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Temporal dynamics of PSR-based soil moisture across spatial scales in an agricultural landscape during SMEX02: A wavelet approach

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Abstract

In this study, we examined the characteristics of soil moisture dynamics of wet and dry fields across hierarchical spatial scales within the region of Soil Moisture Experiment 2002 (SMEX02) hydrology campaign in Iowa. The Polarimetric Scanning Radiometer (PSR)-based remotely sensed surface (~0–5 cm) soil moisture at 800 m × 800 m resolution was used in this study. Wavelet-based multiresolution technique decomposed the soil moisture into large-scale mean soil moisture fields and fluctuations in horizontal, diagonal, and vertical directions at hierarchical spatial resolutions. Results suggested linearity in the log–log dependency of the variance of soil moisture up to a resolution of 6400 m × 6400 m on PSR sampling dates during SMEX02. The wet fields (with high soil moisture) show almost similar variance for all the resolutions signifying the strong spatial correlation. Analysis of the dry fields (with low soil moisture) indicated a log–log linearity of moments with various scales, and the slopes of these relationships exhibit a concave functional form with the order of moments, typically representing a multiscaling process. The scaling exponent of soil moisture during dry-down suggests a transition from simple scaling (in wet fields) to multiscaling (in dry fields) behavior. The fluctuation components of multiresolution analysis in the horizontal, diagonal, and vertical directions for dry and wet fields exhibited self-similarity. Another important finding of this study is the increase of subpixel soil moisture variability with increasing resolution, especially for the wet fields. These findings will help develop appropriate up-and down-scaling schemes of remotely sensed soil moisture data for various hydrologic and environmental modeling applications.
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Keywords: Remote sensing; PSR; Spatial scaling; Soil moisture; Passive microwave remote sensing; Agricultural landscape

1. Introduction

Soil moisture in shallow subsurface is a key state variable that affects hydrological, ecological, and meteorological processes ranging from local land–atmosphere interaction to global water cycle. Soil moisture is highly variable across space scales of few meters to kilometers and time scales of minutes to months. Significant amount of *in situ* and remote sensing research have been conducted to observe and characterize soil moisture at various spatio-temporal scales (Charpentier & Groffman, 1992; Cosh & Brutsaert, 1999; Famiglietti et al., 1999; Hu et al., 1997; Mohanty & Skaggs, 2001; Oldak et al., 2002). Soil moisture pattern (distribution) at a particular spatio-temporal scale evolves from interactions among different geophysical parameters, i.e., soil, topography, rainfall, and vegetation (Dubayah et al., 1997; Western et al., 2002). Despite the fact that soil moisture always exhibits spatio-temporal variability due to overlapping (governing) geophysical parameters, our knowledge of scaling characteristics of soil moisture variation is rather limited. In literature, a number of contradictions appear about the influence of these geophysical parameters on soil moisture variability.

With respect to soil and its properties, it always exhibits significant spatial variability that characterizes soil moisture transport processes. Soil was conceptualized as a hierarchical heterogeneous medium with discrete spatial scale by Cushman (1990), and Roth et al. (1999). They argued natural pattern of soil variability may exhibit embedded, organizational structures that lead to non-stationary soil properties and processes. With an increase of spatial scale, soil properties typically become non-

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stationary. The soil properties may change from deterministic at smaller scale to random at larger scale, with the small scale variation filtered out by larger scale processes (Kavvas, 1999). Rodriguez-Iturbe et al. (1995) also suggested that the spatial organization of soil moisture is a consequence of soil properties. Tomer et al. (2006) found significant correlation between soil properties and soil moisture at watershed scale. Temporal stability in soil moisture patterns can be associated with the arrangement soil types and textures on the landscape scale (da Silva et al., 2001). Also, soil texture is related to topographical attributes such as surface curvature, slope, and elevation. These attributes define the functional organization of soil hydrological processes, and in turn soil moisture variability.

Studies (Famiglietti et al., 1998; Hawley et al., 1983) have shown topographical characteristics have control on spatial variation of soil moisture. Topographic attributes reflecting lateral flows and accumulations at the landscape scale have been statistically related to soil moisture (Tomer and Anderson, 1995) and water retention characteristics (Pachepsky et al., 2001). Western and Blöschl (1999) found the proportion of variation in soil moisture accounted by terrain indices varied from 22 to 61%, depending on average soil moisture. However, Charpentier and Groffman (1992), Niemann and Edgell (1993), and Western et al. (2003) reported no systematic relationship between topography and soil moisture. Chang and Islam (2003) demonstrated that soil physical properties and topography control spatial variations of soil moisture over large areas. They have shown, topographical control will dictate soil moisture distribution under wet conditions, and soil physical properties control variations of soil moisture under relatively dry conditions. Numerous studies (e.g., Henninger et al., 1976; Nyberg, 1996; Robinson & Dean, 1993) have reported negative correlations between soil moisture and topographical attributes i.e., elevation and slope.. This correlation is smaller for finer texture soil and larger for coarser texture soil. The spatio-temporal controls of soil properties and topography on variability of soil moisture are induced by precipitation event and its characteristics (i.e., amount, rate, and spatial variability). Because of the extreme complexity in the inherent relationships among precipitation, soil moisture, and land–atmosphere feedback, relations of soil moisture to subsequent precipitation events are also significant.

The state and evolution of soil moisture are primarily forced by precipitation which is the major source of space and time variability in the hydrologic cycle. Past studies (Gupta & Waymire, 1990; Kumar & Foufoula-Georgiou, 1993a,b; Waymire et al., 1984) investigated the space–time rainfall characteristics at the ground level and have suggested multi-scaling properties. It is conceivable that this attribute of precipitation in conjunction with other geophysical variables may introduce complicated scaling properties in soil moisture depending on spatial scales. At spatial scales of 100 m to kilometers, soil moisture variability could be found due to spatial variability in precipitation events. Sellers et al. (1995) presented spatial heterogeneity introduced by rainfall and removed through dry-down dynamics. At much larger scales, generally variations in precipitation leads to substantial changes in soil moisture conditions between climate regions.

Vegetation also influences soil moisture spatio-temporal variability. Among others, Mohanty et al. (2000) and Qui et al. (2001) have shown that soil moisture responds to variation in vegetation. The primary effect of vegetation is evapotranspiration from the soil profile. During transpiration, vegetation root water uptake is largely controlled by soil moisture status and its spatial (horizontal–vertical) variability. Root and soil interaction tends to homogenize soil water content in the root zone. Infiltration properties of soil are influenced by vegetation at the plant scale (Seyfried & Wilcox, 1995). With the increase in spatial scale, soil moisture variability is affected by variation in vegetation shifts from plant to patch to the community scale.

All these geophysical variables (soil, topography, rainfall, and vegetation) typically interact in a complex fashion to make soil moisture highly variable and introduce nonlinearity in soil moisture dependent processes. Thus, scaling of soil moisture is poorly understood and is difficult to measure and model in a comprehensive manner (Dubayah et al., 1997).

Several studies were conducted to understand the spatio-temporal scale dynamics of soil moisture. Rodriguez-Iturbe et al. (1995) studied and characterized the spatial pattern of soil moisture, and concluded that the variance of soil moisture follows a power law decay, typical of scaling processes, as a function of area over which soil moisture is observed. It results in a linear relation between variance and observation scale, when plotted on a log scale. Hu et al. (1998) used multi-resolution analysis to investigate the scale variation of soil moisture by decomposing soil moisture images into average large-scale and detailed small-scale fluctuation components. They found that average large-scale soil moisture was non-stationary at the scale studied (30 m to 10 km) and the small-scale fluctuations exhibited simple scaling process, while the overall soil moisture variability exhibited multiscaling properties. Kumar (1999) used estimation techniques based on multi-resolution tree to characterize the subgrid variability of soil moisture at multiple scales by combining information, such as soil moisture measurements and soil hydrologic properties available at different scales. Western and Blöschl (1999) examined the effect on the apparent spatial statistical properties of soil moisture (variance and correlation length) with changing measurement scale in terms of spacing (distance between samples), extent (overall coverage), and support (integration area). They found the effect of spatial extent on the correlation length is most important among the three (extent, support, and spacing). The apparent variance increases with increasing extent, decreases with increasing support, and does not change with spacing. Cosh and Brutsaert (1999) showed that grouping soil by textural class was useful to characterize the soil moisture field and their dynamics into groups with different statistical properties. Famiglietti et al. (1999) used ground-based point-scale soil moisture measurements during SGP97 campaign within six selected Electronically Scanned Thinned Array Radiometer (ESTAR) footprints to investigate within-pixel variability of soil moisture data. They found significant variability in soil moisture because of different combinations of soil type, vegetation cover, management practice, and rainfall gradient. Mohanty and Skaggs (2001) also used ground-based

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