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Effect of soil hydraulic properties on the relationship between the spatial mean and variability of soil moisture

Gonzalo Martínez García [a,b,*], Yakov A. Pachepsky [b,1], Harry Vereecken [c,2]

[a] Dept. of Agronomy, University of Cordoba, Ctra. Madrid, km 396, 14071 Córdoba, Spain
[b] USDA-ARS – Environmental Microbial and Food Safety Lab, 10300 Baltimore Avenue, BARC-East Bldg. 173, Beltsville, MD 20705, USA
[c] Agrosphere (IBG-3), Institute of Bio- and Geosciences, Forschungszentrum Jülich GmbH, IBG-3, 52428 Jülich, Germany

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SUMMARY

Knowledge of spatial mean soil moisture and its variability over time is needed in many environmental applications. We analyzed dependencies of soil moisture variability on average soil moisture contents in soils with and without root water uptake using ensembles of non-stationary water flow simulations by varying soil hydraulic properties under different climatic conditions. We focused on the dry end of the soil moisture range and found that the magnitude of soil moisture variability was controlled by the interplay of soil hydraulic properties and climate. The average moisture at which the maximum variability occurred depended on soil hydraulic properties and vegetation. A positive linear relationship was observed between mean soil moisture and its standard deviation and was controlled by the parameter defining the shape of soil water retention curves and the spatial variability of saturated hydraulic conductivity. The influence of other controls, such as variable weather patterns, topography or lateral flow processes needs to be studied further to see if such relationship persists and could be used for the inference of soil hydraulic properties from the spatiotemporal variation in soil moisture.

1. Introduction

Understanding topsoil water content variability is critical for improving the performance of hydrologic and atmospheric models and for up- and down-scaling remotely sensed soil moisture (Vereecken et al., 2008). Surface soil moisture variability has been shown to be related with spatially-averaged soil moisture content and that has been demonstrated at different scales (Choi et al., 2007; Famiglietti et al., 2008, 1999; Martinez-Fernández and Ceballos, 2003; Mittelbach and Seneviratne, 2012; Rosenbaum et al., 2012; Teuling and Troch, 2005; Vereecken et al., 2007).

Soil water content spatial variability was shown to be affected by several local and non-local factors (Grayson et al., 1997). Such controls are: vegetation (Teuling and Troch, 2005), climate (Teuling et al., 2007a), soil hydraulic properties (Vereecken et al., 2007), topography (Grayson et al., 1997) and antecedent soil moisture (Ivanov et al., 2010). Contradictory reports have been published on the shape of the relationship between the spatial mean soil moisture ($\langle\theta\rangle$) and its variability (σ_θ). Works can be found that report an increasing variability with decreasing mean moisture (Famiglietti et al., 1999), decreasing variability with decreasing mean moisture (Martinez-Fernández and Ceballos, 2003) and an increase up to a certain value of $\langle\theta\rangle$ followed by a decrease (Brocca et al., 2010, 2012; Rosenbaum et al., 2012). The range of soil moisture measured in each case (dry or wet states or the full range of soil moisture) can be one of reasons for such differences. The body of literature that addressed this topic for more than a decade (from Famiglietti et al., 1998 to Rosenbaum et al., 2012) generally shows that the graph of this relationship is typically convex (Choi et al., 2007; Rosenbaum et al., 2012; Teuling and Troch, 2005). Regression models for the 'σ_θ–$\langle\theta\rangle$' (referred as σ_θ from here after) relationship have been proposed, including an exponential model (Famiglietti et al., 2008), a third-order polynomial (Rosenbaum et al., 2012) and a linear equation for the dry-end (Teuling et al., 2007b).

Soil properties, and more specifically soil hydraulic properties-related parameters, often had the largest influence on the variability of soil moisture (Choi et al., 2007). The dependence of the standard deviation of soil moisture σ_θ on average soil moisture as affected by soil hydraulic properties was previously studied by

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* Corresponding author at: USDA-ARS – Environmental Microbial and Food Safety Lab, 10300 Baltimore Avenue, BARC-East Bldg. 173, Beltsville, MD 20705, USA. Tel.: +1 301 504 5841.

E-mail addresses: Gonzalo.Martinez@ars.usda.gov, z42magag@uco.es (G. Martínez García).

[1] Tel.: +1 301 504 7468.

[2] Tel.: +49 2461 61 4570.

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Vereecken et al. (2007) using an analytical solution of a stochastic steady state flow model. They used the Brooks-Corey moisture retention characteristic parameters, the saturated hydraulic conductivity and joint-Gaussian spatial distribution of hydraulic parameters with exponential covariance functions and negligible correlation between the hydraulic parameters. They found that the mean water content at which the standard deviation became maximal depended on the shape parameters of the moisture retention characteristic. More specifically, on the parameter describing the pore-size distribution of soils. This work was based on results of the work of Zhang et al. (1998), which stemmed from strong assumptions of stationary flow, gravity-dominated flow, and spatial autocorrelation of parameters. These assumptions are hardly appicable to dry conditions, and using modeling of non-stationary flow with evaporation dominating most of the time may provide more realistic information about soil moisture variability in time and space. In dry conditions, there exists a decoupling of the rate of drying and the vertical profiles of soil moisture in the topsoil (Capehart and Carlson, 1997). This type of conditions are predominant in arid and semiarid conditions.

The objective of this work was to examine the effects of soil texture and climate in the σ_θ for a non-stationary flow model framework. We provide also an explanation to the differences observed in the literature regarding the positive or negative relationship between σ_θ and $\langle\theta\rangle$. Finally, we show that the linearization of the dry part of the relationship σ_θ may be useful to evaluate and estimate soil hydraulic properties and more specifically the spatial variability of K_s and the parameter "n" that measures the pore-size distribution in the van-Genuchten model.

2. Methods

2.1. Simulations setup

We used the HYDRUS code (Šimůnek and van Genuchten, 2008) to simulate water flow by solving the Richard equation numerically. Time-dependent atmospheric boundary conditions were imposed at the soil surface and a constant head boundary condition was imposed at the bottom of a 3-m depth profile. The Initial condition was obtained from a spin up model run of 1 year. Simulations were performed in a 1-D soil profile with homogeneous properties. The profile was deep enough to make the soil moisture of the top 1 m layer insensitive to the bottom boundary condition.

We used different climatic conditions to run our simulations. For that, we generated the corresponding time series of daily rainfall, maximum and minimum temperatures, and solar radiation with the CLIGEN weather generator (Nicks et al., 1995). The daily potential evapotranspiration was calculated following a modified version of the Hargreaves equation (Williams et al., 2008). Selected climates were: humid subtropical (Cfa), humid continental (Dfa), cold semiarid (BSk) and hot semiarid (BWh). Humid subtropical weather (Cfa) is characterized by mild temperatures, with a minimum temperature during the coldest month between −3 and 18 °C, warm summer and rainfall occurring during most of the year. Humid continental (Dfa) weather alike the Cfa has rainfalls during the whole year, the main difference between the two is in temperatures with an average temperature during the coldest month below -3 °C. Dry (semiarid and arid) climates are represented by the BSk (steppe) and BWh (dessert) climates and are characterized by higher potential evapotranspiration than precipitation. The main difference between them comes from the magnitude of dryness and the temperatures. Representative locations for those climates were College station (TX), 30.58°N, 93.35°W, 94 msl for the Cfa, Indianapolis (IN), 39.73°N, 86.27°W, 240 msl for the Dfa, Moscow (ID), 46.73°N, 117.00°W, 801 msl for the BSk, and Tucson (AZ, 32.25°N, 110.83°W, 771 msl) for the BWh. The monthly parameters defining their weather (means, standard deviations, skewness, etc.) were obtained from the CLIGEN database. Fig. 1 shows the generated time series of rainfall and evapotransporation.

Sets of parameters corresponding to seven soil textural classes were used in the analysis (Table 1) and the van Genuchten–Mualem model was chosen for the soil hydraulic properties. For a particular soil and climate we ran an ensemble of models defined with variable saturated hydraulic conductivity (K_s), following the commonly encountered lognormal distribution (Jury, 1985). The value of the spatial variability of $\ln K_s$ ($\sigma_{\ln Ks}$) used in the simulations was 0.8 as it lies inside the range observed for most of the soils (Cosby et al., 1984). Values of $\sigma_{\ln Ks}$ between 0.2 and 1 were also used to illustrate the effect of increasing $\sigma_{\ln Ks}$ on the σ_θ for a soil with the hydraulic properties of the loamy soils and the cold semiarid weather. We simulated spatial variability through an array of point and one-dimensional profiles by fixing soil moisture characteristic parameters and varying K_s.

We used a double porosity model to account for the effects of macropores on preferential flow (Jiang et al., 2010) for the silty clay loam soil following the model proposed by Durner (1994). This model divides the porous medium into two or more overlapping regions in which a van Genuchten–Mualem type of model (Eq. (1)) of the soil hydraulic properties is used.

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha|h|)^n\right]^{1-1/n}} \tag{1}$$

where θ_s and θ_r are the saturation and residual soil moisture respectively [$L^3\ L^{-3}$], h is suction pressure [L], α is related to the inverse of the air entry suction [L^{-1}] and n is a measure of the pore-size distribution (dimensionless). We assumed that macropores account for 5% of the entire pore space that α for the macropores is 100 times larger than for the micropores and n is also larger for the macropores than for the micropores following a similar approach as in Šimůnek and van Genuchten (2008) for fine-textural soils.

We performed simulations of the loamy soil with vegetation also, besides the bare soil cases, to evaluate the effect of evapotranspiration on σ_θ. For that, we simulated root water uptake from a well-established grass (100% soil surface coverage) with a root system extending homogenously to a depth of 0.5 m, under the humid continental weather and with the loamy soil. The imposed rainfall, evaporation or evapotranspiration was kept homogenous throughout all the simulations.

2.2. Data analysis

One-year data of simulated soil moistures for the 0–5 cm depth were used for the analysis as this is widely used depth in many of the remote sensing works for validation of soil moisture products, e.g. Famiglietti et al. (1998) or Teuling et al. (2007a). A spin-up period of one year was chosen to avoid the effect of the initial conditions on the simulated soil moisture data. For each day of simulation we computed the average (average across all different K_s runs) soil moisture for the 0–5 cm depth of the ensemble of simulations and its standard deviation to obtain the σ_θ relationship. We evaluated the effect of increasing the simulation period from one year to two on σ_θ and did not observed any relevant difference.

To illustrate the effect of a different $\sigma_{\ln Ks}$ and to compare effects of soil hydraulic properties and climate we limited our analysis of the σ_θ to its dry part. Tuller and Or (2001) suggested that the dependence of K_s on matric potential changes from capillary flow to film flow. Although film flow might become important in the dry range, we speculate that it would not affect the general tendency in that part and it might not affect the scaling of K_s