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Investigating soil controls on soil moisture spatial variability: Numerical simulations and field observations

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SUMMARY

Due to its complex interactions with various processes and factors, soil moisture exhibits significant spatial variability across different spatial scales. In this study, a modeling approach and field observations were used to examine the soil control on the relationship between mean ($\bar{\theta}$) and standard deviation (σ_θ) of soil moisture content. For the numerical experiments, a 1-D vadose zone model along with van Genuchten parameters generated by pedotransfer functions was used for simulating soil moisture dynamics under different climate and surface conditions. To force the model, hydrometeorological and physiological data that spanned over three years from five research sites within the continental US were used. The modeling results showed that under bare surface conditions, different forms of the $\bar{\theta}$–σ_θ relationship as observed in experimental studies were produced. For finer soils, a positive $\bar{\theta}$–σ_θ relationship gradually changed to an upward convex and a negative one from arid to humid conditions; whereas, a positive relationship existed for coarser soils, regardless of climatic conditions. The maximum σ_θ for finer soils was larger under semiarid conditions than under arid and humid conditions, while the maximum σ_θ for coarser soils increased with increasing precipitation. Moreover, vegetation tended to reduce $\bar{\theta}$ and σ_θ, and thus affected the $\bar{\theta}$–σ_θ relationship. A sensitivity analysis was also conducted to examine the controls of different van Genuchten parameters on the $\bar{\theta}$–σ_θ relationship under bare surface conditions. It was found that the residual soil moisture content mainly affected σ_θ under dry conditions, while the saturated soil moisture content and the saturated hydraulic conductivity largely controlled σ_θ under wet conditions. Importantly, the upward convex $\bar{\theta}$–σ_θ relationship was mostly caused by the shape factor n that accounts for pore size distribution. Finally, measured soil moisture data from a semiarid region were retrieved from the Automated Weather Data Network. The observed moisture data showed that based on soil texture, a positive $\bar{\theta}$–σ_θ relationship existed for sandy soils, while an upward convex one was observed for silty soils. The difference in the observed $\bar{\theta}$–$sigma_\theta$ relationship can be attributed to the differences in water holding capacities between sand and silt, which is consistent with the modeling results. The field data also revealed that increasing spatial variability in soil texture led to increased variability in soil moisture (e.g., the maximum σ_θ). Therefore, the effect of soil texture for verifying remotely sensed soil moisture products should be considered.

1. Introduction

Soil moisture interacts with a range of land surface processes (e.g., precipitation, evapotranspiration, and land surface energy fluxes) in a highly nonlinear manner (Western et al., 2002; Seneviratne et al., 2010). Furthermore, soil moisture dynamics is affected by a number of local factors, such as soil properties, vegetation, and topography (c.f., Vanderlinden et al., 2012; Vereecken et al., 2014). As a result, soil moisture exhibits significant spatiotemporal variability, even at field scales. To meet demands from various research fields (e.g., verifying and downscaling remotely sensed soil moisture data, and validating hydrological and land surface models), considerable efforts have been devoted to understanding spatial patterns of soil moisture across different spatial scales, particularly regarding the relationships among different statistical moments of soil moisture fields (e.g., Famiglietti et al., 1998, 2008; Hupet and Vanclooster, 2002; Teuling and Troch, 2005; Brocca et al., 2007; Choi et al., 2007; Lawrence and Hornberger, 2007; Teuling et al., 2007; Rosenbaum et al., 2012; Li and Rodell, 2013).

One important aspect of studying soil moisture spatial variability (SMSV) is to understand its dependence on mean soil moisture content ($\bar{\theta}$). Several relationships between SMSV (indicated by

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variance or standard deviation) and $\bar{\theta}$ have been observed in field studies. Famiglietti et al. (1998) and Martinez-Fernandez and Ceballos (2003) presented a positive relationship between SMSV and $\bar{\theta}$, while Hupet and Vanclooster (2002) and Brocca et al. (2007) showed an opposite one. Moreover, an upward convex relationship that shows both positive and negative relationships was also reported (Famiglietti et al., 2008; Rosenbaum et al., 2012). Those contradictory observations can be attributed to the contrasting conditions (e.g., soil, vegetation, and climate) across different sites. Due to the complexity of soil water systems, numerical models are usually used to quantify various controls on the relationship between SMSV and $\bar{\theta}$. Based on a bucket model, Teuling and Troch (2005) showed that soil and vegetation could either destroy or create SMSV depending on moisture conditions, and thus control the relationship between SMSV and $\bar{\theta}$. In a following study, Teuling et al. (2007) further revealed that interannual climate variability also affected the relationship pattern of SMSV with $\bar{\theta}$. Using the same bucket model, Lawrence and Hornberger (2007) performed a sensitivity analysis of SMSV to several soil parameters (e.g., wilting point, porosity, and saturated hydraulic conductivity-K_S), and found that the controls of those parameters on the SMSV–$\bar{\theta}$ relationship varied under different moisture conditions. In a theoretical study, Vereecken et al. (2007) used an analytical solution of a stochastic flow model developed by Zhang et al. (1998) to evaluate the controls of the Brooks–Corey parameters on the SMSV–$\bar{\theta}$ relationship, and showed that the soil parameter accounting for pore size distribution mainly controlled the shape of the SMSV–$\bar{\theta}$ curve. Overall, previous modeling studies suggest that soil, vegetation, and climate are the primary factors affecting the relationship between SMSV and $\bar{\theta}$, although it should be noted that topography is usually not considered in those studies with few exceptions (e.g., Lawrence and Hornberger, 2007).

In a recent attempt, a robust mechanistic model that is based on the Richards equation was used by Martinez et al. (2014) to examine soil controls on the SMSV–$\bar{\theta}$ relationship. To account for spatial variability in soil hydraulic properties, the authors used log-normal distributions of K_S, and showed that $\bar{\theta}$, at which the maximum value of SMSV occurred, depended on soil texture. Essentially, Martinez et al. (2014) performed a sensitivity analysis of SMSV to K_S for different soil textures. However, as noticed by Martinez et al. (2013), simulated soil moisture patterns are likely to deviate from field observations if only ln K_S is varied. Moreover, previous studies suggest that other soil hydraulic parameters might play more important roles in controlling soil moisture fluxes and dynamics, especially under dry conditions (Lawrence and Hornberger, 2007; Vereecken et al., 2007; Pollacco et al., 2008; Wang, 2014; Wang et al., 2015a). Therefore, a need still exists to evaluate the controls of various soil hydraulic parameters (e.g., in the van Genuchten model) on the SMSV–$\bar{\theta}$ relationship under different climatic conditions.

Besides modeling efforts, field observations are also crucial for understanding different controls on SMSV and its relationship with $\bar{\theta}$. Famiglietti et al. (2008) investigated the SMSV–$\bar{\theta}$ relationship at spatial scales ranging from 2.5 m to 50 km using field observations, and showed that an upward convex relationship existed at the 800-m and 50-km scales. Li and Rodell (2013) used the SCAN moisture data across the continental US and discussed the effect of climate on the SMSV–$\bar{\theta}$ relationship. The authors showed that the upward convex relationship only existed when soil moisture data from different climate zones were combined together. In spite of previous modeling and field studies, there is still a lack of field evidence as to whether soil (e.g., soil texture) controls the SMSV–$\bar{\theta}$ relationship as demonstrated by modeling results.

The main purposes of this study were two-fold: (1) to evaluate the soil controls on the SMSV–$\bar{\theta}$ relationship under different climate and surface conditions using a modeling approach, and (2) to test the modeling results using field observations. For the first purpose, soil datasets containing van Genuchten parameters were first generated by pedotransfer functions for four selected soil textures and a process-based vadose zone model was then used to simulate soil moisture dynamics under different climate and surface conditions. To force the vadose zone model, hydrometeorological and physiological data that spanned over three years were obtained from five research sites within the continental US. In addition, the controls of different van Genuchten parameters on the SMSV–$\bar{\theta}$ relationship were assessed at the five study sites. For the second purpose, observed soil moisture data were retrieved from the Automated Weather Data Network (AWDN). Based on soil texture classifications at the AWDN sites, the relationship of SMSV with $\bar{\theta}$ was investigated using the observed data.

2. Methods and materials

2.1. Model description

Similar to the work of Martinez et al. (2013, 2014) and Wang (2014), the Hydrus-1D model (Simunek et al., 2005) was chosen in this study for simulating soil moisture dynamics. The Hydrus-1D model is based on the 1-D Richards equation and can simulate vertical soil moisture flow in porous media:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[K(h)\left(\frac{\partial h}{\partial x}\right)-K(h)\right]-S(h) \tag{1}$$

where θ [L^3/L^3] is volumetric moisture content, t [T] is time, x [L] is spatial coordinate, h [L] is pressure head, K [L/T] is hydraulic conductivity, and S [1/T] is root water uptake. At the surface, an atmospheric boundary condition was imposed, and surface runoff was immediately removed (i.e., without ponding), when precipitation exceeded soil infiltration capacity or soil was saturated. At the lower boundary, a unit hydraulic gradient condition was applied. The length of simulated soil columns was 5 m with a total of 501 spatial nodes evenly distributed across the soil columns.

Both bare surface and vegetated conditions were considered in this study. Under bare surface conditions, potential soil evaporation (E_p) was equal to potential evapotranspiration (ET_p). Under vegetated conditions, ET_p was partitioned between potential transpiration (T_p) and E_p according to Beer's law:

$$E_p(t)=ET_p(t)\times e^{-k\times LAI(t)} \tag{2}$$

$$T_p(t)=ET_p(t)-E_p(t) \tag{3}$$

where k is an extinction coefficient and $k = 0.5$ was used in this study, and LAI is leaf area index [m^2/m^2]. The root water uptake $S(h)$ was simulated according to the method of Feddes et al. (1978):

$$S(h)=\beta(h)\times S_p \tag{4}$$

where $\beta(h)$ is a dimensionless function with a range from 0 to 1, and S_p [1/T] is potential root water uptake and assumed to be equal to T_p. The distribution of S_p over the root zone was based on root density distributions.

2.2. Model parameters and hydrometeorological forcing

The van Genuchten model (Mualem, 1976; van Genuchten, 1980) was used in this study to describe the constitutive relations among θ, h, and K in Eq. (1):