On the Use of the Force–Restore SVAT Model Formulation for Stratified Soils

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ABSTRACT

An approach to simulate soil moisture content with the force–restore soil–vegetation–atmosphere transfer (SVAT) model in the case of stratified soils is proposed. Typical soil profiles possess marked variation in soil hydraulic properties from the soil surface to the base of the root zone. The force–restore method is extensively used for land surface modeling in atmospheric models but without any specific consideration for dealing with stratified soils. Drainage from and recharge to the near-surface soil layer is classically estimated on the basis of the volumetric soil moisture differences between the near surface and lower root zone, with an adjustment for gravitational effects. However, moisture differences do not relate uniquely to differences in hydraulic potentials when the soil properties are vertically inhomogeneous. As a consequence, the classical force–restore formulation does not correctly represent vertical fluxes, and it results in biased time series of predicted near-surface soil moisture. This bias will result in potentially incorrect land surface flux calculations and will also frustrate any efforts to assimilate periodic near-surface soil moisture data into the model. The authors propose a simple model modification that employs knowledge of vertical differences in soil texture and demonstrate its improved performance vis-à-vis the classical formulation. The focus of this study is on the special case of hydrostatic conditions for four theoretical soil profiles and on dynamic model performance in the context of an experimental field dataset.

1. Introduction

Rarely do soils possess vertically homogeneous hydraulic properties; it is more common to find soils that have well-defined layers or a continuous vertical gradient in texture and structure (Hadas and Hillel 1972). In regions with partial vegetation cover, it is common for a less permeable soil-surface layer to develop over a preexisting layer by sealing, crusting, and collimation, in which suspensions of clay or fine particles are deposited on the soil surface or within the soil profile (e.g., Kutílek and Nielsen 1994). Other, more complex layering is also common, resulting in soil profiles with marked variation in soil hydraulic properties from the soil surface to the base of the root zone. In fact, in the absence of detailed field information, soils are often assumed to possess a saturated hydraulic conductivity that decreases exponentially with depth (e.g., Beven and Kirby 1979). Numerous studies have demonstrated how this soil layering affects hydrologic processes such as evaporation and infiltration (Willis 1970; Hadas and Hillel 1972; Kutílek and Nielsen 1994).

The exchange of heat and moisture between the land surface and the atmosphere affects the dynamics and thermodynamics of the weather and climate systems. The states of the surface and root-zone soil moisture reservoirs are key variables controlling surface water and energy balances. In response to this, soil–vegetation–atmosphere transfer (SVAT) models have been developed to simulate these mass and energy transfers and to determine soil moisture conditions correctly from the solution of moisture and energy balance equations (e.g., Noilhan and Planton 1989; Blondin 1991; Famiglietti and Wood 1994). The accuracy of the land surface flux estimates is potentially limited by the accuracy of the soil moisture predictions. Furthermore, emerging efforts in data assimilation seek to guide models with periodic observations of certain state variables, such as surface soil moisture, and any structural bias that may exist in the predicted soil moisture variables will limit the utility of the data–model merger.

The force–restore method is a popular SVAT approach for simulating surface water and energy balances in contemporary meteorological modeling (e.g., Manzi and Planton 1994; Bringfelt et al. 1999; Douville and Chauvin 2000; Giard and Basile 2000; Mölders 2001). This approach has its roots in early work that was restricted to heat exchange and conservation (Bhumralkar

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1975; Blackadar 1976; Deardorff 1978) in which, through an approximation of the heat diffusion equation, the surface thermal status is forced by the net energy exchange with the atmosphere (i.e., net radiation − sensible heat flux − latent heat flux) and is restored on a slower timescale toward the deep-soil temperature. The early form was extended to include simulation of soil moisture content (Deardorff 1978; Noilhan and Planton 1989). For its parsimonious parameterization and reasonable skill, the force–restore SVAT model form is now widely used in land surface modeling (e.g., Manzi and Planton 1994; Noilhan and Mahfouf 1996; Bringfelt et al. 1999; Calvet and Noilhan 2000; Douville and Chauvin 2000; Giard and Basile 2000; Albertson and Kiely 2001; Mölders 2001). This approach is also finding use in the development of operational assimilation protocols (e.g., Ragab 1995; Li and Islam 1999; Wigneron et al. 1999; Montaldo et al. 2001).

Despite the prevalence of vertically inhomogeneous soils in nature and their notable effects on surface and root-zone soil moisture modeling, the widely used force–restore SVAT modeling approach of Noilhan and Planton (1989) has not, to our knowledge, been evaluated or modified for treatment of these typical soil profiles. In this SVAT model, a surface zone and a larger root-zone layer are distinguished for soil moisture modeling, and the restoring term (vertical flow) depends on the contrast of the soil moisture status between the surface and root-zone regions, with an adjustment for gravitational effects. This approach is reasonable for vertically homogeneous soils because the matric potential gradient can be expanded by the chain rule ($\partial\psi/\partial z = \partial\psi/\partial\theta\ \partial\theta/\partial z$) to express a Darcian flux in terms of the moisture content gradient. However, with stratified soil texture, the water-retention relationships vary in the vertical, such that moisture-content gradients do not relate directly to matric potential gradients. We explore this issue here, and we propose and test an improved treatment of stratified soil profiles in the force–restore SVAT formulation.

2. The model equations of the soil water

The basic force–restore equations for the prediction of the land surface fluxes and the evolution of surface temperature and moisture content are described well elsewhere (Noilhan and Planton 1989; Noilhan and Mahfouf 1996). For context, we review the soil moisture evolution equations here. The model considers near-surface and deep (root zone) soil layers of depths d_1 and d_2 and volumetric water contents θ_g and θ_2, respectively, and the state variables evolve according to

$$\frac{\partial\theta_g}{\partial t} = \frac{C_1}{\rho_w d_1}(P_g - E_g) - \frac{C_2}{\tau}(\theta_g - \theta_{geq}) \qquad 0 \le \theta_g \le \theta_s \qquad (1)$$

$$\frac{\partial\theta_2}{\partial t} = \frac{1}{\rho_w d_2}(P_g - E_g - E_{tr} - q_2) \qquad 0 \le \theta_2 \le \theta_s, \qquad (2)$$

where P_g is the precipitation rate infiltrating into the soil, E_g is the bare-soil evaporation rate, E_{tr} is the transpiration rate from the root zone d_2, q_2 is the rate of drainage out of the bottom of the root zone, ρ_w is the density of the water, θ_s is the saturated soil moisture content, C_1 and C_2 are the force and restore coefficients for soil moisture, and θ_{geq} is the equilibrium surface volumetric moisture content describing the hypothetical state in which gravity balances the capillary forces such that there is no vertical water flow into or out of the thin surface zone of depth d_1 (Noilhan and Planton 1989).

The drainage formulation that we adopt (unit gradient) to estimate q_2 is different from that of Mahfouf and Noilhan (1996) and is described in Albertson and Kiely (2001). The value of θ_{geq} is a function of θ_2 and the soil hydraulic properties as derived by Noilhan and Planton (1989):

$$\theta_{geq} = y\theta_s, \qquad (3)$$

$$y = x - ax^p(1 - x^{8p}), \quad \text{and} \qquad (4)$$

$$x = \theta_2/\theta_s, \qquad (5)$$

with the two parameters a and p adjusted according to soil texture, because they account in a lumped sense for soil hydraulic properties. The relationships between soil moisture θ, hydraulic conductivity K, and matric potential ψ are described by

$$\psi = \psi_s(\theta/\theta_s)^{-b} \quad \text{and} \qquad (6)$$

$$K = K_s(\theta/\theta_s)^{2b+3}, \qquad (7)$$

where K_s is the saturated hydraulic conductivity, ψ_s is the air entry potential, and b is the slope of the retention curve in logarithmic space (Clapp and Hornberger 1978).

The force and restore coefficients C_1 and C_2 are described by

$$C_1 = C_{1sat}(\theta_s/\theta_g)^{(b/2)+1} \quad \text{and} \qquad (8)$$

$$C_2 = C_{2ref}[\theta_2/(\theta_s - \theta_2 + \theta_l)], \qquad (9)$$

where C_{1sat} and C_{2ref} are parameters that capture effects of soil texture and θ_l is a small numerical value that constrains C_2 as θ_2 approaches θ_s (Noilhan and Planton 1989). The C_{1sat} and C_{2ref} values are estimated from the literature on the basis of soil texture (Noilhan and Planton 1989).

In stratified soils, for which the soil hydraulic properties and texture characteristics differ from the surface layer to the deep soil, it is generally necessary to define values of K_s, ψ_s, θ_s, and b for each layer. However, the structure of the restoring term in (1), describing drainage from and recharge to θ_g, is not directly adaptable to a stratified soil. The role of the restoring term is to capture the effect of flow across the plane $z = d_1$ on the volumetric moisture content above $z = d_1$. The difference $\theta_g - \theta_{geq}$ must represent the effect of the vertical gra-

Table 1. Soil hydraulic properties and texture in surface and root-zone regions for the four soil types.

	$z < d_1$		$d_2 < z < d_1$							
Soil type	Sand (%)	Clay (%)	Sand (%)	Clay (%)	$\theta_{s,g}$	$\Psi_{s,g}$ (cm)	b_g	$\theta_{s,2}$	$\Psi_{s,2}$ (cm)	b_2
Homogenous	50	37.5	50	37.5	0.497	3.54	9.5	0.497	3.54	9.5
Sand/clay	80	20	20	55	0.440	0.57	8.4	0.530	48.95	10.4
Clay/sand	20	55	80	20	0.540	54.32	10.6	0.450	5.95	8.7
Exponential	80	20	38	47.1	0.440	0.54	8.5	0.509	19.65	10.4

dient of hydraulic potential (between surface zone and lower root-zone region), with C_2 serving to map moisture content to matric potential units and to scale by the conductivity. The most significant obstacle for the stratified soil case is the $\theta_{g\mathrm{eq}}$ term. Recall from (3)–(5) that $\theta_{g\mathrm{eq}}$ is a function of θ_2, with adjustments to account for the relative importance of capillary and gravity forces. Hence, if θ_g is greater than the equilibrium value $\theta_{g\mathrm{eq}}$, then the upper soil is expected to be draining to the lower portion of the root zone, but if θ_g is less than $\theta_{g\mathrm{eq}}$, then the upper layer is expected to be recharging from below. This approach is flawed for a stratified soil, because vertical water movement is based on the vertical contrast in matric potential, and the mapping function between matric potential and moisture content varies over the vertical with soil texture.

The unsuitability of moisture-content gradients for estimating water flow in inhomogeneous soils can be demonstrated by considering the interface between two distinct soil texture layers: the water flux across the interface must be finite, and therefore the matric potential gradient must be finite, which restricts the matric potential to a smooth profile; however, the sharp discontinuity in soil hydraulic properties [(6)–(7)] translates the smooth matric potential profile into a sharp discontinuity (infinite gradient) in moisture content at the interface (Kutílek and Nielsen 1994).

First, we explore the impact of stratified soil profiles on the restoring term of (1) for an important reference case, that of zero vertical flow under a hydrostatic matric potential profile. We consider four different soil profiles that span a wide range of conditions:

1) homogenous soil of intermediate texture characteristics (‘‘homogeneous’’);
2) layered soil with a sand surface layer and a clay deep layer (‘‘sand/clay’’);
3) layered soil with a clay surface layer and a sand deep layer (‘‘clay/sand’’); and
4) layered soil with a classic exponential decrease of hydraulic conductivity with depth (‘‘exponential’’) as, for example, is widely assumed in the use of ‘‘TopModel’’ (Beven and Kirby 1979).

Table 2. Soil hydraulic properties and texture for the fourth soil type (the classic soil with an ‘‘exponential’’ decrease of hydraulic conductivity with depth).

Lower limit (cm)	Upper limit (cm)	Sand (%)	Clay (%)	θ_s	Ψ_s (cm)	b
0	10	80	20	0.440	0.57	8.5
10	20	67	31	0.474	0.74	10.1
20	30	57	39	0.494	1.53	10.9
30	40	48	43	0.506	3.90	10.7
40	50	40	47	0.516	8.99	10.7
50	60	34	50	0.524	16.62	10.7
60	70	29	52	0.530	26.65	10.7
70	80	25	53	0.534	36.82	10.5
80	90	22	54	0.537	46.34	10.5
90	100	20	55	0.540	54.32	10.6

In this case, all the soils are assigned a root-zone depth d_2 equal to 1 m and a surface zone depth d_1 equal to 0.1 m for analysis in the force–restore framework. In Table 1 the depth-averaged values of the sand and clay contents are reported for the two model zones (where % silt = 100% − % sand − % clay). In Table 2, sand and clay contents for layers of the exponential soil type are listed. The Clapp and Hornberger (1978) parameters are defined by continuous pedotransfer functions (PTFs), which differ from the class PTFs because they enable the estimation of soil hydraulic characteristics directly from soil texture, bulk density, and organic matter content (e.g., Wösten et al. 1995; Tietje and Tapkenhinrichs 1993; Cresswell and Paydar 2000). For this demonstration, we adopted simple PTFs derived by Saxton et al. (1986) for the estimation of ψ_s, θ_s, and b values from knowledge of the sand and clay contents. These functions are reported to be effective for soils with clay contents between 5% and 60%, sand content greater than 5%, and for absolute water potential greater than 10 kPa (Saxton et al. 1986). The estimated values of the hydraulic properties are reported in Table 1 for the surface zone and the total root zone (depth d_2) for each soil type. Table 2 contains the estimated hydraulic properties versus depth for the exponential soil type.

For this case with soils in hydraulic equilibrium, that is, in hydrostatic conditions, and assuming a water table depth of 2 m, the soil water content as a function of the soil type and depth can be estimated for each soil type. Figure 1 demonstrates the significant influence that soil stratification has on the soil water content profile, even under this simple hydrostatic (no flow) case.

The soil moisture contents averaged over the surface zone θ_g and over the entire root zone θ_2 are reported in Table 3 and are used to estimate the second term on the right-hand side of (1) that describes predicted vertical recharge to (when $\theta_g - \theta_{g\mathrm{eq}} < 0$) or drainage from (when

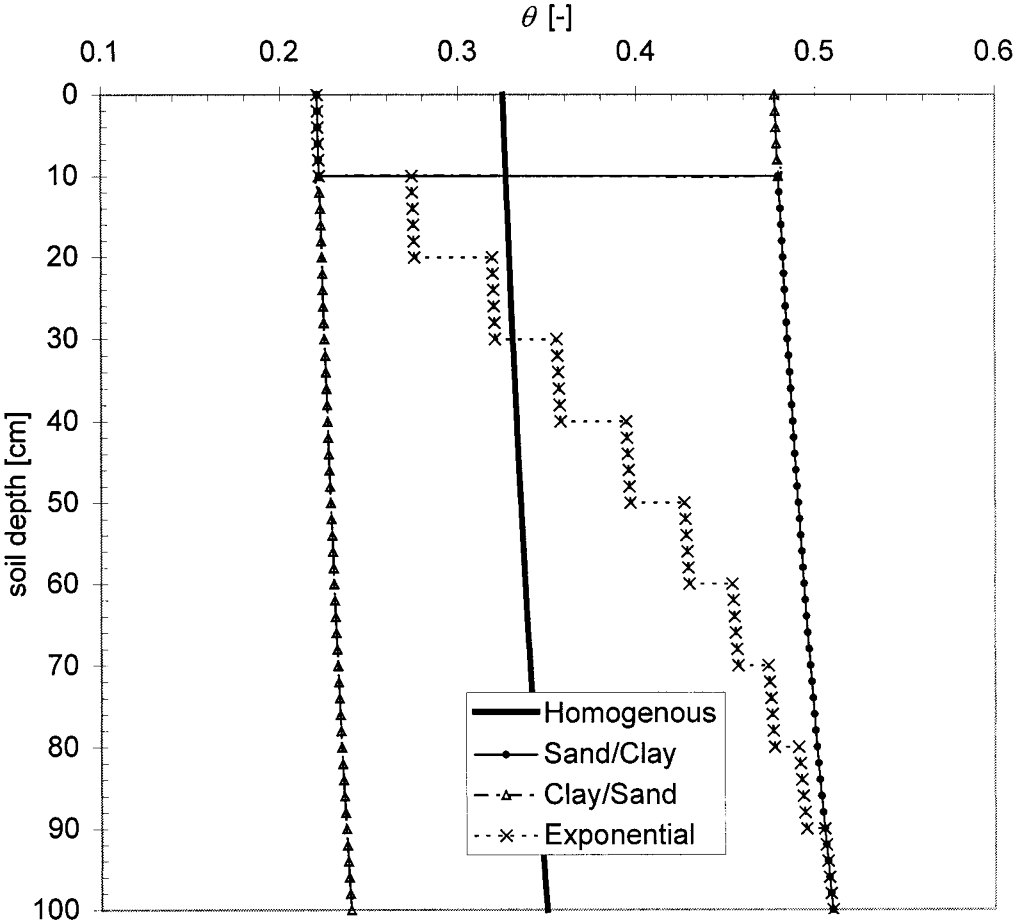

FIG. 1. Soil moisture content vs depth for the four profiles under hydrostatic conditions.

$\theta_g - \theta_{geq} > 0$) the surface zone. In stratified soils, the estimate of the restoring term of (1) is not generally correct, as demonstrated by the "$\theta_g - \theta_{geq}$" column of Table 3 for this important and fundamental hydrostatic case. In fact, it fails for all the layered cases. In this hydrostatic condition, by the definition of θ_{geq}, the $\theta_g - \theta_{geq}$ term should be identically 0. This condition is only satisfied for the homogenous soil type. The force–restore SVAT model would erroneously predict a significant upward flow for the sand/clay and exponential soils and a significant downward flow for the clay/sand soil profile. Hence, the coarse-over-fine profiles would have a positive bias in the near-surface soil moisture whereas the fine-over-coarse soils would have a negative bias vis-à-vis observations. These biases would lead to errors in land surface flux estimation and, furthermore, would frustrate data assimilation efforts using remotely sensed near-surface soil moisture.

To remedy this glaring model deficiency, we propose to rescale the root-zone soil moisture to an "equivalent" root-zone soil moisture that more accurately reflects (in evaluation against θ_g) the vertical water-flow status. This is accomplished by calculating the root-zone matric potential from (6) and then determining what the corresponding root-zone soil moisture value would be [from inverse of (6)] if the root-zone soil properties where identical to those in the surface zone. Hence, this is the equivalent homogeneous-profile root-zone mois-

TABLE 3. Soil moisture contents for the four profile cases in hydrostatic conditions: $\theta_g - \theta_{geq}$ is the restoring impulse to θ_g in the original model and $\theta_g - \hat{\theta}_{geq}$ is the restoring impulse with the proposed modification.

Soil type	θ_g	θ_2	θ_{geq}	$\theta_g - \theta_{geq}$	$\hat{\theta}_2$	$\hat{\theta}_{geq}$	$\theta_g - \hat{\theta}_{geq}$
Homogenous	0.326	0.335	0.329	−0.003	0.335	0.329	−0.003
Sand/clay	0.221	0.476	0.458	−0.236	0.228	0.221	0.000
Clay/sand	0.478	0.311	0.289	0.189	0.490	0.472	0.006
Exponential	0.221	0.419	0.403	−0.182	0.228	0.221	0.000

Table 4. Soil hydraulic properties estimated in the experimental site in Duke Forest (Lai and Katul 2000).

Depth (cm)	Soil texture	K_s (cm day^{-1})	θ_s	$\lvert\Psi_s\rvert$ (cm)	b
0–16	Silt loam	15.1	0.30	32.0	4.0
17–22	Loam	5.1	0.38	10.0	4.5
24–33	Silt clay loam	5.5	0.45	62.6	6.5
34–37	Silt clay	3.5	0.56	20.0	7.0
38–45	Clay	1.5	0.63	30.0	10.6

ture content, which is based on the matric potential profile and consequently will reflect more directly the vertical water-flow status. The contrast between θ_g and the equivalent or adjusted root-zone soil water content $\hat{\theta}_2$ is directly related to the contrast between ψ_g and ψ_2. Combining several algebraic steps, the root-zone adjusted value is given by

$$\hat{\theta}_2 = \theta_{s,g}(\theta_2/\theta_{s,2})^{b_2/b_g}(\psi_{s,2}/\psi_{s,g})^{-(1/b_g)}, \qquad (10)$$

where the subscripts g and 2 indicate the soil parameters of, respectively, the surface zone of depth d_1 and the root zone of depth d_2.

Values of $\hat{\theta}_{geq}$ from (3) and C_2 from (9) are calculated using $\hat{\theta}_2$ and soil hydraulic properties of the surface zone. In this way, the restoring term of (1) should estimate more accurately the drainage and recharge fluxes between the surface and deeper soil layers. In the last three columns of Table 3, the derived values of $\hat{\theta}_2$ and $\hat{\theta}_{geq}$ are shown, and we note that the recalculated values of $\theta_g - \hat{\theta}_{geq}$ effectively vanish, as required for a hydrostatic profile. This parsimonious modification (correction) to the force–restore model structure is evaluated next under dynamic conditions in the context of field data.

3. Application of the proposed approach for stratified soil

We explore the dynamic behavior of the proposed approach for the stratified soil encountered during a field campaign carried out in the summer of 1997 in a grass-covered field near the Duke Forest in Durham, North Carolina. The general experimental setup and conditions are described elsewhere (Lai and Katul 2000). Soil moisture measurements were made with eight CS615 soil water content reflectometers (Campbell Scientific, Inc., Logan, Utah) that were positioned horizontally every 0.05-m depth increment between 0.05 and 0.45 m below the ground surface. All data were time averaged to a resolution of 20 min. The soil is composed of several layers of different hydraulic properties and textural characteristics. The soil profile is qualitatively similar to the exponential soil profile considered above. In Table 4, the estimated values of the soil characteristics are reported (Lai and Katul 2000).

In Table 5, parameter values used in the SVAT model are reported; the values of root-zone soil hydraulic properties are averaged over the full d_2 depth. Model parameters were measured by Lai and Katul (2000) or were taken from the literature on the basis of measured texture, thus avoiding the use of parameter calibration. We do not report surface temperature and surface fluxes, because they are outside the scope of the study, but they too were in good agreement with measurements, where available. Figure 2 shows the simulated and observed soil moisture contents of the surface and root-zone layers for each of three model versions: 1) in the top panel, the original force–restore method is used; 2) in the middle panel, we used a version of the model that simply takes account of the different hydraulic properties for the surface and root-zone layers [note that this version

Table 5. Parameter values used in the SVAT model for the Duke Forest experimental site [L2000: Lai and Katul (2000); N1989: Noilhan and Planton (1989); D1977: Donahue et al. (1977); B1982: Brutsaert (1982); obs: approximate value from field observations].

Parameter	Description	Value	Source
K_{s2} (m s^{-1})	Whole soil depth average value of the saturated hydraulic conductivity	7.1×10^{-7}	L2000
$\theta_{s,2}$	Whole soil depth average value of the saturated soil moisture content	0.46	L2000
$\lvert\Psi_{s,2}\rvert$ (m)	Whole soil depth average value of the air entry soil tension	0.31	L2000
b_2	Whole soil depth average value of the slope of the retention curve in logarithmic space	6.5	L2000
K_{sg} (m s^{-1})	Surface zone value of the saturated hydraulic conductivity	1.75×10^{-6}	L2000
$\theta_{s,g}$	Surface zone value of the saturated soil moisture content	0.30	L2000
$\lvert\Psi_{s,g}\rvert$ (m)	Surface zone value of the air entry soil tension	0.32	L2000
b_g	Surface zone value of the slope of the retention curve on logarithmic profile	4	L2000
$C_{1\mathrm{sat}}$	Value of C_1 parameter in (1) at saturation	0.15	N1989
$C_{2\mathrm{ref}}$	Reference value of the C_2 parameter in (1)	0.8	N1989
θ_{wilt}	Wilting point	0.10	D1977
θ_{fc}	Field capacity	0.20	D1977
f_v	Fraction of vegetation	0.85	Obs
$r_{s,\min}$ (s m^{-1})	Minimum stomatal resistance	300	Obs
LAI (m^2 m^{-2})	Leaf area index	3	L200
z_{0m} (m)	Roughness length for momentum	0.1	L200
z_{0s} (m)	Roughness length for scalars	$z_{0m}/7.4$	B1982
d_2 (m)	Depth of root zone	0.45	L2000
d_1 (m)	Surface zone scaling depth	0.1	N1989

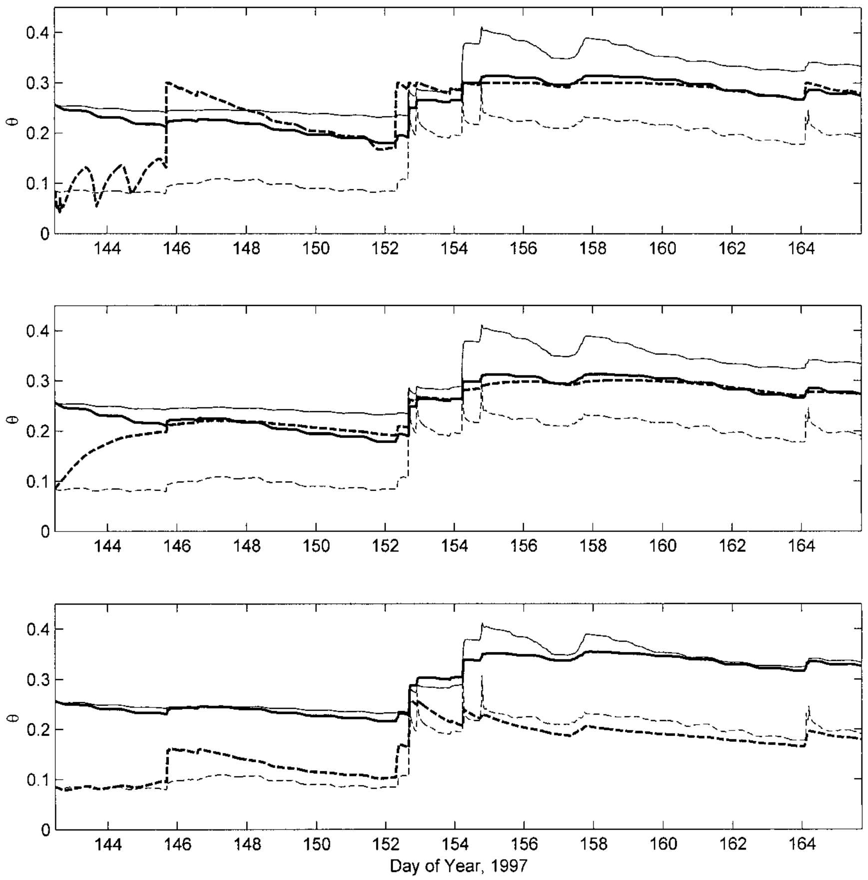

FIG. 2. Time series of the soil moisture content simulated in the surface zone ($\theta_{g,\mathrm{sim}}$, bold dashed line), simulated in the root zone ($\theta_{2,\mathrm{sim}}$, bold solid line), observed in the surface zone ($\theta_{g,\mathrm{obs}}$, dashed line), and observed in the root zone ($\theta_{2,\mathrm{obs}}$, solid line): (top) the original model results, (middle) simulation results using different hydraulic properties for surface and root zone soil layers (i.e., adjusted C_1), and (bottom) results from the proposed modification to the SVAT model.

only modifies the C_1 calculation given by (8); there is no modification to $\theta_{g\mathrm{eq}}$]; and 3) in the bottom panel, the results of the force–restore SVAT model modified for stratified soils as described above are shown [e.g., (10)]. A significant improvement in the simulation results vis-à-vis the measurements is obtained using the proposed correction. The rmse values of the θ_g predictions, with respect to the observed values, decreased from 0.099 for the original force–restore method to 0.027 using the proposed method [per (10)]. The rmse values of the θ_2 simulations similarly improved from 0.048 to 0.017 when the proposed model correction is used. These are relatively large changes in terms of volumetric soil moisture. In Fig. 3, a comparison of the observed and simulated soil moisture values for the three model versions is reported for each in the surface zone (top panel) and the entire root zone (bottom panel). The analysis of these scatterplots confirms the effectiveness of the proposed approach for reducing the bias in simulations of soil moisture content in stratified soil systems, for the near-surface zone and also the entire root zone.

To demonstrate more clearly the soil moisture prediction improvements obtained from the proposed approach for stratified soils, we tested the proposed approach in the presence of uncertainties in the soil physical parameters. The uncertainties were included by varying the $\theta_{s,2}$, b_2, and $\psi_{s,2}$ parameter values over a reasonable range of variability (e.g., Clapp and Hornberger 1978). The proposed approach and the original force–restore formulation were each run with the intentionally biased soil properties, and the resulting predicted θ_g and θ_2 time series were compared with the measured series (Fig. 4). The simulation results confirm that the proposed approach yields improved predictions over the full range of soil parameter values, thus reinforcing the apparent robustness of the proposed approach.

4. Conclusions

In the case of layered soils, the application of the force–restore method can lead to poor simulations of the surface and deep soil moisture. The classical model formulation leads to a biased time series of near-surface

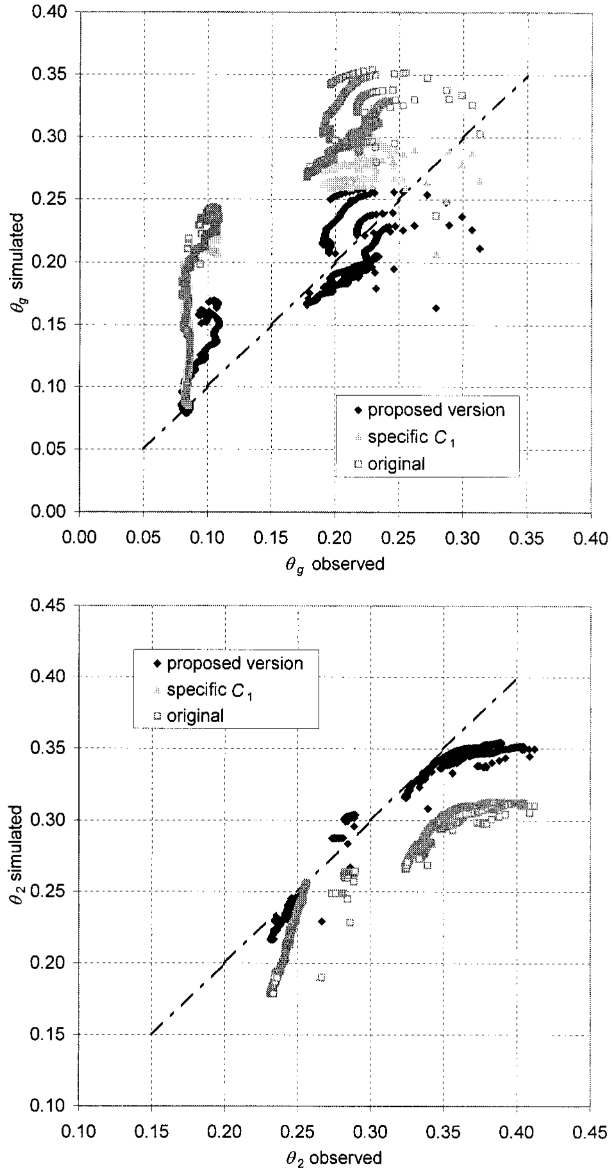

FIG. 3. Comparison of measured and simulated surface soil moisture for the original SVAT model, the form with differentiation of soil surface and root-zone soil hydraulic properties (i.e., adjusted C_1), and with the proposed modifications to the SVAT model: (top) surface soil moisture comparison results and (bottom) results for the root zone.

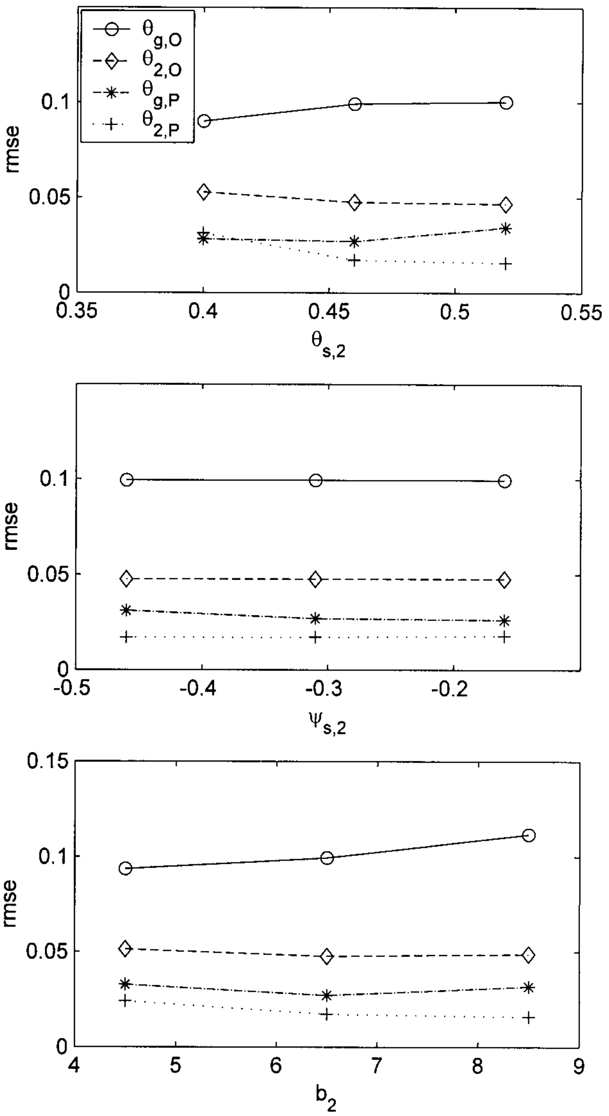

FIG. 4. Comparison of rmse in surface and root-zone soil moisture simulations using the original method and the proposed approach in the presence of uncertain values of (top) $\theta_{s,2}$, (middle) $\psi_{s,2}$, and (bottom) b_2 parameter values. Labels $\theta_{g,O}$ and $\theta_{g,P}$ indicate results for surface-zone soil moisture predictions using, respectively, the original model and the proposed approach; $\theta_{2,O}$ and $\theta_{2,P}$ indicate results for root-zone soil moisture predictions using, respectively, the original model and the proposed approach.

soil moisture, which injects errors to land surface flux estimation and frustrates efforts for the assimilation of periodic observations. Only for soil profiles that are vertically homogenous can the drainage and capillarity movements into and from the surface layer be readily represented by water content differences between two depth layers. A demonstration of the force–restore method for four theoretical (vertically heterogeneous) soil profile types under hydrostatic conditions revealed the significant errors that can be realized from the classical model structure. The modification proposed here rescales the deep soil moisture content by the relative difference of top and bottom soil properties to estimate correctly the restoring (recharge–discharge) term of the surface soil water balance.

In addition to satisfying the important hydrostatic case, the proposed correction significantly improves model performance in the soil moisture simulations under field conditions for a typical layered soil. These results motivate use of this parsimonious model modification to the force–restore SVAT model formulation for stratified soils. These results are especially important and promising to ongoing efforts to assimilate remotely sensed soil moisture into land surface models.

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