.

The data on scaling in 1992 and 1997 have one important common feature: once a dependency on resolution is established at the beginning of a drying period, its shape is maintained during the drydown. This empirical evidence warrants the further studies to understand reasons of the persistence in shapes of scaling dependencies and factors that form this shape before a drydown starts. Slopes of the dependencies change only slightly, whereas the intercepts decrease as the drying progresses. This implies that if the slope is found from an image of the first day of a drydown, it can be used with reasonable accuracy on the following days of the drying period. The rate of the decrease of the intercept seems to be the same per unit of decrease in soil moisture. The shape of the scaling dependencies remains the same during drydowns, and that gives an opportunity to reduce the volume of observations needed to predict scaling of surface soil moisture during drydowns.

References

Blöschl, G., Sivapalan, M., 1995. Scale issues in hydrological modelling: a Review. Hydrological Processes 9, 251–290.

Charpentier, A.C., Groffman, P.M., 1992. Soil moisture variability within remote sensing pixels. Journal of Geophysical Research 97 (D17), 18,987–18,995.

Cosh, M.H., Brutsaert, W., 1999. Aspects of soil moisture variability in the Washita '92 study region. Journal of Geophysical Research 104, 19,751–19,757.

Crow, W.T., Wood, E.F., 2000. Impacts of upscaling soil moisture during SGP'97. AGU Spring 2000 Meeting, American Geophysical Union, Washington, DC.

Daniel, C., Wood, F.S., 1973. Fitting Equations to Data. Wiley-Interscience, New York.

Dubayah, R., Wood, E.F., Lavallee, D., 1997. Multiscaling analysis in distributed modeling and remote sensing: an application using soil moisture. In: Quatrocchi, D.A., Goodchild, M. (Eds.). Scale in Remote Sensing and GIS. Lewis Publishers, New York, pp. 93–112.

Golden Software Inc., 1999. Surfer Version 7.00, Surface Mapping System, Golden, Colorado.

Gupta, V.K., Waymire, E.C., 1990. Multiscaling properties of spatial rainfall and river flow distribution. Journal of Geophysical Research 95, 1999–2009.

Gupta, V.K., Waymire, E.C., 1993. A statitical analysis of mesoscale rainfall as a random cascade. Journal of Applied Meteorology 32, 251–267.

Hu, Z., Islam, S., Cheng, Y., 1997. Statistical characterization of remotely sensed soil moisture images. Remote Sensing of Environment 61, 310–318.

Jackson, T.J., 1993. Measuring surface soil moisture using passive microwave remote sensing. Hydrological Processes 7, 139–152.

Jackson, T.J., 2001. Multiple resolution analysis of L-band brightness temperature for soil moisture. IEEE Transactions on Geoscience and Remote Sensing 39, 151–164.

Jackson, T.J., Le Vine, D.M., Swift, C.T., Schmugge, T.J., Schiebe, F.R., 1995. Large area mapping of soil moisture using the ESTAR passive microwave radiometer in Washita '92. Remote Sensing of Environment 53, 27–37.

Jackson, T.J., Le Vine, D.M., Hsu, A.Y., Oldak, A., Swift, C.T., Isham, J., Haken, M., 1999. Soil moisture mapping at regional scales using microwave radiometry: the Southern Great Plains Hydrology Experiment. IEEE Transaction on Geoscience and Remote Sensing 37, 2136–2151.

Kumar, P., 1999. A multiple scale state-space model for characterizing subgrid scale variability of near-surface soil moisture. IEEE Transactions on Geoscience and Remote Sensing 37, 182–197.

Le Vine, D.M., Griffis, A.J., Calvin, T.S., Jackson, T.J., 1994. Estar: a synthetic aperture microwave radiometer for remote sensing applications. Proceedings of the IEEE 82, 1787–1801.

Malinverno, A., 1990. A simple method to estimate the fractal dimension of a self-affine series. Geophysical Research Letters 17, 1953–1956.

Mattikalli, N.M., Engman, E.T., Jackson, T.J., Ahuja, L.R., 1998. Microwave remote sensing of temporal variations of brightness temperature and near-surface water content during a watershed scale field experiment, and its application to the estimation of soil physical properties. Water Resource Research 34, 2289–2299.

Neter, J., Wasserman, W., 1974. Linear Statistical models. Richard D. Irwin, Inc, Homewood.

Rodriguez-Iturbe, I., Vogel, G.K., Rigon, R., Entekhabi, D., Castelli, F., Rinaldo, A., 1995. On the spatial organization of soil moisture fields. Geophysical Research Letters 22 (20), 2757–2760.

Schmugge, T.J., Jackson, T.J., McKim, H.L., 1980. Survey of methods for soil moisture determination. Water Resource Research 16, 961–969.