Do surface lateral flows matter for data assimilation of soil moisture observations into hyperresolution land models?

Running title: HYPERRESOLUTION LAND DATA ASSIMILATION

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Key Points:

1. Surface lateral flows matter when soil moisture observations are assimilated into high-resolution integrated surface-groundwater land models.
2. The efficiency of an ensemble Kalman filter to assimilate soil moisture observations depends on soil characteristics.

Keywords: data assimilation, hyperresolution land model, soil moisture

Abstract

Hyperresolution land modeling is expected to innovate the simulation of terrestrial water, energy, and carbon cycles. One of the major advantages of existing hyperresolution land models against conventional 1-demensional land surface models is that surface and subsurface lateral water flows can be explicitly simulated. Despite a lot of efforts on assimilating hydrological observations into the hyperresolution integrated surface-groundwater land models, how and in what case topography-driven surface water flows matter for data assimilation of soil moisture observations has yet to be clarified. In this study, I perform a minimalist synthetic numerical experiment, in which shallow soil moisture observations are assimilated into an integrated surface-groundwater land model by the ensemble Kalman filter. Propagation of a model error due to surface lateral water flows is crucially important to adjust the unobserved model state and parameter variables by horizontally propagating the information of soil moisture observations. However, the non-Gaussianity of the model error induced by the nonlinear dynamics of topography-driven surface flows harms the performance of an ensemble Kalman filter and the efficiency of data assimilation strongly depends on soil characteristics. The new capability of data assimilation with the hyperresolution land models found in this study may improve the monitoring and prediction of flash floods caused by local severe rainfalls.

1. Introduction

Hyperresolution land modeling is expected to innovate the simulation of terrestrial water, energy, and carbon cycles, which is crucially important for meteorological, hydrological and ecological applications. While conventional land surface models (LSMs) assume that lateral water flows are negligible at a coarse resolution and solve vertical 1-demensional Richards equation for the soil moisture simulation (e.g., Sellers et al. 1996; Lawrence et al. 2011), currently proposed hyperresolution land models, which can be applied at a finer resolution (<1km), explicitly consider surface and subsurface lateral water flows (e.g., Maxwell and Miller 2005; Tian et al. 2012; Shrestha et al. 2014; Niu et al. 2014). Previous works indicated that a lateral transport of water plays important roles in terrestrial water and energy cycles (e.g., Maxwell and Condon 2016; Ji et al. 2017; Fang et al. 2017) and land-atmosphere interactions (e.g., Williams and Maxwell 2011; Keune et al. 2016).

Data assimilation has contributed to improving the performance of LSMs by fusing simulation and observation. The grand challenge of land data assimilation is to estimate unobservable variables from observations by propagating observations' information into model's high dimensional state and parameter space. In previous works on the conventional 1-D LSMs, many land data assimilation systems (LDASs) have been proposed to accurately estimate model's state and parameter variables, which cannot be directly observed, by assimilating satellite and in-situ observations. For example, the optimization of LSM's unknown parameters (e.g., hydraulic conductivity) has been implemented by assimilating remotely sensed microwave observations (e.g., Yang et al. 2007; Yang et al. 2009; Bandara et al. 2014; Bandara et al. 2015; Sawada and Koike 2014; Han et al. 2014). Kumar et al. (2009) analyzed the simulated correlation between surface soil moisture and root-zone soil moisture to improve the simulation of root-zone soil moisture by assimilating remotely sensed surface soil moisture observations. Sawada et al. (2015) successfully improved the simulation of root-zone soil moisture by assimilating microwave brightness temperature observations which include the information of vegetation water content. Gravity Recovery and Climate Experiment total water storage observation has been intensively used to improve the simulation of groundwater and soil moisture (e.g., Li et al. 2012; Houborg et al. 2012). Improving the simulation of state variables such as soil moisture and biomass by LDASs has contributed to accurately estimating fluxes such as evapotranspiration (e.g. Martens et al. 2017) and CO2 flux (e.g., Verbeeck et al. 2011). However, in most of the studies on the conventional 1-D LDASs, observations impacted state and parameter variables only in a single model's horizontal grid which is identical to the location of the observation. The assumption that the surface and subsurface water flows are restricted to vertical direction in LSMs makes it difficult to propagate observation's information horizontally, which limits the potential of land data assimilation to fully use land hydrological observations.

The hyperresolution land models, which explicitly solve surface and subsurface lateral flows, provide a unique opportunity to examine the potential of land data assimilation to propagate observation's information horizontally in a model space and efficiently use land hydrological observations. Previous works successfully applied Ensemble Kalman Filters (EnKF) to 3-D Richards' equation-based integrated surface-groundwater models. For example, Camporese et al. (2009) and Camporese et al. (2010) successfully assimilated the synthetic observations of surface pressure head and streamflow into the Catchment Hydrology (CATHY). Kurtz et al. (2016) coupled the Parallel Data Assimilation Framework (PDAF) (Nerger and Hiller 2013) with the Terrestrial System Modelling Framework (TerrSysMP) (Shrestha et al. 2014). The performance of TerrSysMP-PDAF to assimilate soil moisture observations was evaluated by a simple synthetic experiment (see also Zhang et al. (2018)).

Although the data assimilation of hydrological observations into the hyperresolution land models has been successfully implemented in the synthetic experiments, it is unclear how and in what case topography-driven surface lateral water flows matter for data assimilation of soil moisture observations. Previous studies on data assimilation with high resolution models mainly focused on assimilating groundwater observations (e.g., Ait-El-Fquih et al. 2016; Rasmussen et al. 2015; Hendricks-Franssen et al. 2008). There are some applications which focused on the observation of soil moisture and pressure head in shallow unsaturated soil layers. However, in those literatures, topography-driven surface flows have not been considered in the experiment (Kurtz et al. 2016) or the role of them in assimilating observations into the hyperresolution land models has not been quantitatively discussed (Camporese et al. 2010; Camporese et al. 2009). This study aims at clarifying if surface lateral flows matter for data assimilation of soil moisture observations into hyperresolution land models by a minimalist numerical experiment.

2. Methods

2.1. Model

ParFlow is an open source platform which realizes fully integrated surface-groundwater flow modeling (Kollet and Maxwell 2006; Maxwell et al. 2015). This parallel simulation platform has been widely used as a core hydrological module in hyperresolution land models (e.g., Maxwell and Kollet 2008; Maxwell and Condon 2016; Fang et al. 2017; Kurtz et al. 2016; Maxwell et al. 2011; Williams and Maxwell 2011; Shrestha et al. 2014). The brief description on the method of ParFlow to simulate integrated surface-subsurface water flows can be found below and the complete description of ParFlow can be found in Kollet and Maxwell (2006), Maxwell et al. (2015) and references therein.

In the subsurface, ParFlow solves the variably saturated Richards equation in three dimensions.

$$S_S S_W(h)\frac{\partial h}{\partial t} + \phi S_W(h)\frac{\partial S_W(h)}{\partial t} = \nabla\cdot\mathbf{q} + q_r \quad (1)$$

$$\mathbf{q} = -\boldsymbol{K_s}(\boldsymbol{x})k_r(h)[\nabla(h+z)cos\theta_x + sin\theta_x] \quad (2)$$

In equation (1), h is the pressure head [L]; z is the elevation with the z axis specified as upward [L]; S_S is the specific storage [L^{-1}]; S_W is the relative saturation; ϕ is the porosity [-]; q_r is a general source/sink term. Equation (2) describes the flux term $\mathbf{q}$ [LT^{-1}] based on Darcy's law, and $\boldsymbol{K_s}$ is the saturated hydraulic conductivity tensor [LT^{-1}]; k_r is the relative permeability [-]; θ is the local angle of topographic slope (see Maxwell et al. 2015). In this paper, the saturated hydraulic conductivity is assumed to be isotropic and the function of z:

$$\boldsymbol{K_s} = K_s(z) = K_{s,surface}\exp(-f(z_{surface} - z)) \quad (3)$$

where $K_{s,surface}$ is the saturated hydraulic conductivity at the soil surface, and $z_{surface}$ is the elevation of the soil surface. The saturated hydraulic conductivity decreases exponentially as the soil depth increases (Beven 1982). The van Genuchten relationship (van Genuchten 1980) is used to describe the relative saturation and permeability functions.

Overland flow is solved by the two-dimensional kinematic wave equation. The dynamics of the surface ponding depth, h [L], can be described by:

$$\mathbf{k}\cdot[-K_s(z)k_r(h)\cdot\nabla(h+z)] = \frac{\partial\|h,0\|}{\partial t} - \nabla\cdot\|h,0\|\boldsymbol{v}_{sw} + q_r \quad (4)$$

In equation (4), $\mathbf{k}$ is the unit vector in the vertical and $\|a, b\|$ indicates the greater value of the two quantities following the notation of Maxwell et al. (2015). If h < 0, equation (4) describes that vertical fluxes across the land surface boundary is equal to a general source/sink term q_r (i.e., rainfall and evapotranspiration). If h > 0, the terms on the right-hand side of equation (4), which indicates water fluxes routed according to surface topography, are active. $\boldsymbol{v}_{sw}$ is the two-dimensional depth-averaged overland flow velocity [LT^{-1}] and estimated by the Manning's law:

$$\boldsymbol{v}_{sw} = \begin{pmatrix} \frac{\sqrt{S_{f,x}}}{n} h^{\frac{2}{3}} \\ \frac{\sqrt{S_{f,y}}}{n} h^{\frac{2}{3}} \end{pmatrix} \quad (5)$$

where $S_{f,x}$ and $S_{f,y}$ are the friction slopes [-] for the x- and y-direction, respectively; n is the Manning's coefficient [$TL^{-1/3}$]. In the kinematic wave approximation, the friction slopes are set to the bed slopes. The methodology of discretization and numerical implementation to solve equations (1-5) can be found in Kollet and Maxwell (2006).

2.2. Data Assimilation

In this paper, the ensemble Kalman filter (EnKF) was applied to assimilate soil moisture observations into ParFlow. The general description of the Kalman filter is the following:

$$\boldsymbol{x}^f(t) = \mathcal{M}[\boldsymbol{x}^a(t-1)] \quad (6)$$

$$\boldsymbol{x}^a(t) = \boldsymbol{x}^f(t) + \boldsymbol{K}[y^o - \mathcal{H}\boldsymbol{x}^f(t)] \quad (7)$$

$$\mathbf{K} = \boldsymbol{P}^f \boldsymbol{\mathcal{H}}^{\boldsymbol{T}} (\boldsymbol{\mathcal{H}} \boldsymbol{P}^{\boldsymbol{f}} \boldsymbol{\mathcal{H}}^{\boldsymbol{T}} + \boldsymbol{R})^{-\mathbf{1}} \quad (8)$$

$$\boldsymbol{P}^{\boldsymbol{a}} = (\boldsymbol{I} - \boldsymbol{K}\boldsymbol{\mathcal{H}})\boldsymbol{P}^{\boldsymbol{f}} \quad (9)$$

I follow the notation of Houtekamer and Zhang (2016). In equation (6), a forecast model $\mathcal{M}$ (ParFlow in this study) is used to obtain a prior estimate at time t, $\boldsymbol{x}^f(t)$, from the estimation at the previous time $\boldsymbol{x}^a(t-1)$. In equation (7), a prior estimate $\boldsymbol{x}^f(t)$ is updated to the analysis state, $\boldsymbol{x}^a(t)$, using new observations y^o. The Kalman gain matrix $\mathbf{K}$ calculated by equation (8) is used to give an appropriate weight between the observations with an error covariance matrix $\boldsymbol{R}$, and the prior with an error covariance matrix $\boldsymbol{P}^f$. To calculate $\mathbf{K}$, the observation operator $\boldsymbol{\mathcal{H}}$ is needed to map from model space to observation space. It should be noted that the equations (6-9) give an optimal estimation only when the error in model and observation follows the Gaussian distribution. When the probabilistic distribution of the error in either model or observation has non-Gaussian structure, results of the Kalman filter are suboptimal. This point is important to interpret the results of this study.

EnKF is the Monte Carlo implementation of equations (6-9). To compute the Kalman gain matrix, **K,** ensemble approximations of $\boldsymbol{P^f \mathcal{H}^T}$ and $\boldsymbol{\mathcal{H} P^f \mathcal{H}^T}$ can be given by:

$$\boldsymbol{P^f \mathcal{H}^T} \equiv \frac{1}{k-1}\sum_{i=1}^{k}\left(x_i^f - \overline{x^f}\right)\left(\mathcal{H}x_i^f - \overline{\mathcal{H}x^f}\right)^T \quad (10)$$

$$\boldsymbol{\mathcal{H} P^f \mathcal{H}^T} \equiv \frac{1}{k-1}\sum_{i=1}^{k}\left(\mathcal{H}x_i^f - \overline{\mathcal{H}x^f}\right)\left(\mathcal{H}x_i^f - \overline{\mathcal{H}x^f}\right)^T \quad (11)$$

where x_i^f is the ith member of a k-member ensemble prior and $\overline{x^f} = \frac{1}{k}\sum_{i=1}^{k} x_i^f$ and $\overline{\mathcal{H}x^f} = \frac{1}{k}\sum_{i=1}^{k} \mathcal{H}x_i^f$.

Once $\overline{x^a} = \sum_{i=1}^{k} x_i^a$ (x_i^a is the ith member of a k-member ensemble analysis) and $\boldsymbol{P^a} = \boldsymbol{\frac{1}{k-1}}\sum_{i=1}^{k}(x_i^a - \overline{x^a})(x_i^a - \overline{x^a})^T$ are computed by equations (6-11), there are still many possible choices of an analysis ensemble. There are many proposed flavors of EnKF and one of the main differences among them is how to choose the analysis ensemble x_i^a. In this paper, the Ensemble Transform Kalman Filter (ETKF; Bishop et al. 2001; Hunt et al. 2007) was used to transport forecast ensembles to analysis ensembles.

In the ETKF, the analysis update for an ensemble mean is done by the following equations:

$$\tilde{P}^a = [(k-1)I + (Y^f)^T R^{-1} Y^f]^{-1} \quad (12)$$

$$\overline{w}^a = \tilde{P}^a (Y^f)^T R^{-1}(y^o - \overline{y^f}) \quad (13)$$

$$\overline{x^a} = \overline{x^f} + X^f \overline{w}^a \quad (14)$$

where the ith columns of Y^f and X^f are $y_i^f - \overline{y^f}$ and $x_i^f - \overline{x^f}$, respectively. y_i^f is defined by $y_i^f = \mathcal{H}x_i^f$ and $\overline{y^f}$ is the ensemble mean of y_i^f. I is the identity matrix.

The analysis covariance $\boldsymbol{P^a}$ is given by:

$$P^a = \frac{1}{k-1} X^a (X^a)^T = X^f \tilde{P}^a (X^f)^T \quad (15)$$

where the ith column of X^a is $x_i^a - \overline{x^a}$. The perturbations of the analysis ensemble members can be generated by the square root of $\tilde{P}^a$:

$$W^a = [(k-1)\tilde{P}^a]^{1/2} \quad (16)$$

$$X^a = X^f W^a \quad (17)$$

Please refer to Hunt et al. (2007) for the complete description of the ETKF and its localized version, the Local Ensemble Transform Kalman Filter (LETKF).

In many ensemble Kalman filter systems, the ensemble spread tends to become underdispersive without any ensemble inflation methods (Houtekamer and Zhang, 2016). In this paper, the relaxation to prior perturbation method (RTPP) of Zhang et al. (2004) was used to maintain an appropriate ensemble spread. In the RTPP, the computed analysis perturbations are relaxed back to the forecast perturbations:

$$x_{i,new}^{a} = (1-\alpha)(x_i^a - \overline{x^a}) + \alpha\left(x_i^f - \overline{x^f}\right),\ 0 \le \alpha \le 1 \quad (18)$$

where α was set to 0.975 in this study.

3. Experiment Design

The synthetic experiment was implemented to examine how topography-driven surface lateral flows contribute to efficiently propagating observation’s information horizontally in the data assimilation of soil moisture observation. Two synthetic reference runs were created by Parflow. The 2-D domain has a horizontal extension of 4000m and a vertical extension of 5m. The domain of the virtual slope was horizontally discretized into 40 grid cells with a grid cell size of 100m and vertically discretized into 50 grid cells with a grid cell size of 0.10m. The domain has a 25% slope. In two synthetic reference runs, it heavily rains only in the upper half of the slope ($2000m<x<4000m$). A constant rainfall rate of 50mm/h was applied for 3 hours and then the period with no rainfall and evaporation of 0.075mm/h lasted for 117 hours. This 120-hour rain/no rain cycle was repeatedly applied to the domain. The configurations described above were schematically shown in Figure 1a. The parameters of the van Genuchten relationship, alpha and n, were set to 1.5 and 1.75, respectively. The porosity, ϕ in equation (1), was set to 0.40. The Manning’s coefficient, n in equation (5), was set to 5.52×10^{-6} [$m^{-1/3}h$]. The initial groundwater table was located in z=3m and the hydrostatic pressure gradient was assumed for the initial pressure heads in the unsaturated soil layers.

The difference between two synthetic reference runs is the value of saturated hydraulic conductivity. The surface saturated hydraulic conductivity, $K_{s,surface}$ in equation (3), was set to 0.005 [m/h] in one reference, and 0.02 [m/h] in the other. Figure 1 shows the difference of the response to heavy rainfall between the two synthetic reference runs. In the case of the low saturated hydraulic conductivity (hereafter called the LOW_K reference), larger surface lateral flows are generated than the case of the high saturated hydraulic conductivity (hereafter called the HIGH_K reference). In the LOW_K reference, the topography-driven surface lateral flows reach the left edge of the domain

(Figure 1b). In the HIGH_K reference, supplied water moves vertically rather than horizontally and the topography-driven surface flows reach around x = 1000~1500m (Figure 1d).

For the data assimilation experiment, an ensemble of 50 realizations were generated. Each ensemble member has different saturated hydraulic conductivity and rainfall rate. Lognormal multiplicative noise was added to surface saturated hydraulic conductivity and rainfall rate of the synthetic reference runs. The two parameters of the lognormal distribution, commonly called μ and σ, were set to 0 and 0.15, respectively. The initial groundwater depth of each ensemble member was drawn from the uniform distribution from 2.0m to 3.5m and the hydrostatic pressure gradient was assumed for the initial pressure heads in the unsaturated soil layers.

The virtual hourly observations were generated by adding the Gaussian white noise whose mean is zero to the volumetric soil moisture simulated by the synthetic reference runs. The observation error (the standard deviation of the added Gaussian white noise) was set to 0.05 m^3/m^3. It was assumed that the volumetric soil moistures can be observed in every soil layer from surface to the depth of 1m at the specific location. The two scenarios of the observation's location are provided. In the first scenario (hereafter called the UP_O scenario), the volumetric soil moisture at the upper part of the slope (x = 2500m) was observed. In the UP_O scenario, I could observe the volumetric soil moisture in the upper part of the slope where it heavily rains and tried to infer the soil moisture in the lower part of the slope where it does not rain by propagating the observation's information downhill. In the second scenario (hereafter called the DOWN_O scenario), the volumetric soil moisture at the lower part of the slope (x = 1500m) was observed. In the DOWN_O scenario, I could observe the volumetric soil moisture in the lower part of the slope where it does not rain and tried to infer the soil moisture in the upper part of the slope where it heavily rains by propagating the observation's information uphill.

Since I had the two synthetic reference runs (the HIGH_K and LOW_K references) and the two observation scenarios (the UP_O and DOWN_O scenarios), I implemented totally four data assimilation experiments. Table 1 summarizes the data assimilation experiments implemented in this study. For instance, in the HIGH_K-UP_O experiment, I chose the HIGH_K reference and generated an ensemble of 50 realizations from the HIGH_K reference. The soil moisture observations were generated from the HIGH_K reference at the location of x = 2500m and assimilated into the model every hour. The simulated volumetric soil moisture of the data assimilation experiment was compared with that of the HIGH_K reference.

In the data assimilation experiments, I adjusted pressure head by data assimilation so that x^f in section 2.2 is pressure head. Since the surface saturated hydraulic conductivity was also adjusted, x^f in section 2.2 includes $K_{s,surface}$. It should be noted that I adjusted a single surface saturated hydraulic conductivity which is applied to the whole domain so that the estimated parameter was not spatially distributed. Spatial regularization has been applied to calibrate spatially distributed parameters by adjusting a single parameter (Pokhrel and Gupta 2010). I suppose to apply the spatial regularization in the real-world application of the hyperresolution land data assimilation. Since I assimilated volumetric soil moisture observations (y^f and y^o in section 2.2 are simulated and observed volumetric soil moisture, respectively), the van Genuchten relationship works as an observation operator $\mathcal{H}$ in this study.

In addition to the data assimilation (DA) experiments, I implemented the NoDA experiment (also called the open-loop experiment in the literatures of the LDAS study) in which the ensemble was used but no observation data were assimilated. As evaluation metrics, root-mean-square-error (RMSE) was used:

$$\mathrm{RMSE} = \sqrt{\frac{1}{k}\sum_{i=1}^{k}(F_i - T)^2} \quad (19)$$

where k is the ensemble number, F_i is the volumetric soil moisture simulated by the i-th member in the DA or NoDA experiment, T is the volumetric soil moisture simulated by the synthetic reference run.

To evaluate the impact of data assimilation, the improvement rate (IR) was defined and calculated by the following equation:

$$\mathrm{IR} = \frac{\overline{RMSE_{DA}} - \overline{RMSE_{NoDA}}}{\overline{RMSE_{NoDA}}} \quad (20)$$

where $\overline{RMSE_{DA}}$ and $\overline{RMSE_{NoDA}}$ are time-mean RMSE of the DA and NoDA experiments, respectively. The negative IR indicates that data assimilation positively impacts the simulation of soil moisture.

Four of 120-hour rain/no rain cycles were applied so that the computation period was 480 hours. The spin-up results in the first 120 hours were not used to calculate the evaluation metrics.

4. Results

Figure 2a shows the IR of the LOW_K-UP_O experiment. The time series of the DA and NoDA experiment and the synthetic reference run in the LOW_K-UP_O experiment can be found in Figure S1. The data assimilation efficiently propagates the information of the observations located in the upper part of the slope (see the black arrow in Figure 2a) both horizontally and vertically. RMSE is reduced by data assimilation not only directly under the observation but also the lower part of the slope where it does not rain. However, the increase of RMSE by data assimilation can be found at the left edge of the domain, which is far from the location of the observation. Please note that the impact of data assimilation on the surface soil moisture simulation is small because the RMSE of the NoDA experiment is already small (≤ 0.01m^3/m^3) there in the case of the LOW_K reference.

Figure 2b shows the IR of the LOW_K-DOWN_O experiment (see also Figure S2 for time series). The IR's spatial pattern of the LOW_K-DOWN_O experiment is similar to that of the LOW_K-UP_O experiment. It is promising that I can accurately infer soil moisture in the region where it heavily rains from the shallow soil moisture observations in the region where it does not rain.

Figure 3a shows the difference of time-mean RMSEs ($\overline{RMSE_{DA}}$ in equation (20)) between the LOW_K-UP_O and LOW_K-DOWN_O experiments. Although observing the lower part of the slope slightly improves the soil moisture simulation at the left edge of the domain compared with observing the upper part of the slope, there are few differences between the UP_O and DOWN_O scenarios in the case of the LOW_K reference. In the data assimilation system of this study, the soil moisture observations have large representativeness and I can efficiently infer soil moisture in the soil columns which are horizontally and vertically far from the observations.

Figure 2c shows the IR of the HIGH_K-UP_O experiment (see also Figure S3 for time series). The data assimilation significantly reduces RMSE of the soil moisture simulation directly under the observations (see the black arrow in Figure 2c), which indicates that the data assimilation efficiently propagates the information of the observations vertically. However, the impact of the data assimilation on the soil moisture simulation in the lower part of the slope around x=1500m is marginal although there are large RMSE in the NoDA experiment (>0.05m^3/m^3) at the edge of the area where topography-driven surface flows reach in the HIGH_K reference (see Figure 1d).

Figure 2d shows the IR of the HIGH_K-DOWN_O experiment (see also Figure S4 for time series). Although the observations in the lower part of the slope (see the black arrow in Figure 2d) significantly improve the soil moisture simulation in the downstream area of the observation, the impact of the data assimilation on the shallow soil moisture simulation around x=500~1000m is marginal. As I found in the LOW_K-DOWN_O experiment, the shallow soil moisture observations in the region where it does not rain can improve the soil moisture simulation in the region where it heavily rains. However, the IR of the HIGH_K-DOWN_O experiment in the upper part of the slope is smaller than that of the LOW_K-DOWN_O experiment (see Figure 2b and 2d).

The high representativeness of the observations which I found in the case of the LOW_K reference cannot be found in the case of the HIGH_K reference. Figure 3b shows the difference of time-mean RMSEs ($\overline{RMSE_{DA}}$ in equation (20)) between the HIGH_K-UP_O and HIGH_K-DOWN_O experiments. Compared with the LOW_K reference case (Figure 3a), there are significant differences between the UP_O and DOWN_O scenarios in the case of higher saturated hydraulic conductivity. In this case, the vertical propagation of the observations' information is more efficient than the horizontal propagation.

The relatively low efficiency of the data assimilation and the low representativeness of the soil moisture observations in the case of the HIGH_K reference are caused by the non-Gaussian model error distribution. To evaluate the non-Gaussianity of the model error sampled by an ensemble, I used the Kullback-Leibler divergence (KLD) (Kullback and Leibler 1951):

$$D_{KL}(p,q) = \sum_i p(i) log \frac{p(i)}{q(i)} \quad (21)$$

where $D_{KL}(p,q)$ is the KLD between two probabilistic distribution functions (PDFs), p and q. If two PDFs are equal for all i, $D_{KL}(p,q) = 0$. A large value for $D_{KL}(p,q)$ indicates that p and q are not close to each other. Therefore, the KLD is appropriate as a benchmark to evaluate the closeness of two PDFs. It should be noted that the KLD is not symmetric ($D_{KL}(p,q) \neq D_{KL}(q,p)$). In this study, I compared the PDF of the NoDA ensemble (p in equation (21)) with the Gaussian PDF which has the mean and variance of the NoDA ensemble (q in equation (21)).

Figure 4 shows that the NoDA ensemble in the case of the HIGH_K reference has stronger non-Gaussianity than the case of the LOW_K reference especially in the shallow soil layers. The strong non-Gaussianity of the NoDA ensemble generated from the HIGH_K reference can be found at the edge of the area where topography-driven surface flows reach (Figure 1d). Figure 5 shows that there is the bifurcation of the ensemble in this region when the ensemble is generated from the HIGH_K reference. The process of topography-driven surface flows is switched on if and only if the surface soil is saturated (see equation (4)) so that the ensemble tends to be bifurcated into the members with surface flows and without surface flows. As I mentioned in section 2.2, in the ETKF, the state and parameter variables are adjusted assuming the Gaussian PDF of the model's error and the linear relationship between observed variables and unobserved variables. Therefore, the non-Gaussianity of the prior ensemble induced by the strong non-linear dynamics of surface lateral flows makes the ETKF inefficient. It should be noted that the non-Gaussianity can also be found in the LOW_K reference at the edge of the domain (x=500m) due to the non-linear dynamics, which causes the degradation of the soil moisture simulation in the LOW_K-UP_O experiment (see Figure 2a).

5. Discussion

In this study, I revealed that the hyperresolution integrated surface-subsurface hydrological model gives the unique opportunity to effectively use soil moisture observations to improve the soil moisture simulation. I found that the explicit calculation of topography-driven surface flows has an important role in propagating the information of soil moisture observation horizontally by data assimilation even if there is considerable heterogeneity of meteorological forcing. It is possible that the soil moisture observations in the area where it does not heavily rain can improve the soil moisture simulation in the severe rainfall area. This potential cannot be brought out in the conventional 1-D LSM where sub-grid scale surface runoff is parameterized and the surface flows in one grid do not move to the adjacent grids. This new potential of hyperresolution land data assimilation is expected to be useful to monitor and predict flash floods induced by local severe rainfall on complex terrain.

However, I also found that the conventional ensemble data assimilation (i.e. ETKF) severely suffers from the non-Gaussian model error PDFs caused by the strongly nonlinear dynamics of topography-driven surface flows. The efficiency of ETKF to propagate the information of observations horizontally in the model space is limited when capacity of soil to hold water is high (i.e. high saturated hydraulic conductivity). It should be noted that the low representativeness of the soil moisture observations in the case of the HIGH_K reference is due to the core assumption of the Kalman filter that the error

PDFs follow the Gaussian distribution so that the increase of the ensemble size cannot solve this issue. I implemented the data assimilation experiment in the case of the HIGH_K reference with the 500 ensemble size, which is 10 times larger than the experiments shown in section 4, and found no significant improvement of the soil moisture simulation (not shown).

The results of the HIGH_K-UP_O and the HIGH_K-DOWN_O imply that the spatially dense soil moisture observations are needed to efficiently constrain state variables at the edge of surface flows. High resolution soil moisture remote sensing based on satellite active and passive combined microwave observations (e.g., He et al. 2018) and the assimilation of those data (Lievens et al. 2017) may be the important technologies in the era of the hyperresolution land modeling. The high resolution observations of surface inundated water from satellite imagery (e.g., Sakamoto et al. 2007 RSE; Arnesen et al. 2013 RSE) may also be useful.

Since there is the nonlinear relationship between observed and unobserved variables sampled by an ensemble, a localization method, which spatially restricts the impact of assimilating observation, is crucially needed for the real-world application. The results of this study imply that the optimal localization radius strongly depends on the model parameter (i.e. saturated hydraulic conductivity). Rasmussen et al. (2015) successfully applied the adaptive localization method (Anderson 2007; Bishop and Hodyss 2009) to the data assimilation of groundwater observations into a hydrological model. It is appropriate to adaptively determine the localization radius considering the lack of prior knowledge of how soil moistures simulated by an ensemble are horizontally correlated.

Reducing the uncertainty in rainfall positively impacts the efficiency of data assimilation since the bifurcation of simulated soil moisture found in Figure 5c is originally induced by the uncertainty in rainfall. Although assimilating land hydrological observations to improve the rainfall input has been intensively investigated (e.g., Sawada et al. 2018; Herrnegger et al. 2015; Crow et al. 2011; Vrugt et al. 2008), it has yet to be applied to the hyperresolution land models. It should be noted that the parameters of the lognormal distribution to model the uncertainty in rainfall were specified to make the rainfall PDF similar to the Gaussian distribution. I chose the lognormal distribution in order not to generate the negative value of rainfall and I did not intend to introduce non-Gaussianity into the external forcing. The rainfall input which follows the Gaussian PDF was transformed into the non-Gaussian PDF of the model error by the strongly nonlinear dynamics of topography-driven surface flows.

To explicitly consider the non-Gaussianity and non-linear relationship between observed and unobserved variables induced by topography-driven surface flows, the particle filters may be useful. The particle filtering can represent a probability distribution (including non-Gaussian distributions) directly by an ensemble. The particle filters have been intensively applied to conventional 1-D LSMs (e.g., Sawada et al. 2015; Qin et al. 2009) and lumped hydrological models (e.g., Yan and Moradkhani 2016; Vrugt et al. 2013). Although particle filtering in the high dimensional system suffers from the "curse of dimensionality" (e.g., Snyder et al. 2008), the applicability of particle filtering to the 3-D hyperresolution land models should be assessed in the future.

Since the synthetic numerical experiment implemented in this paper assumed the extreme heterogeneity of rainfall, the findings of this paper may be exaggerated. In the future work, the contributions of the topography-driven surface runoff process to the data assimilation of hydrological observations should be quantified in the real-world application. In addition, in the virtual experiment of this paper, I neglected some of the important land processes such as transpiration, canopy interception, snow, and frozen soil. Although they are generally not important processes in terms of the generation of topography-driven surface lateral flows, those processes should be considered in the future.

6. Conclusions

Lateral surface flows induced by heavy rainfalls do matter for data assimilation of soil moisture observations into hyperresolution land models. Even if there is extreme heterogeneity of rainfall, I can effectively propagate the information of the soil moisture observations horizontally in the model space and improve the soil moisture simulation by the ensemble Kalman filter. This new capability of the data assimilation with the hyperresolution land models may innovate the monitor and prediction of flash floods caused by local severe rainfalls. However, the non-Gaussianity of the model error induced by the nonlinear dynamics of topography-driven surface flows harms the efficiency of the data assimilation of soil moisture observations. When topography-driven surface slope runoff exists, the efficiency of assimilating shallow soil moisture observations into the hyperresolution land models depends on soil characteristics of the study area.

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Table 1. Configuration of the data assimilation experiments

	hydraulic conductivity [m/h]	observation's location [m]
LOW_K-UP_O	0.005	2500
LOW_K-DOWN_O	0.005	1500
HIGH_K-UP_O	0.02	2500
HIGH_K-DOWN_O	0.02	1500

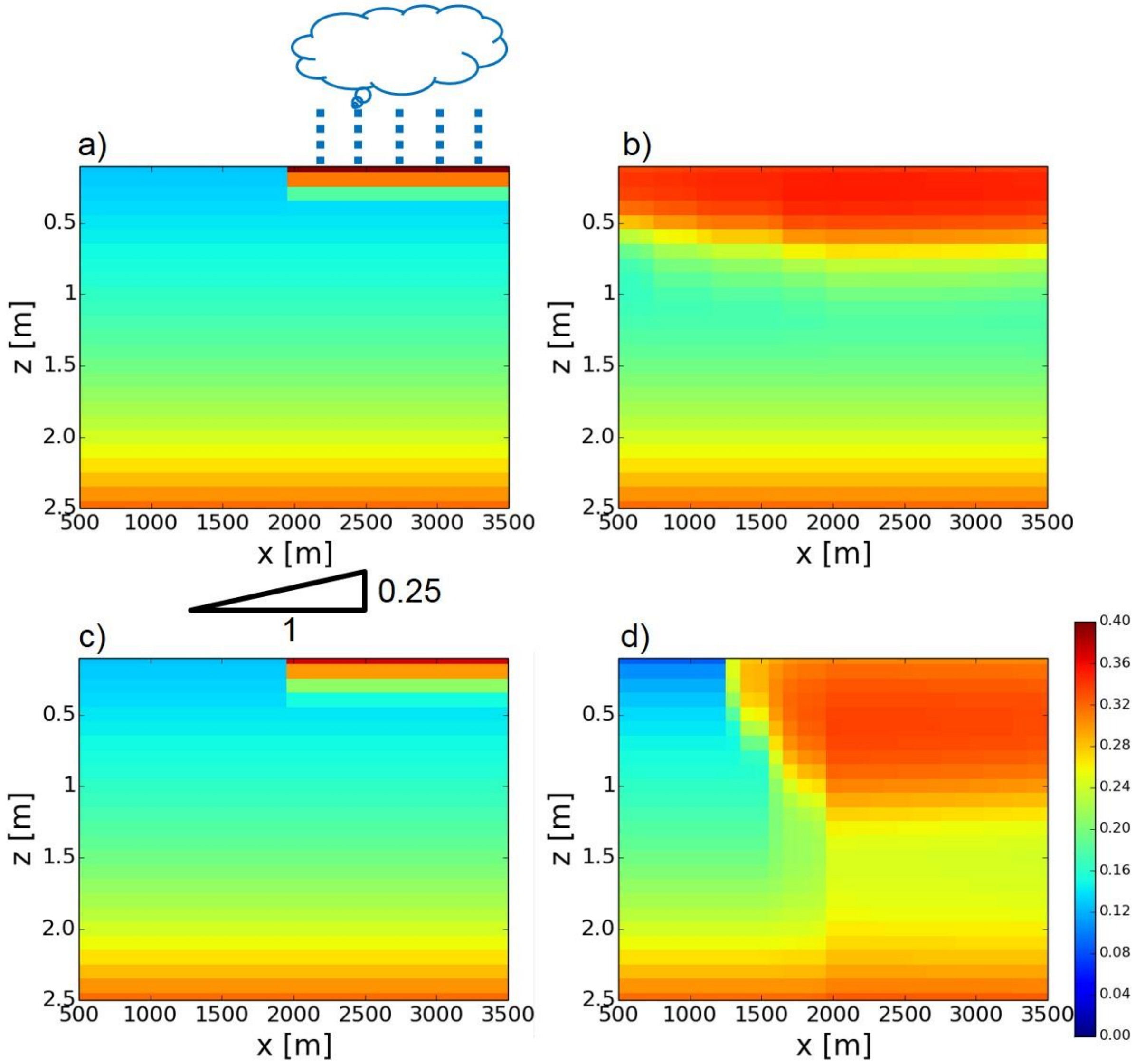

Figure 1. Distributions of volumetric soil moisture simulated by the synthetic reference runs. (a) The distribution of volumetric soil moisture [m^3/m^3] simulated by the LOW_K synthetic reference run at t = 0h. The schematic of the configuration of the synthetic reference runs is also shown (see also section 3). (b) same as (a) but at t = 130h. (c,d) same as (a,c) but for the HIGH_K synthetic reference run.

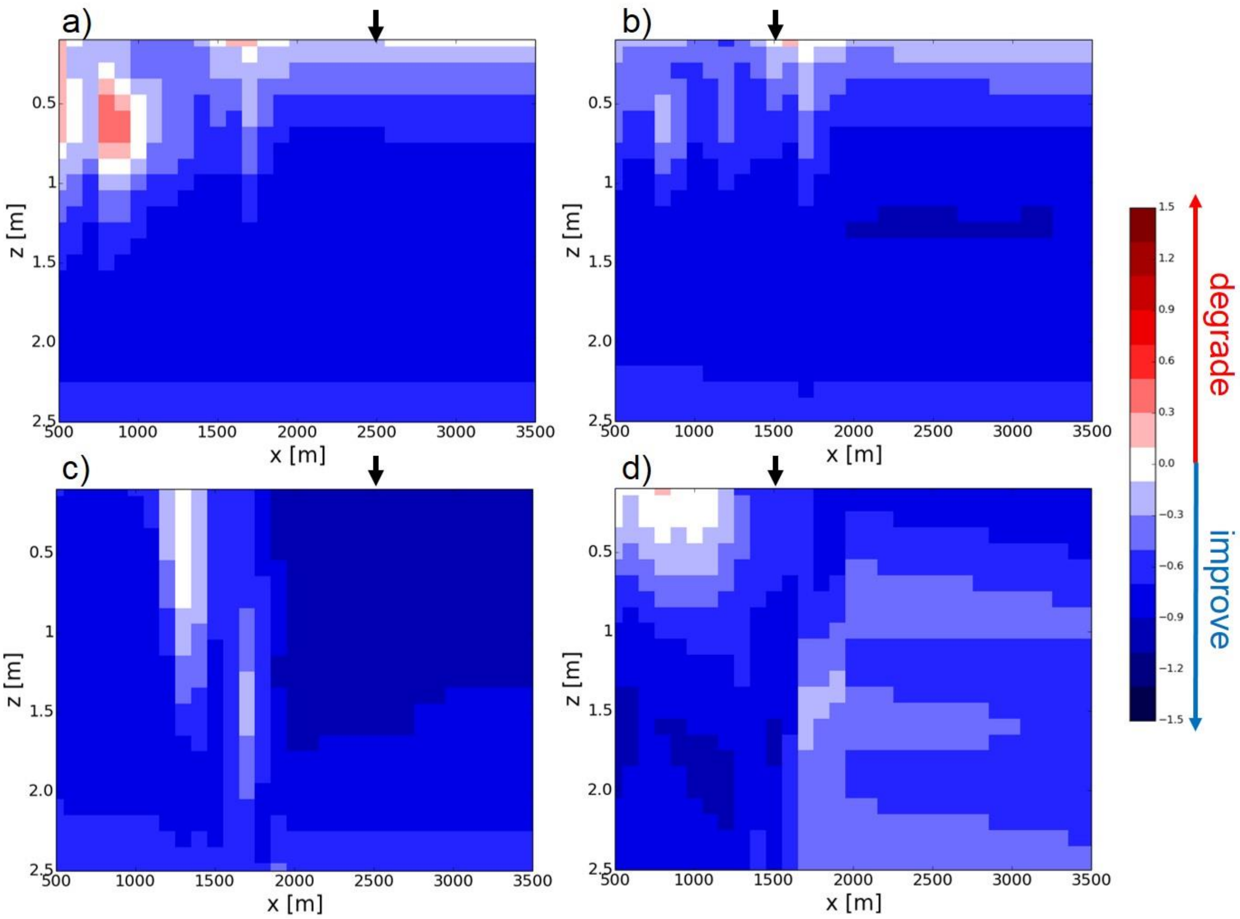

Figure 2. The improvement rates of the (a) LOW_K-UP_O, (b) LOW_K-DOWN_O, (c) HIGH_K_UP_O, (d) HIGH_K-DOWN_O experiments (see Table 1 and section 3). Black arrows show the locations of the soil moisture observations in each experiment.

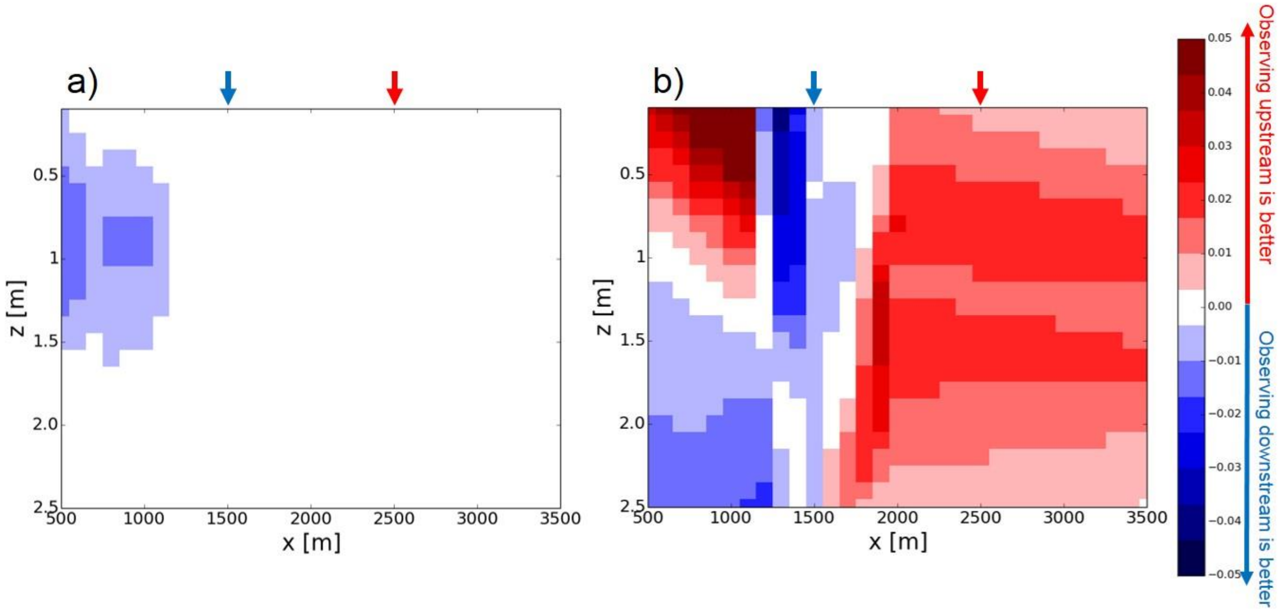

Figure 3. (a) The difference of time-mean RMSEs between the LOW_K-UP_O and LOW_K-DOWN_O experiments (see Table 1 and section 3). Red (blue) color indicates that the observations in the upper (lower) part of the slope reduce time-mean RMSE by data assimilation better than those in the lower (upper) part of the slope (see also arrows which are the locations of the observations). (b) same as (a) but for the difference between the HIGH_K-UP_O and HIGH_K-DOWN_O experiments.

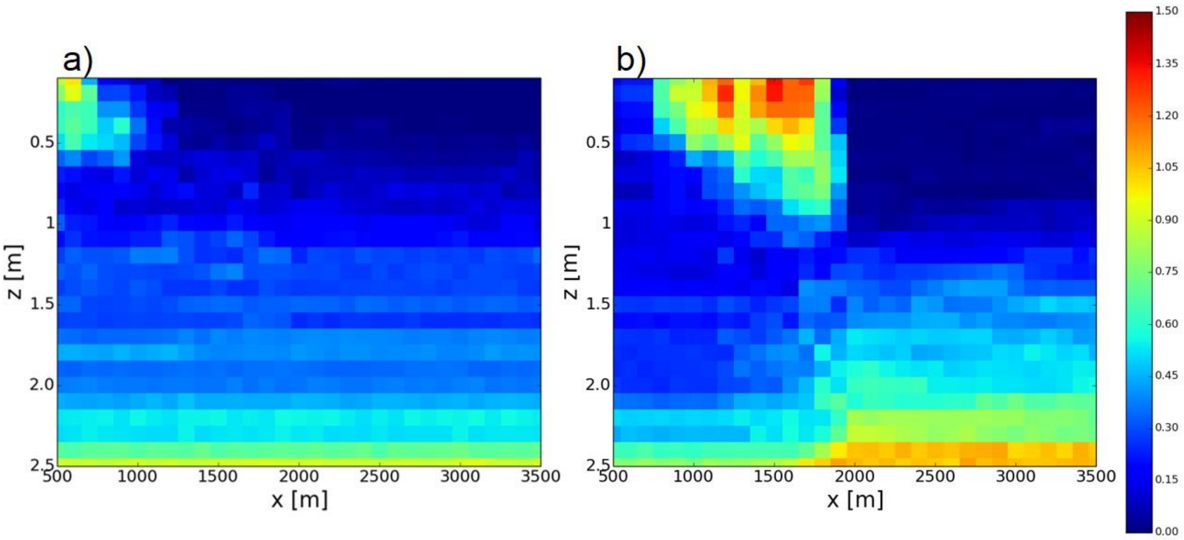

Figure 4. The Kullback-Leibler divergence of the NoDA experiment generated by (a) the LOW_K reference and (b) the HIGH_K reference at t = 130h (see also Figure 1b and 1d).

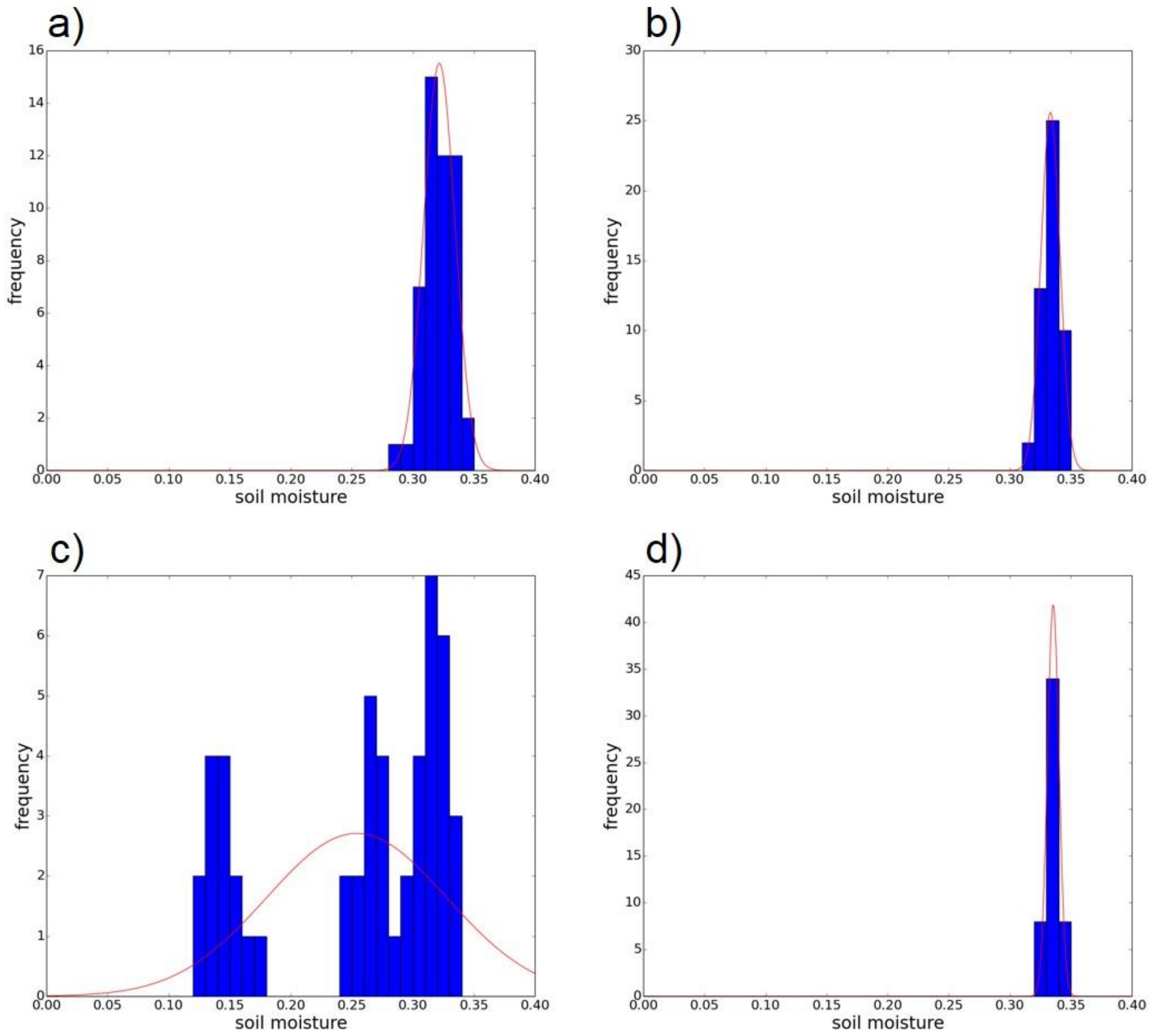

Figure 5. (a) The histogram (blue bars) of the volumetric soil moisture simulated by the NoDA experiment (see section 3) with the LOW_K reference at x=1500m, z=0.5m, and t=130h (see also Figure 4). Red line shows the Gaussian distribution with the mean and variance sampled by the ensemble. (b) same as (a) but at x=2500m, z=0.5m, and t=130h. (c) same as (a) but for the HIGH_K reference. (d) same as (c) but at x=2500m, z=0.5m, and t=130h.

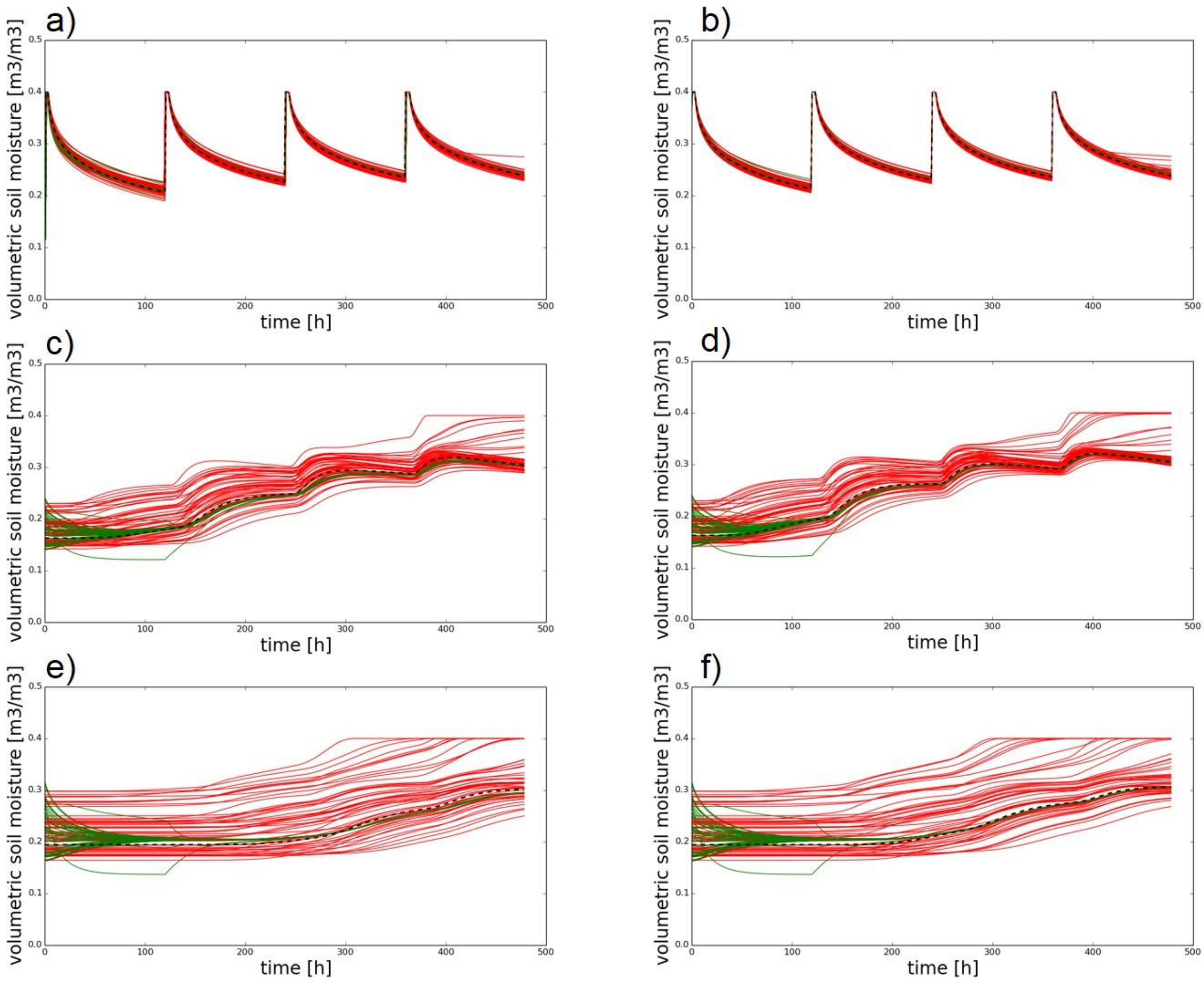

Figure S1. Time series of volumetric soil moisture simulated by the synthetic reference run (black dashed line), the NoDA experiment (red lines), and the DA experiment (green lines) in the LOW_K-UP_O experiment at a) x=1500m, z=0.05m; (b) x=2500m, z=0.05m; c) x=1500m, z=1.0m; (d) x=2500m, z=1.0m; e) x=1500m, z=1.5m; (f) x=2500m, z=1.5m.

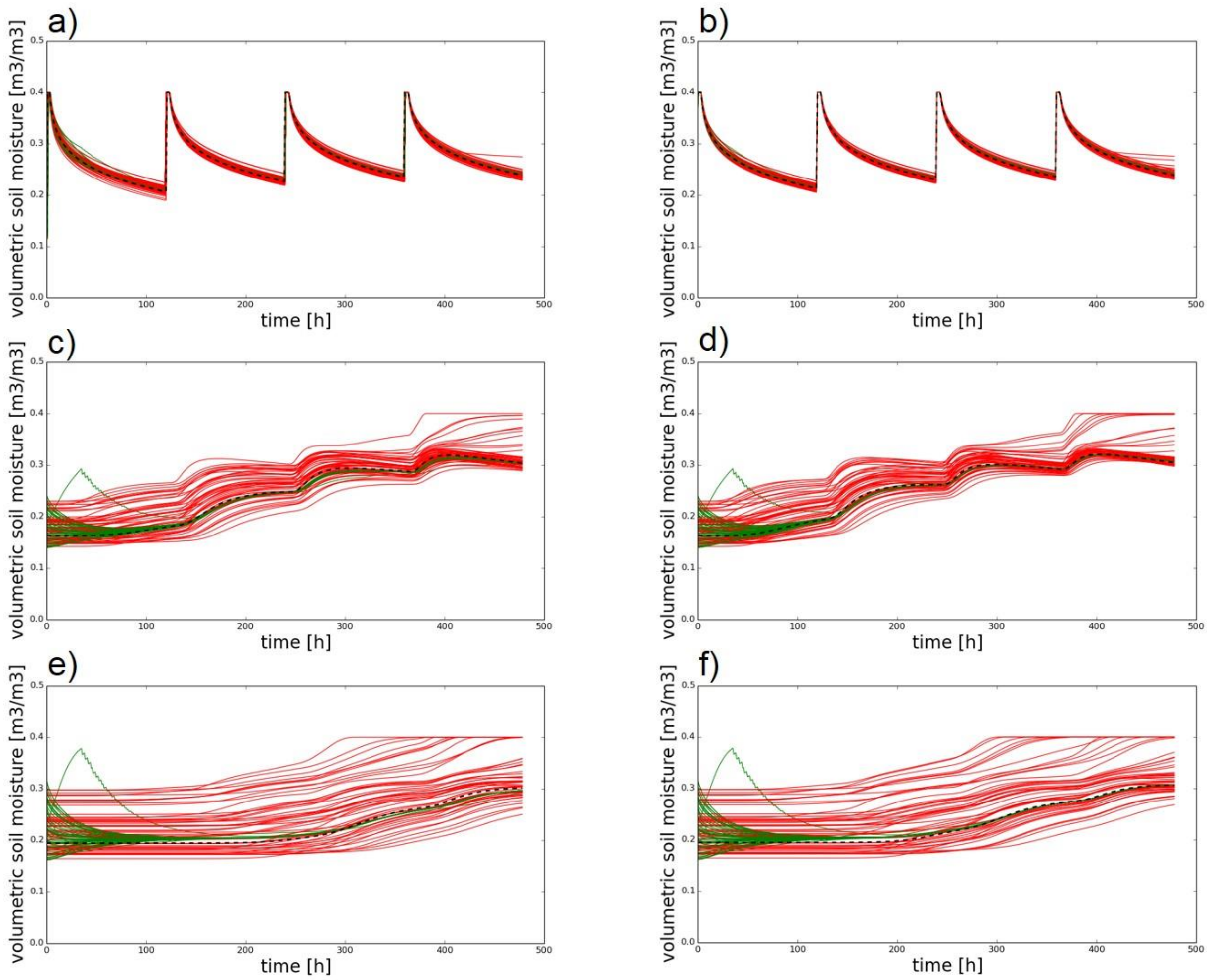

Figure S2. Same as Figure S1 but for the LOW_K-DOWN_O experiment.

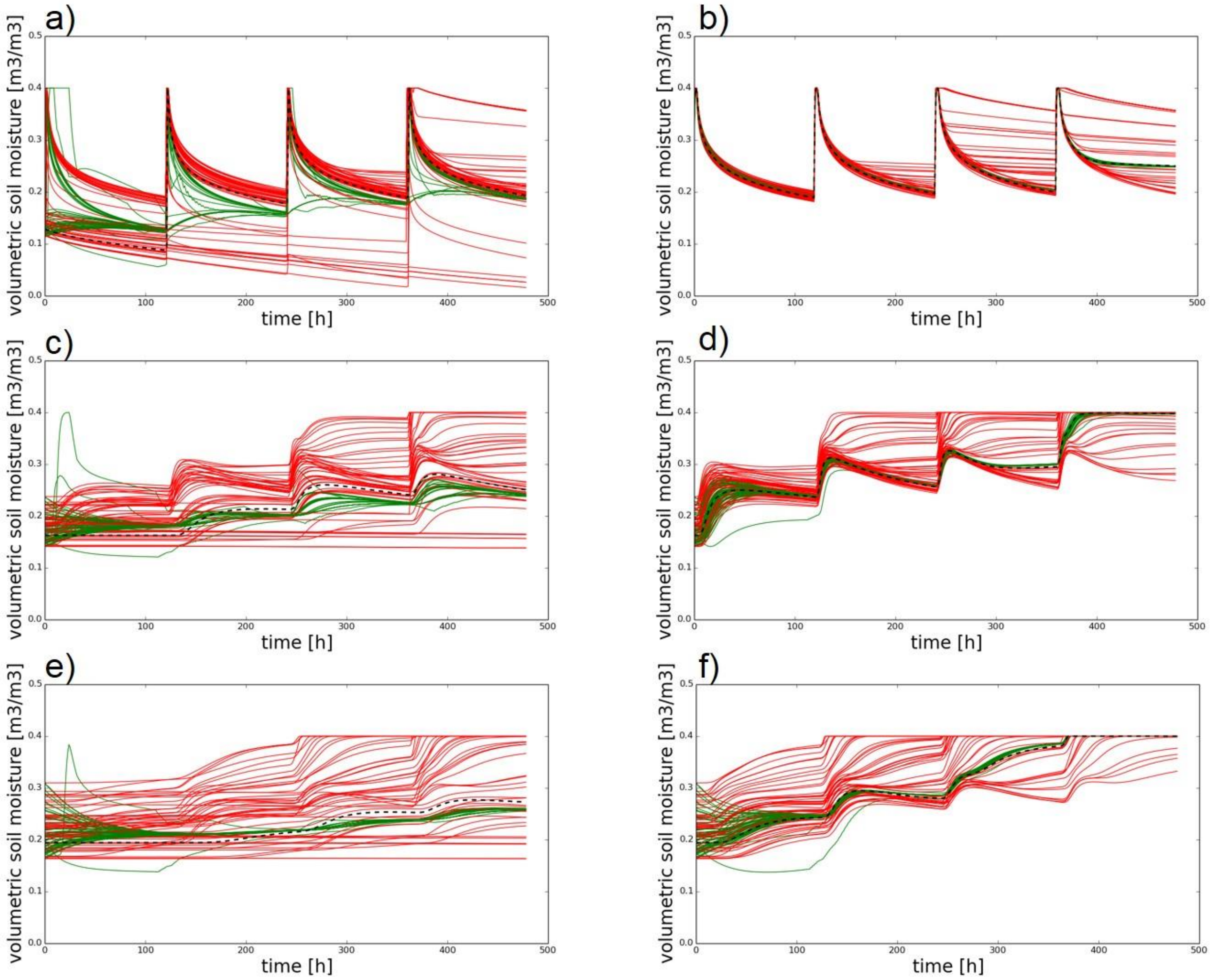

Figure S3. Same as Figure S1 but for the HIGH_K-UP_O experiment.

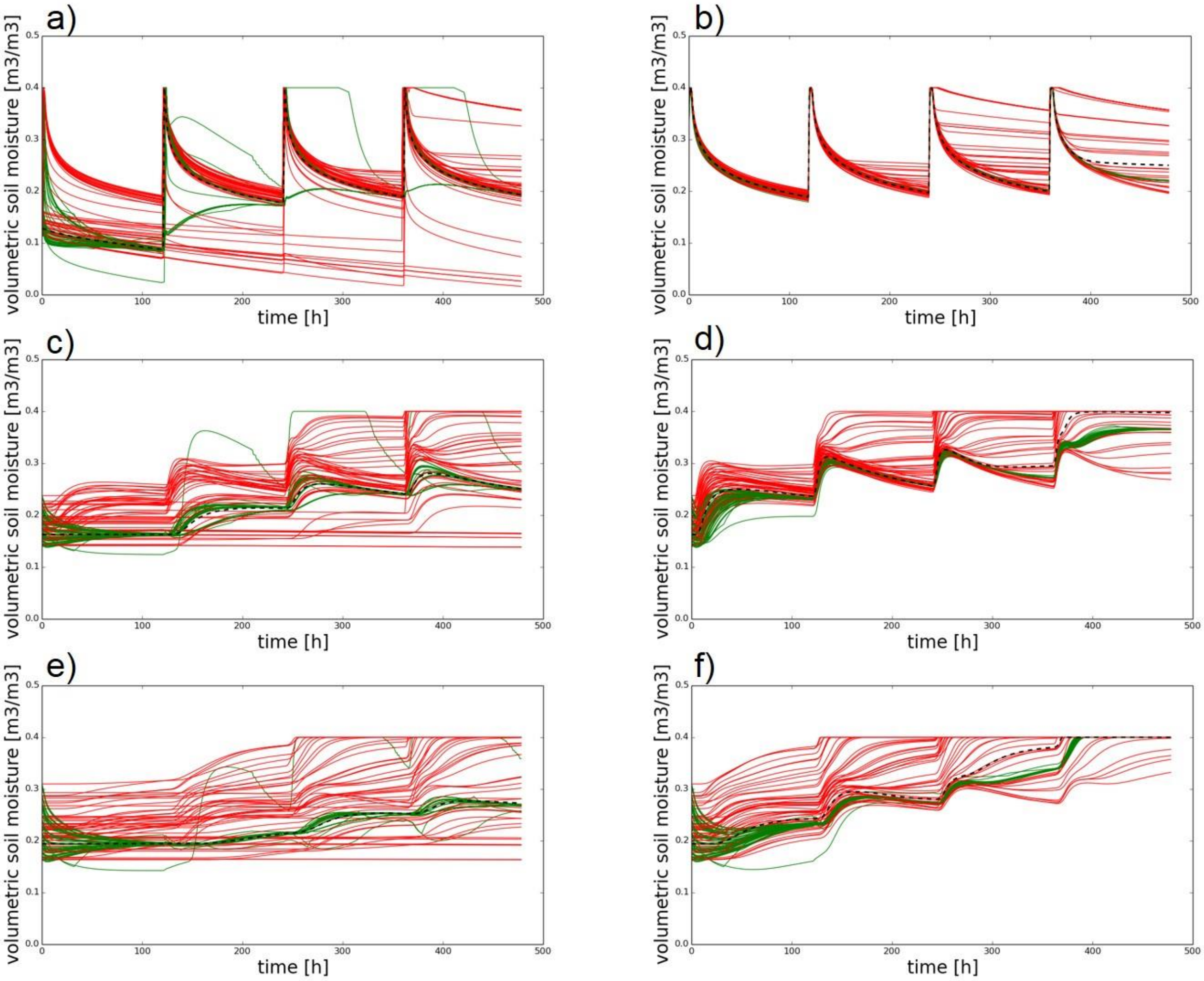

Figure S4. Same as Figure S1 but for the HIGH_K-DOWN_O experiment.