Comment on "Field observations of soil moisture variability across scales" by James S. Famiglietti et al.

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1. Introduction

[1] In a recent paper, *Famiglietti et al.* [2008] analyzed more than 36,000 ground-based soil moisture measurements to characterize soil moisture variability across spatial scales ranging from 2.5 m to 50 km. They concluded that the relationship between soil moisture standard deviation versus mean moisture content, σ_θ ($\langle\theta\rangle$), has a convex upward behavior with maximum values occurring at mean moisture contents of 0.17 cm^3 cm^{-3} and 0.19 cm^3 cm^{-3} for the 800-m and 50-km scale, respectively. On the basis of these data, they derived empirical relationships between the coefficient of variation and the mean soil moisture content in order to estimate the uncertainty in field observations of mean moisture content. The authors are to be commended for providing this valuable database to the scientific community. We agree with the authors that such data are important in improving our understanding about the importance of subgrid moisture variability in the parameterization and simulation of land surface processes. However, the authors limited themselves to an empirical description of the observed data by fitting exponential relationships to the mean moisture content versus coefficient of variation (CV) data. We feel that this is a missed opportunity and would like to argue that an interpretation based on established theories and concepts in soil hydrology and upscaling theories could provide alternative methods and new insights for interpreting such data sets. Specifically, it can be shown from soil physical concepts that for a homogeneous soil, the shape of the moisture retention curve can largely explain observed variations in surface soil moisture, at any specific observation scale. For heterogeneous soils, stochastic upscaling theories may be used to relate σ_θ ($\langle\theta\rangle$) to spatial variability in soil hydraulic properties. These theories can be used to predict σ_θ ($\langle\theta\rangle$) and to examine the sensitivity of this function with respect to soil hydraulic properties.

2. Heuristic Analysis of Soil Moisture Variability for Homogeneous Soils

[2] To better illustrate the potential contributions of the soil water retention curve on spatial variations of surface soil moisture we first consider a homogeneous soil with spatially variable surface soil moisture as caused by spatial variable boundary conditions, such as surface topography, plant water uptake, evaporation/infiltration, or fluctuating water tables. The soil water retention curve defines the relation between soil water potential, expressed by soil water pressure head (h, cm) and soil water content (θ, cm^3 cm^{-3}), as determined by the soil's pore size distribution. Different retention curves are typically measured for a drying and wetting soil, and are defined by the main inhibition and draining curves [*Scott et al.*, 1983] with the wetting curve below the drying curve. Hysteretic soil water retention curves for a sand, silt and clay are presented in Figure 1, with corresponding parameters [*van Genuchten*, 1980] for the main drying and wetting retention curves listed in Table 1, as determined by *Carsel and Parrish* [1988]. We chose to present the curves using a logarithmic scale, to better illustrate the soil's water retention in the dry range. In the following, we use the soil water retention curves of Figure 1 to show that soil water content variations are expected to be the largest for intermediate values of soil water content, θ, thus providing for a simple soil physical explanation for the upward concave shape of Figure 1 of *Vereecken et al.* [2007b] and Figure 6 of *Famiglietti et al.* [2008].

[3] In this comment, we like to impress the notion that observed spatial variations in field soil water content can be explained by the shape of the soil water retention curve, as determined by the slope of the retention curve, $d\theta/dh$, also known as the soil water capacity, C (cm^{-1}). For the drying van Genuchten relationship, it is given by

$$C(\theta) = \frac{d\theta}{dh} = -\frac{(\theta_s - \theta_r)\alpha_{dry} m}{1-m}\Theta^{1/m}\left(1-\Theta^{1/m}\right)^m, \qquad (1)$$

where θ_r and θ_s denote the residual and saturated soil water content, and α_{dry} and m are curve shape parameters and $\Theta = (\theta - \theta_r)/(\theta_s - \theta_r)$, according to *van Genuchten* [1980]. The soil water capacity for each of the three soils

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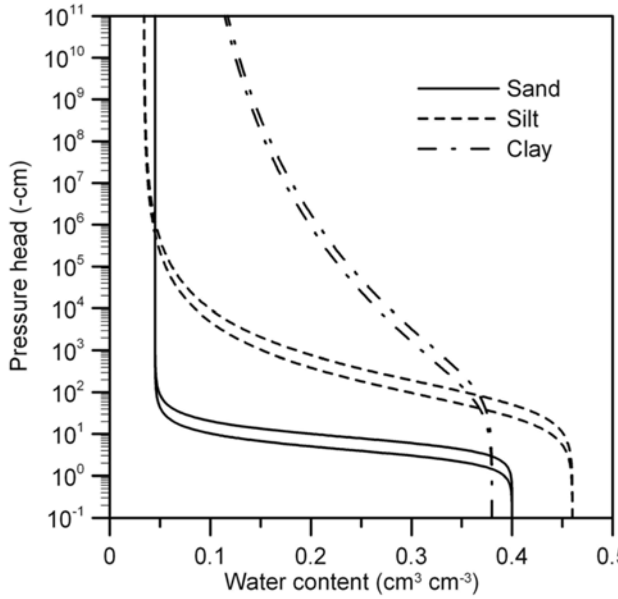

Figure 1. Retention curves with hysteresis for the three soils in Table 1. Main drying and wetting curves are represented by top and bottom curves, respectively, for each soil.

listed in Table 1 is shown in Figure 2. To better understand the role of the soil water capacity on observed spatial water content variation, $\Delta\theta$, we write

$$\Delta\theta = \frac{d\theta}{dh}\Delta h = C(\theta)\Delta h, \qquad (2)$$

where Δh describes the field spatial variability of h caused by spatial variations in the soil moisture regime. We note that $C(\theta)$ is a continuous function as defined by equation (1), whereas we write equation (2) to explain spatial variations, $\Delta\theta$, from spatial variations in Δh. Thus, according to equation (2), for a sampling area with a single soil type and spatially variable boundary conditions, one expects the coefficient of variation of soil water content as expressed by $\Delta\theta$, to be largest in the intermediate θ range, for which $C(\theta)$ (solid line, Figure 2) is maximum for any of the soils shown in Figure 1.

[4] In addition to presenting the soil water capacity curves in Figures 2a–2c (solid line) for each of the 3 soil types of Figure 1, we show two additional curves to further explain the typical concave shapes associated with spatial variations of surface soil moisture using heuristic arguments. These two $\Delta\theta(\theta)$ curves (dashed and dash dotted) provide for additional explanations that shift the maximum $\Delta\theta$ closer to reported θ ranges [e.g., *Famiglietti et al.*, 2008]

Table 1. Van Genuchten Parameters[a]

	θ_r	θ_s	α_{dry} (cm^{-1})	α_{wet} (cm^{-1})	n
Sand	0.045	0.4	0.145	0.29	2.68
Silt	0.034	0.46	0.016	0.032	1.37
Clay	0.068	0.38	0.008	0.016	1.09

[a]See *Carsel and Parrish* [1988].

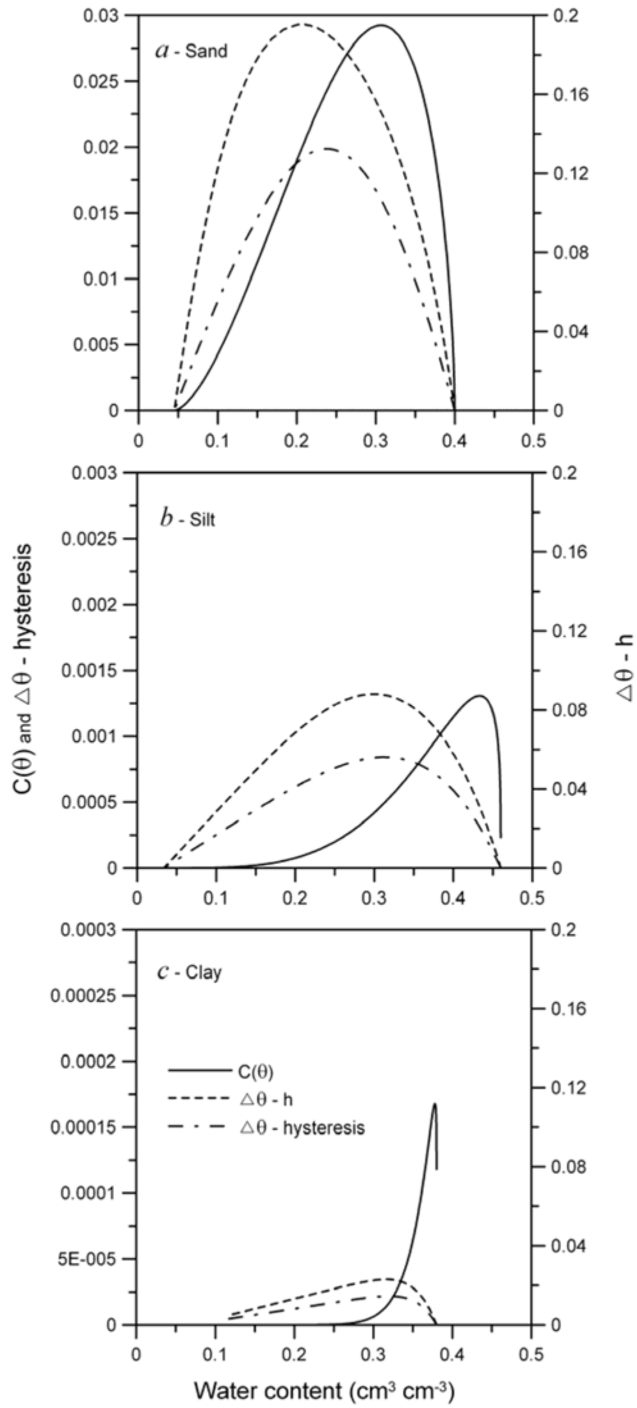

Figure 2. Slope of the retention curve, $C(\theta)$, $\Delta\theta - h$, and $\Delta\theta$ minus hysteresis, as a function of mean soil water content, θ, for (a) sand, (b) silt, and (c) clay soil.

than explained by $C(\theta)$ alone. The dashed line curves for each of the 3 soil types in Figure 2, present $\Delta\theta$ as a function $\theta(h)$, with corresponding Δh defined by $\Delta h = |h|$. For example, for $h(\theta) = -1{,}000$ cm, $\Delta h = 1{,}000$ cm with $\Delta\theta$ computed from θ values corresponding with $h = -500$ and $-1{,}500$ cm, using the drainage curves in Figure 1. The proportional increase in Δh with h is typically observed in the field where the largest spatial variations in soil water potential occur in the dry range. As shown in Figure 2 for all 3 soil types, this approach with the curve designated by label $\Delta\theta - h$ results in a shift of maximum $\Delta\theta$ to the left.

[5] In addition, hysteresis of the soil water retention curve can further impart observed spatial soil moisture variations. To illustrate the additional effect of hysteresis, we added a third (dash-dotted) curve to Figure 2. These $\Delta\theta$ minus hysteresis curves show $\Delta\theta$ between the main drying and wetting curves as a function of soil water content, computed by substituting values for *h* and the corresponding α_{dry} and α_{wet} values of the *van Genuchten* [1980] relationships. Again, we obtain a curve that indicates spatial variations in soil water content arriving from a spatially variable drying/wetting status to have the typical upward concave shape with maximum $\Delta\theta$ values occurring nearer to the measured water content ranges of about 0.2 cm^3 cm^{-3} [*Famiglietti et al.*, 2008; *Vereecken et al.*, 2007b], caused here solely by spatial variations of the wetting and drying regime of the surface soil.

[6] It is important to note that the same concepts apply for a sampling area that includes all of the 3 soil types. This provides for an intuitive simple soil physical explanation for the upward concave shape of Figure 1 of *Vereecken et al.* [2007b] and Figure 6 of *Famiglietti et al.* [2008]. We hope that the presented illustration makes a clear case that soil physical concepts can be used to explain observed variations in surface soil moisture across spatial scales even for a homogeneous soil.

3. Mathematical Analysis of Soil Moisture Variability for Heterogeneous Soils

[7] For the case of heterogeneous soils, it is well known that the intrinsic soil variability, that is the spatial variability of the parameters that define the moisture retention characteristic play an important role in determining soil moisture variability [e.g., *Vereecken et al.*, 2007a]. Numerical simulations of soil moisture variability at different degrees of saturation in heterogeneous unsaturated porous media were performed by *Roth* [1995] and *Harter and Zhang* [1999] among others. Their results show that soil moisture variability peaks at medium soil moisture content values. Closed form expressions for the relationship between soil moisture variance and the statistical properties of soil hydraulic parameters were derived by *Russo* [1998] for steady state unsaturated flow using the Gardner-Russo model of the moisture retention characteristic. An overview of the state of the art in using stochastic methods for unsaturated flow in heterogeneous soils was given by *Zhang* [2002]. Recently, *Vereecken et al.* [2007b] used results from stochastic analysis of unsaturated flow in heterogeneous soils obtained by *Zhang et al.* [1998] to predict the observed convex upward shapes of σ_θ ($\langle\theta\rangle$) also reported by *Famiglietti et al.* [2008]. Using this relationship for eleven textural classes, *Vereecken et al.* [2007b] showed that the standard deviation of soil moisture peaked between 0.17 and 0.23 cm^3 cm^{-3} for most textural classes. In addition, the parameter describing the pore size distribution of soils controlled the maximum value of the soil moisture standard deviation. The mean soil moisture values at which the maximum soil moisture variability occurs are in very good agreement with the values obtained by *Famiglietti et al.* [2008] from their very large database. This indicates the potential value of stochastic theories of soil water processes in explaining and predicting the observed spatial variability of soil moisture across scales. In this respect, we would like to argue that σ_θ ($\langle\theta\rangle$) can be considered as a fundamental property of a heterogeneous soil, which is related to the spatial variability in the moisture retention characteristic. Perturbations of the σ_θ ($\langle\theta\rangle$) relationship may be caused by spatially and temporally heterogeneous fluxes and sink/sources such as infiltration, evaporation, root water uptake, evaporation and surface runoff. Taking stochastic theory as a starting point for the interpretation of observed soil moisture variability and integrating and further developing upscaling approaches combined with integrating knowledge from the fields of remote sensing and hydrology may finally lead to a better understanding and a more fundamental interpretation of the role of soil moisture variability in land surface processes across scales.

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