Extension of an Existing Model for Soil Water Evaporation and Redistribution under High Water Content Conditions

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Most crop, hydrology, and water quality models require the simulation of evaporation from the soil surface. A model developed by J.T. Ritchie in 1972 provides useful algorithms for estimating soil evaporation, but it does not calculate the soil water redistribution resulting from evaporation. A physically-based model using diffusion theory, described previously by Suleiman and Ritchie in 2003, provides efficient algorithms for soil water redistribution and soil evaporation. However, the model is appropriate only for second stage drying when the soil in the entire profile being simulated is below the drained upper limit (θ_{DUL}) and no more drainage occurs due to gravity. This paper extends the Suleiman–Ritchie model for soil water contents higher than θ_{DUL} where soil evaporation rates are usually higher than second stage drying. New algorithms were developed for these wetter conditions that are functions of soil depth and the wetness of the near-surface soil. New model parameters were calibrated with data measured in laboratory soil column studies. The resulting model was integrated into DSSAT-CSM (Decision Support System for Agrotechnology Transfer Cropping Systems Model). Simulated soil evaporation rates and soil water contents obtained using the Suleiman–Ritchie model with the developed extensions and the previous DSSAT soil evaporation model were compared and evaluated with field measurements of soil water content during several drying cycles for parts of 3 yr in North Central Florida. Computed soil water contents from the model agreed well with the measured soil water contents near the surface, and provided more accurate estimations than the original DSSAT soil evaporation model, especially for the 5-cm surface layer.

Abbreviations: θ_{DUL}, Soil water content at drained upper limit (cm^3 cm^{-3}); CSM, Cropping Systems Model; DSSAT, Decision Support System for Agrotechnology Transfer; ES, evaporation of water from soil surfaces (cm); ESR, Extended Suleiman and Ritchie soil evaporation model; LAI, Leaf area index (m^2 m^{-2}); MAE, mean average error; MicroWEX, Microwave, Water, and Energy Balance Experiment; ORD, Original Ritchie DSSAT soil evaporation model; SR, Suleiman and Ritchie method of soil evaporation using diffusion theory.

Evaporation of water from soil surfaces (ES) is a major component in the soil water balance for field crops with incomplete cover and for bare soil conditions. Quantification of ES is necessary in evaluating the water balance of soils for use in environmental and hydrologic studies and for crop management. Two basic approaches have been used to simulate ES: (i) mechanistic models of soil water and heat transfer following basic theory reported by Philip and DeVries (1957), and (ii) functional models similar to that of Ritchie (1972). The mechanistic models have proven to work well for uniform laboratory soil conditions and have been demonstrated to work reasonably well for field conditions (Jackson et al., 1974; Rose, 1968a, 1968b; Lascano and van Bavel, 1983, 1986). Mechanistic models require more detailed spatial and temporal inputs and calculations (Ritchie and Johnson, 1990).

Functional models have also proven to work well for field conditions (Ritchie, 1972; Black et al., 1969). Unlike mechanistic models, functional models for ES have used crude but logical approximations for soil water redistribution (Ritchie, 1998). Recently, Suleiman and Ritchie (2003), hereafter referred to as SR, introduced a physically-based model for soil water redistribution during evaporation using a diffusion-based concept. The procedure required an initial condition of soil water content being equal to or less than the drained upper limit (θ_{DUL}) throughout the profile being simulated. Under these conditions, water would no longer drain from the profile. When the soil water content is above θ_{DUL} in any part of the profile, the empiricisms in the SR procedure underestimate ES and thus do not simulate the soil water distribution accurately. Without modification, the SR model was not suitable for implementation in a general soil water simulation model because it could not adequately model wet soil conditions. This paper develops and tests an extension to the SR approach when all or part of the soil profile is above θ_{DUL} such as after rainfall or irrigation or when a shallow water table is present. The model has been implemented in the comprehensive DSSAT-CSM (Jones et al., 2003), which uses a daily time increment.

Soil Sci. Soc. Am. J. 73:792-801
doi:10.2136/sssaj2007.0325
Received 6 Sept. 2007.
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The objectives of this study were: (i) to extend the SR soil evaporation model for use with wetter soil water conditions; (ii) to implement this extended model into DSSAT-CSM; (iii) to evaluate the model performance within DSSAT using field and lab experimental data; and (iv) to compare soil evaporation rates and soil water contents predicted by the extended SR model with those of the previous soil evaporation model within DSSAT-CSM.

BACKGROUND

The SR paper presented two sets of laboratory soil column studies using different initial conditions. Although not mentioned in the procedures section of that paper, 60 cm deep columns were brought to the initial conditions of θ_{DUL} throughout the profile by using suction at the bottom of the columns. The columns were placed in a container of dry soil to provide the suction until the θ_{DUL} water contents were obtained. Under those initial conditions, measured soil water in depth and time was in good agreement with the model based on the SR diffusion theory. A second set of 150 cm deep columns were used with stable initial conditions established by gravity drainage with no suction at the bottom. Measured soil water contents during drying of these columns did not result in values that agreed with the diffusion theory concept. The slope of cumulative ES values plotted against square root of time was about four times larger than those obtained when the boundary condition of θ_{DUL} were met throughout the soil profile. Water contents plotted against the Boltzmann transformation (depth · time$^{-0.5}$) did not result in a single-valued function as did the soils with the appropriate water content boundary conditions.

The model of Ritchie (1972) simulates ES in two stages: (i) first stage or energy-limited, whereby soil water can move to the surface faster than the evaporativity of the air could remove it and (ii) second stage, whereby soil properties control the rate of water movement to the surface. There was assumed to be a constant amount of water available for evaporation in the energy limited stage, ranging from 2 to 15 mm. This value was a required input parameter to the model and was thought to be a function of the soil hydraulic properties below the surface. However, the laboratory columns in the SR study that were not drained with a suction at the bottom had a much larger ES in the energy limited stage than the Ritchie (1972) paper implied for both the sandy loam and loam soil. This evidence suggests that the energy limited evaporation stage is primarily controlled by hydraulic properties of the soil below the surface that prevent water from draining out of the soil as rapidly as it does in well-drained soils.

Data from the SR paper also demonstrate that ES was smaller than the potential evaporation after about 3 d of drying but much higher than the typical second stage evaporation. Thus, true second stage drying, when ES is proportional to the square root of time after wetting, only occurs when the water in both the upper and the lower levels of the soil have drained to near or below θ_{DUL}. This implies that there are no clear boundaries to describe first and second stage ES.

MATERIALS AND METHODS

Soil Evaporation Model Based on Diffusion Theory

The primary equation derived from diffusion theory by Suleiman and Ritchie (2003) is shown below. This equation was derived for soils after they had been allowed to drain to θ_{DUL} throughout the soil profile.

$$\Delta\theta_{ESz,t} = -\left(\theta'_{z,t} - \theta_{ADz}\right)F_z \quad \text{for } \theta'_{z,t} < \theta_{DULz} \qquad [1]$$

where $\Delta\theta_{ESz,t}$ = daily change in volumetric water content at depth z, due to evaporation on day t (cm^{3}cm^{-3}d^{-1}). $\theta'_{z,t}$ = volumetric water content at depth z, on day t calculated from the previous day's $\theta_{z,t-1}$ and simultaneous drainage and infiltration processes on day t (cm^{3}cm^{-3}). Computation of this term is detailed later in this paper. θ_{ADz} = air dry volumetric water content at depth z (cm^{3}cm^{-3}). θ_{DULz} = volumetric water content at drained upper limit at depth z (cm^{3}cm^{-3}). F_z = transfer coefficient for soil at depth z (d^{-1}). z = mean depth of soil layer (cm).

The upward flow coefficient (F_z) in Eq. [1], as reported by SR is computed as:

$$F_z = a_z z^{(b_z)} \quad \text{for } z > 1 \text{ cm} \qquad [2]$$

Coefficients a_z and b_z are empirical coefficients at depth z, which were developed according to diffusion theory. The parameters used to compute these coefficients were based on laboratory experiments. These regression equations are independent of soil type and are given by the following equations:

$$a_z = 0.5 + 0.24\theta_{DULz} \qquad [3]$$

$$b_z = -2.04 + 0.20\theta_{DULz} \qquad [4]$$

The total daily soil evaporation, ES_t, is computed by summing the evaporation from each soil layer, accounting for layer thickness, d_z, and by limiting the total to no more than the potential soil evaporation, E_{OSt}, as shown in Eq. [5].

$$ES_t = MIN\left\{E_{OSt}, \sum_z \Delta\theta_{ESz,t} d_z\right\} \qquad [5]$$

The potential evapotranspiration is calculated separately in DSSAT-CSM by the user's choice of several methods. When the total soil evaporation is limited by potential soil evaporation, the computed evaporation from each layer is reduced proportionally.

Pseudo-Integration Step for Modular Daily Model

The modular structure of DSSAT-CSM (Jones et al., 2003) requires that all rate processes be calculated each day based on state variables computed on the previous day, using a daily time step. Integration of the model processes such as drainage and evaporation, which occur simultaneously and are computed in separate modules, becomes problematic. The $\theta'_{z,t}$ in Eq. [1] would normally represent the soil water content at the end of the previous day. However, soil evaporation calculations need to take into account the effects of both drainage and infiltration, which are occurring simultaneously during the current day of simulation. Therefore, a pseudo-integration step computes $\theta'_{z,t}$, which represents an average value of soil water content on day t as computed in Eq. [6a] and [6b].

$$\theta'_{z,t} = \theta_{z,t-1} + 0.5\Delta\theta_{Dz,t} \quad \text{for } \Delta\theta_{Dz,t} > 0 \qquad [6a]$$

$$\theta'_{z,t} = \theta_{z,t-1} + \Delta\theta_{Dz,t} \quad \text{for } \Delta\theta_{Dz,t} \le 0 \qquad [6b]$$

where $\theta_{z,t-1}$ = volumetric water content at depth z, on day $t-1$ (cm^{3}cm^{-3}) and $\Delta\theta_{Dz,t}$ = change in volumetric water content at depth z, due to drainage and infiltration on day t (cm^{3}cm^{-3}d^{-1}).

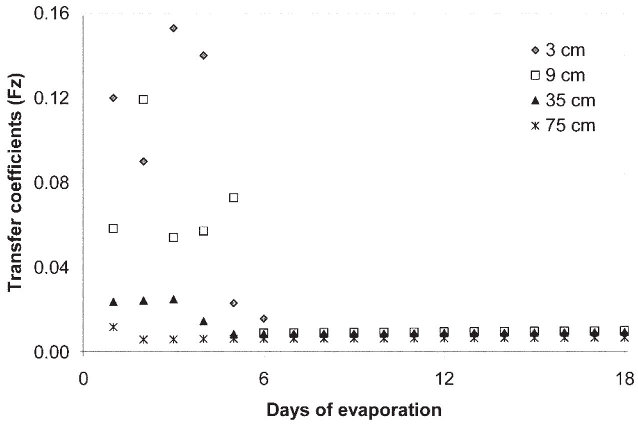

Fig. 1. Transfer coefficients computed from measured data in the Suleiman and Ritchie 150-cm wet soil column study for four depths of the Loam soil.

Any increase in soil water content due to rainfall on the current day would normally not be "seen" by the soil evaporation routine until the following day. The 0.5 parameter in Eq. [6a] allows half of the simultaneously occurring increase in soil water content to become available for evaporation on the current day of simulation rather than on the subsequent day, implying that rainfall or irrigation occur closer to midday than midnight. Equation [6b] applies to days where drainage reduces the soil water available for evaporation. This equation prevents calculation of excess evaporation that could lead to negative computed soil water content.

Drainage is computed in a separate module of DSSAT-CSM. This procedure uses a tipping-bucket approach for computing soil water drainage when water content in a soil layer is greater than θ_{DUL} (Ritchie et al., 1986). Drainage through the profile is first calculated based on an overall soil drainage parameter assumed to be constant with depth. The rate of drainage in each soil layer is limited by the saturated hydraulic conductivity of the layer.

Extension of Suleiman and Ritchie Model for Wetter Soils

In the SR paper, soil water data for wet conditions were presented, but not used in deriving the transfer coefficients for Eq. [1]. When the water contents were plotted against the Boltzmann transformation

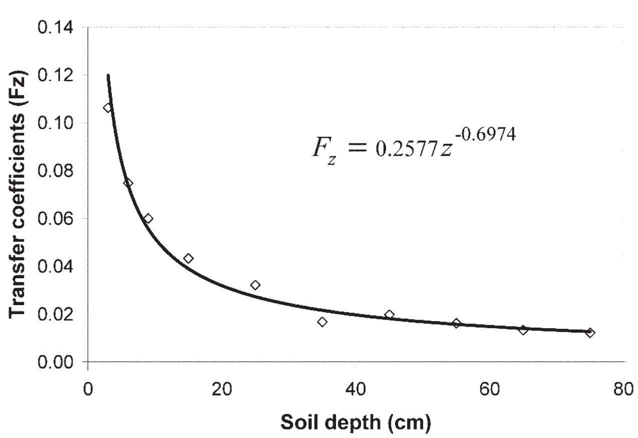

Fig. 2. Transfer coefficients averaged from both soils in the Suleiman and Ritchie 150-cm wet soil column study for the first 4 d of the drying cycle as a function of depth.

(depth · time$^{-0.5}$), no single-valued function could be obtained, indicating that the diffusivity theory was not valid for conditions where there was a water table within 150 cm of the soil surface.

Equations [1] and [2] can be applied to the wetter soil profiles, but the coefficients used in the transfer equation must be re-evaluated. Equation [1] can be rearranged to solve for F_z when all other factors are known:

$$F_z = \frac{-\Delta\theta_{ESz,t}}{\left(\theta'_{z,t} - \theta_{ADz}\right)} \qquad [7]$$

Data from the SR soil column studies during the 18-d drying cycle were used to compute the transfer coefficients for wetter soils using Eq. [7]. Typical values obtained are depicted in Fig. 1 for four depths for the loam soil. Results from the sandy loam were similar to those for the loam soil. The transfer coefficients were approximately constant after about 5 d of drying with a value of about 0.011 d^{-1}. Both the sandy loam and the loam soil lost water at approximately this rate at all depths. However for the first 4 to 5 d of drying the transfer coefficients were higher and decrease rapidly with soil depth. These transfer coefficients were similar for both soils with depth and time, thus they were averaged for the first 4 d of the drying cycle. The averages are depicted as a function of depth in Fig. 2. The data were fit to the transfer coefficient function in Eq. [2] resulting in a parameters of best fit, a_z = 0.26 and b_z = -0.70. These results provide the necessary transfer coefficients to describe evaporation from the wetter soil profiles. We refer to three conditions of soil water, each with a different set of transfer coefficients as: (i) wet, when the upper layers have the highest water contents, as in Fig. 2; (ii) equilibrium, when the lower layers have water content above θ_{DUL} with constant transfer coefficients, as in Fig. 1; and (iii) dry, when the soil water contents in all layers are below θ_{DUL} and the SR transfer coefficients (Eq. [3] and [4]) are appropriate to use.

We developed an appropriate empiricism to determine the conditions for transitioning between the three soil moisture conditions based on the data available from the SR paper for the wetter initial soil conditions. The soil water content near the surface appears to be the factor that controls the timing of the change from the wet condition with higher transfer coefficients to the equilibrium condition with smaller transfer coefficients. The thickness of the surface layer is a factor in the time of transition to the equilibrium condition since there is a steep water content gradient near the surface at the time of the transition. We extrapolated the water content with depth on day four for the sandy loam and day five for the loam and found resulting water contents of 0.13 cm^{3}cm^{-3} for the sandy loam (θ_{DUL} = 0.24 cm^{3}cm^{-3}) and 0.20 cm^{3}cm$^-$3 for the loam (θ_{DUL} = 0.32 cm^{3}cm^{-3}). Since θ_{DUL} varies with soil type, we fit an empiricism to θ_{DUL} to approximate the point of transition between wet and equilibrium conditions. The resulting equation defines θ_{eq}, the threshold water content for transitioning between wet and equilibrium conditions:

$$\theta_{eq} = 0.275\theta_{DULz} + 1.165\left(\theta_{DULz}\right)^2 + 1.2z\left(\theta_{DULz}\right)^{3.75} \qquad [8]$$

This equation extrapolates to a logical zero when θ_{DUL} is zero. For practical reasons, a depth of 100 cm was used to determine when to transition to the dry transfer coefficients of the SR paper. When all soil water contents within the top 100 cm are at or below θ_{DUL}, the SR equations are applied. The theory assumes that there is no water table at infinite depth, however our data did not include greater depths and many simulation models simulate only the upper 100 cm. Further testing with deeper soil water measurements in the presence of a water table may allow for improvements in these transition details. However, it appears that these equations can provide a reasonable approximation of soil evaporation from systems with dynamic soil water conditions for various soil types until more data are available from a broader range of soils.

Implementation of the Extended Suleiman and Ritchie Model in Decision Support System for Agrotechnology Transfer

The modeling details presented herein were developed for functional models such as the DSSAT system using a 1 d time step and a relatively small number of depth increments. The depth increments used in the development and testing of the model within the DSSAT system were 5, 10, 15, 15, 15, 30, and 30 cm for the 120-cm soil profile for the field experiments, which are described below. An additional 30-cm layer was used in the simulations of the 150-cm laboratory soil column study. The procedure should not be used, at least without modification, for the simulation of a surface layer thinner than 1.5 cm. Such a shallow layer could result in a transfer coefficient extrapolated to near or above one, which could result in negative water content calculations.

Using the extension of the SR model for wetter soils and the SR model for the dry conditions, the equations were included in the DSSAT-CSM system using the three-threshold system described above. Equations [3] and [4] are used to compute the transfer coefficients for the dry soil profile condition, when the soil water contents of all layers within the top 100 cm are less than θ_{DUL}. The wet soil profile transfer coefficients are computed using a_z = 0.26 and b_z = -0.70, from Fig. 2, when any soil layer in the top 100 cm has a water content above θ_{DUL} and the top soil layer is wetter than a threshold value, θ_{eq} (Eq. [8]). The equilibrium transfer coefficient, F_z = 0.011, is used when the soil profile is wet, but the top layer is dryer than the threshold value.

Field Experiments—Microwave, Water, and Energy Balance Experiments

Microwave, Water, and Energy Balance Experiments (MicroWEXs) are intensive, season-long field experiments conducted to monitor micrometeorological, soil, and vegetation conditions as well as the remotely sensed microwave signatures during growing seasons for corn and cotton. In this study, we use data from the second (Judge et al., 2005), third (Lin et al., 2005), fourth (Casanova et al., 2005), and fifth (Casanova et al., 2007) MicroWEXs. Table 1 lists the starting and ending dates of simulations associated with each of the four MicroWEXs analyzed.

The experimental site was a 3.6 ha field located at the University of Florida Plant Science Education and Research Unit (29° 24’ 0” N, 82° 10’ 12” W) in Citra, Florida. The soils of the site were Millhopper Fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults), with 92% sand and a bulk density of 1.4 g/cm^3. Water and fertilizer were applied through a linear-move irrigation/fertigation system. Datasets used for the study included observations of soil water at depths of 2, 4, 8, 16, 32, 64, and 100 cm, downwelling solar radiation, air temperature, water table depth, and precipitation/irrigation. In addition, weekly leaf area index (LAI) measurements were used to determine when to end the simulations of soil evaporation.

Table 1. List of datasets from experiments used for analyses.

Experiment†	Crop‡	Planting Date	Simulation Start Date	Simulation End Date
MicroWEX-2	Corn	18 Mar. 2004	26 Mar. 2004	16 Apr. 2004
MicroWEX-3	Cotton	9 July 2004	13 July 2004	6 Aug. 2004
MicroWEX-4	Corn	11 Mar. 2005	17 Mar. 2005	8 Apr. 2005
MicroWEX-5	Corn	9 Mar. 2006	14 Mar. 2006	5 Apr. 2006

† MicroWEX, Microwave, Water, and Energy Balance Experiment.
‡ Corn (*Zea mays* L.) and Cotton (*Gossypium hirsutum* L.).

Although extensive soil and environmental measurements were recorded throughout the growing season, the soil evaporation model simulations were run only for the early portion of the season, before significant shading of the soil surface by plant leaves and soil water uptake by roots. The simulation start dates corresponded to dates of availability of observed data during each experiment after planting. The simulation end dates for each experiment corresponded to the date when plant transpiration just exceeded 10% of the total potential evapotranspiration. Based on simulations of the maize growth in MicroWEX-2, this criterion was met at a measured LAI of approximately 0.3 m^{2}m^{-2}. Under these conditions the losses of soil water resulted only from evaporation and drainage since significant soil shading or root uptake had not yet occurred. When the water content dropped below θ_{DUL}, the daily change in soil water content represented soil evaporation only.

The values of θ_{DUL} used in the simulations for these experiments were determined based on graphical inspection of the detailed soil water data collected in the MicroWEXs. Values of θ_{DULz}, empirical coefficients, a_z and b_z, and the transfer coefficients, F_z, for the upper two layers as used in the MicroWex simulations are presented in Table 2. The soil layers have similar properties. The soil profile drainage parameter used for simulations of the MicroWEX studies was computed based on a method outlined by Suleiman and Ritchie (2004).

Model Comparisons and Evaluation

The extended SR soil evaporation model as described herein was implemented in DSSAT v4.5 (Hoogenboom et al., 2009) as an optional method for computing soil evaporation. Table 3 presents the differences between the computer algorithms of the original DSSAT soil evaporation model (Ritchie, 1972, 1998) (ORD) and the extended (ESR) model. The ESR routine is simpler with fewer input parameters.

Table 2. Extended Suleiman and Ritchie (ESR) soil evaporation transfer coefficients for the soils used in the simulations of Microwave, Water, and Energy Balance Experiments (MicroWEXs) for the three soil moisture conditions. Values of the volumetric water content at drained upper limit at depth *z* (θ_{DULz}) are 0.096 and 0.105 cm^3 cm^{-3}, respectively for the 0- to 5-cm and 5- to 15-cm layers.

	a_z†	b_z†	F_z†
Dry profile condition:			
0–5 cm	0.523	–2.02	0.0821
5–15 cm	0.525	–2.02	0.00503
Equilibrium profile condition:			
0–5 cm	0.011	0.0	0.011
5–15 cm	0.011	0.0	0.011
Wet profile condition:			
0–5 cm	0.26	–0.70	0.137
5–15 cm	0.26	–0.70	0.0519

† a_z and b_z, empirical coefficients at depth z; F_z, upward flow coefficient.

Table 3. Comparison of the two algorithms used for modeling soil evaporation in Decision Support System for Agrotechnology Transfer (DSSAT).

	ORD†	ESR†
Input data required		
Soil properties	•	•
Soil water content, mm^3 mm^{-3}	•	•
Potential soil evaporation, cm	•	•
Change in soil water content due to drainage, mm^3 mm^{-3}	•	•
Stage-1 evaporation limit, cm	•	
Infiltration from rainfall or irrigation, cm	•	
Procedures		
Multi-stage evaporation	•	•
Evaporation and redistribution calculated for each soil layer		•
Lines of computer code	252	91

† Original Ritchie DSSAT (ORD) and Extended Suleiman and Ritchie (ESR) soil evaporation models.

Weather and soil inputs to the DSSAT model during the four MicroWEX field experiments were obtained from the observations. Each experiment was simulated using both the ORD and ESR soil evaporation models within DSSAT-CSM to predict soil water content at various depths. The DSSAT system divides the soil into several layers, the upper two layers having depth increments of 5 and 10 cm, respectively. Water content changes at depths below 15 cm were small and thus not provided in this paper although they were both simulated and measured. The simulated soil water contents from both models were compared with the measured data from the MicroWEXs, both qualitatively (graphically) and quantitatively (statistically) for their capability to simulate soil water contents and soil evaporation.

For each of the models, the bias, mean average error (MAE), root mean square error (RMSE), relative root mean square error (RRMSE), model efficiency (ME), and Wilmott D-index were computed. Methods described in Wallach et al. (2006), Nash and Sutcliffe (1970), and Willmott (1982) were used for these calculations.

Kobayashi and Salam (2000) presented an approach for model evaluation based on the mean squared error and showed that it is better suited to model evaluation than regression. The method uses mean squared error (MSE) and breaks it down into its relevant components, which can be calculated from common statistical parameters such as bias, standard deviation and correlation coefficient:

$$\text{MSE} = \text{SB} + \text{SDSD} + \text{residual error} \qquad [9]$$

where SB is the squared bias of error and SDSD is the squared difference of standard deviations. The SDSD component indicates how well the model simulates the magnitude of fluctuation between measured values. A smaller SDSD indicates that the model provides a better simulation of the magnitude of fluctuation.

$$\text{SB}=\left[\frac{1}{N}\sum_{i=1}^{N}\left(y_i-x_i\right)\right]^2 \qquad [10]$$

where N is the number of observations and x_i and y_i are the simulated and observed values, respectively.

$$\text{SDSD}=\left(\sigma_x-\sigma_y\right)^2 \qquad [11]$$

where σ_x and σ_y are the standard deviations of the simulated and measured values.

Modeling efficiency (Nash and Sutcliffe, 1970), ranges from minus infinity (poor model) to 1.0 (perfect model) and can be computed as:

$$\text{ME}=1-\frac{\text{MSE}}{\sigma_y^{\;2}} \qquad [12]$$

Willmott index of agreement, or D-index, is calculated as:

$$\text{D-index}=1-\frac{\sum_{i=1}^{N}\left(y_i-x_i\right)^2}{\sum_{i=1}^{N}\left(\left|x_i-\overline{y}\right|+\left|y_i-\overline{y}\right|\right)^2} \qquad [13]$$

where $\overline{y}$ = mean of observed values. D-index varies from 0.0, for a poor model, to 1.0, for a perfect model.

Each of these measures are used in this paper to quantify and compare errors between simulated and observed soil water values for the top two soil layers for both the ORD and the ESR soil evaporation models. Additionally, for the ESR model, statistical parameters were computed for data grouped by the individual MicroWEXs, for the 0- to 5-cm soil layer.

Soils and environmental conditions for the wetter soil column study from the SR paper were also input to the ESR model within DSSAT-CSM to simulate soil water content and soil evaporation rates for this laboratory study. The model outputs were compared graphically with the measured laboratory data to evaluate the ESR model performance. Because model transfer coefficients were developed using these SR experimental data, this analysis does not represent an independent evaluation of the ESR as it does for the MicroWex field studies. Therefore, only graphical rather than statistical analyses are presented for the simulations of the data from the SR column study.

RESULTS AND DISCUSSION

Qualitative Comparison of Model Errors with Graphical Analyses for MicroWEXs

Table 4 presents a summary of environmental conditions and simulated outputs for each of the four MicroWEXs including the rainfall and irrigation inputs to the fields and simulated evaporation. Figures 3a and 3b present graphical comparisons of the simulated model outputs with the data collected during MicroWEX-2 for the 0- to 5-cm and 5- to 15-cm soil layers, respectively. Similar graphs are presented in Fig. 4a and 4b for MicroWEX-3, in Fig. 5a and 5b for MicroWEX-4, and in Fig. 6a and 6b for MicroWEX-5.

Changes in water content were greatest on days with rainfall or irrigation events when water was added to the system. Drainage and evaporation caused the subsequent loss of water. Most of the simulated water content in the 0- to 5-cm top soil layer agreed well with the trend in the measured water content. The ORD model simulated soil water values that responded well after rainfall or irrigation, but were consistently lower than measured water contents thereafter. The ESR model behaved much more realistically in the upper soil layer. Both models agreed well with the measured data in the 5- to 15-cm depth and for lower soil layers, which are not shown.

Figure 7 presents daily simulated soil evaporation rates for both models for the four MicroWEXs. For all four experiments, the cumulative soil evaporation simulated by the ESR model is higher than that computed by the ORD model

Table 4. Comparisons of environmental conditions and simulated evaporation during the four MicroWEXs.

Measured or computed data	MicroWEX-2 2004 Corn†	MicroWEX-3 2004 Cotton†	MicroWEX-4 2005 Corn	MicroWEX-5 2006 Corn
Simulation duration, d	22	25	23	23
Measured total rainfall, mm	26	196	162	4
Measured total irrigation, mm	55	15	76	48
Average rainfall + irrigation, mm d^{-1}	3.7	8.4	10.3	2.3
Measured maximum temperature, °C	29.6	34.3	31.1	30.2
Measured minimum temperature, °C	4.2	20.1	1.0	0.3
Measured average solar radiation, MJ m^{-2} d^{-1}	21.1	18.7	14.8	22.1
Computed total potential evapotranspiration, mm	121	132	83	117
Computed total soil evaporation (ORD model), mm ‡	37	48	40	31
Computed total soil evaporation (ESR model), mm ‡	53	68	55	45

† Corn (Zea mays L.) and Cotton (Gossypium hirsutum L.).

‡ Original Ritchie DSSAT (ORD) and Extended Suleiman and Ritchie (ESR).

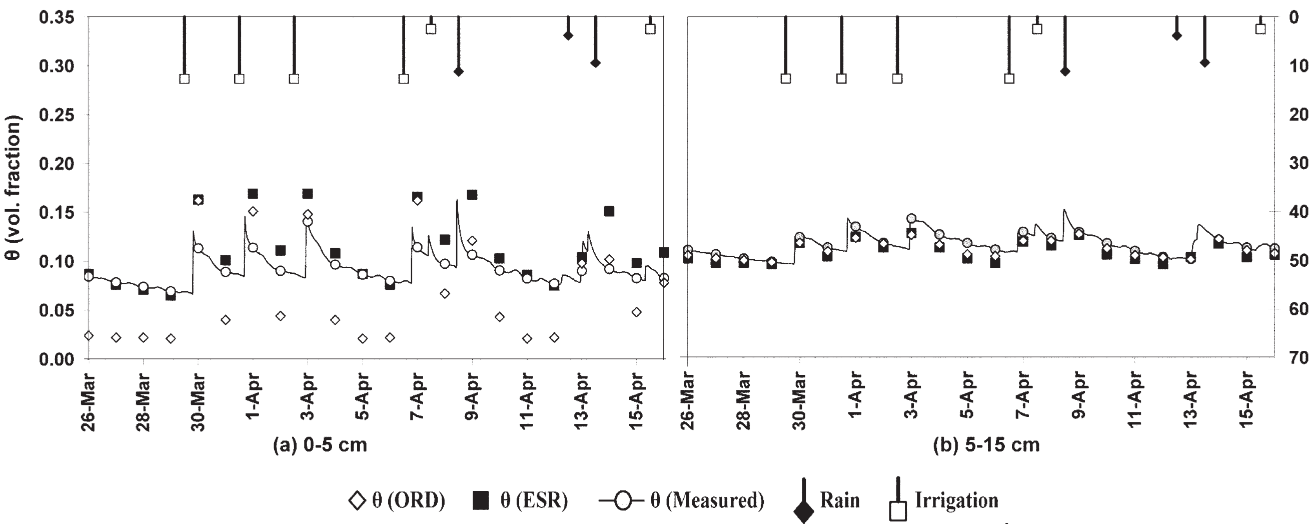

Fig. 3. Simulated and measured volumetric soil water content by date for the Extended Suleiman and Ritchie (ESR) and the Original Ritchie DSSAT (ORD) soil evaporation models during Microwave, Water, and Energy Balance Exp. 2 (MicroWEX-2) in 2004 for (a) 0- to 5-cm and (b) 5- to 15-cm soil layers. Measured points used in statistical analyses are shown.

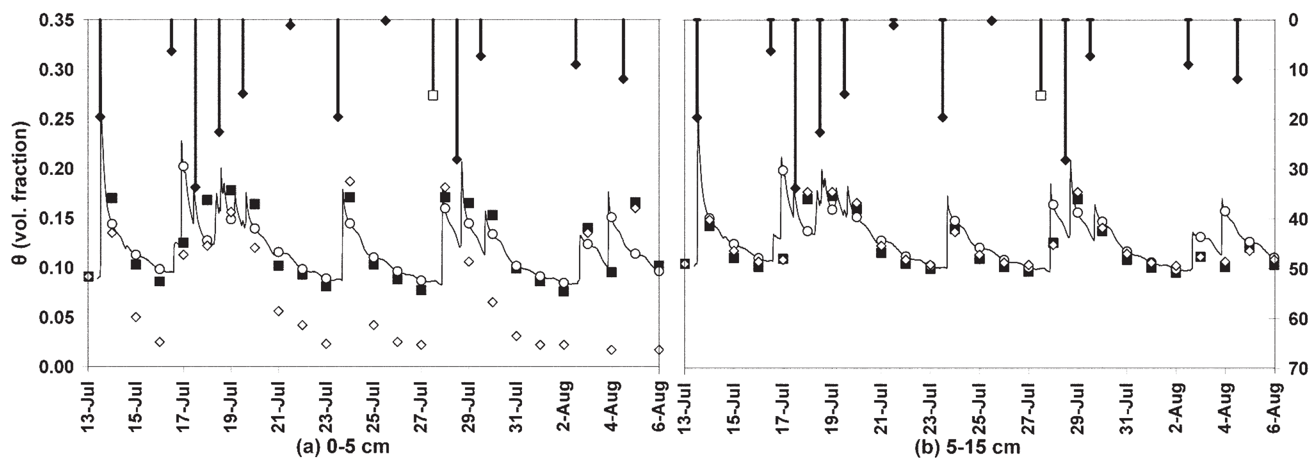

Fig. 4. Simulated and measured volumetric soil water content by date for the Extended Suleiman and Ritchie (ESR) and the Original Ritchie DSSAT (ORD) soil evaporation models during Microwave, Water, and Energy Balance Exp. 3 (MicroWEX-3) in 2004 for (a) 0- to 5-cm and (b) 5- to 15-cm soil layers. Legend as in Fig. 3.

(Table 4), and the pattern of evaporation is quite different (Fig. 7). In these sandy soils, drainage is fast, the soils do not reach saturation, and simulated soil evaporation rates rarely exceed potential evaporation for either model. The ORD model limits soil evaporation to available water in the top 5-cm soil layer and quickly depletes the soil water in this layer, resulting in the chaotic behavior shown in Fig. 7. The ESR model simulated more stable evaporation rates and soil water contents, consistent with the measured data.

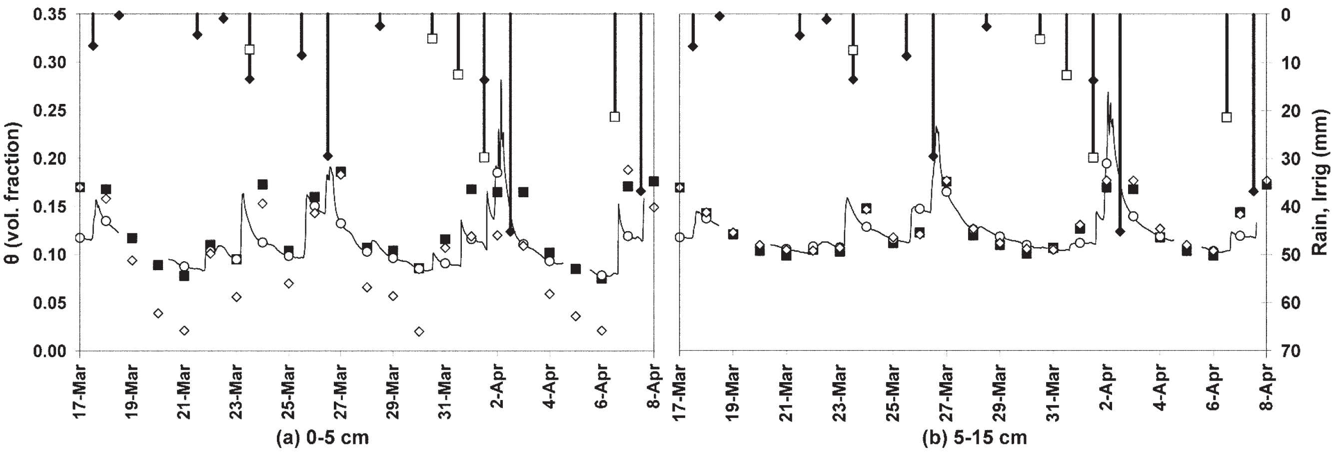

Fig. 5. Simulated and measured volumetric soil water content by date for the Extended Suleiman and Ritchie (ESR) and the Original Ritchie DSSAT (ORD) soil evaporation models during Microwave, Water, and Energy Balance Exp. 4 (MicroWEX-4) in 2005 for (a) 0- to 5-cm and (b) 5- to 15-cm soil layers. Legend as in Fig. 3.

The daily time step of the DSSAT-CSM model produces a potential source of errors as rainfall is assumed to occur at the beginning of the day with 24 h of drainage occurring subsequently. Timing of rainfall and irrigation events can have a major impact on the actual drainage and soil evaporation amounts which occur in a day because the processes can occur so rapidly. The use of pseudo-integration in Eq. [6a] and [6b] was an attempt to minimize this source of error. This error is particularly evident on the days with rainfall or irrigation, where the timing of these additions of water to the system is critical to the simulated end-of-day soil water content. For this reason, the simulated soil water contents are not adequately simulated by either model on wet days.

Graphical Analyses for Column Studies Data

Figure 8 presents simulated versus measured soil evaporation data for the wetter soil column studies in the SR paper using the ESR model. The measured and simulated soil water contents are presented in Fig. 9a for the sandy loam soil and in Fig. 9b for the loam soil. The graphs of cumulative evaporation indicate that the ESR model works well under these conditions. The soil water distribution near the surface was in good agreement with measurements for the sandy loam soil. The loam was biased with too much water removed from the 0- to 5-cm layer, although there was apparent compensation with errors in the opposite direction in the lower layers, resulting in the total evaporation being adequately simulated. The bias in the loam soil indicates that a more accurate assessment of other soils using the ESR approach is needed.

Quantitative Comparisons of Model Errors

Table 5 summarizes the statistical comparisons of the simulated versus measured data for the four MicroWex's for both the ORD and ESR models. The bias, or sum of the residuals, is a measure of how much the simulated results differ from the observed. The positive values for bias shown in Table 5 indicate that the simulations for the ORD model tended to underpredict volumetric soil water content on average. The biases for the ESR model were improved, or decreased in magnitude, although the model tended to overpredict soil water content for the surface layer and underpredict for the 5- to 15-cm layer. The overall bias for the 0- to 5-cm layer for the ESR model was near zero. The magnitudes of biases for the individual experiments were small although the model tended to overpredict soil water content for the top layer.

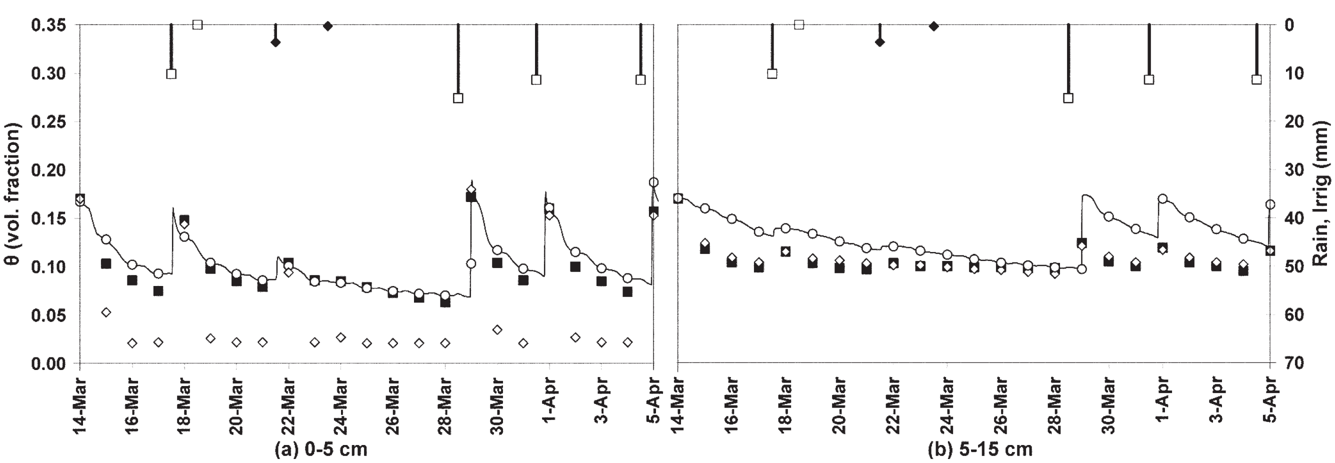

Fig. 6. Simulated and measured volumetric soil water content by date for the Extended Suleiman and Ritchie soil evaporation model (ESR) and the Original Ritchie DSSAT (ORD) soil evaporation models during Microwave, Water, and Energy Balance Exp. 5 (MicroWEX-5) in 2006 for (a) 0- to 5-cm and (b) 5- to 15-cm soil layers. Legend as in Fig. 3.

The mean average error in Table 5 is a measure of the overall magnitude of the errors. The MAE was decreased overall for the surface layer with the ESR model, although the 5- to 15-cm layer showed a slight increase in MAE. All indicators of error demonstrated the improvement in the ESR model's ability to simulate soil water content in the top soil layer. The measures for the grouped data were consistent with that of the entire data set.

The model efficiency for the ESR model is improved over that of the ORD model for the top 5-cm layer, from a −3.003 to +0.051. This efficiency is better than the previous model, but still not a good indication of model adequacy. However, as shown in Fig. 2 through 6, the measured values used in the analysis were the last value of the day (i.e., at midnight), corresponding to the simulated end-of-day values. The inability of a daily model to capture the temporal dynamics of the soil water balance system is expected on days with rainfall or irrigation, when large variations in soil water content occur.

For the 5- to 15-cm layer, the model efficiency was not improved. Model efficiencies for the MicroWex-3 and MicroWex-5 experiments were better than for the overall dataset for the top soil layer; however, MicroWex-2 and MicroWex-4 had negative model efficiencies, indicating poor performance of the model for those experiments. Again, the pattern of simulated soil water content for MicroWex-2 and MicroWex-4 seems to follow measured values closely. The bad model performance is due to timing of intense short duration rainfall events which occurred early in the day.

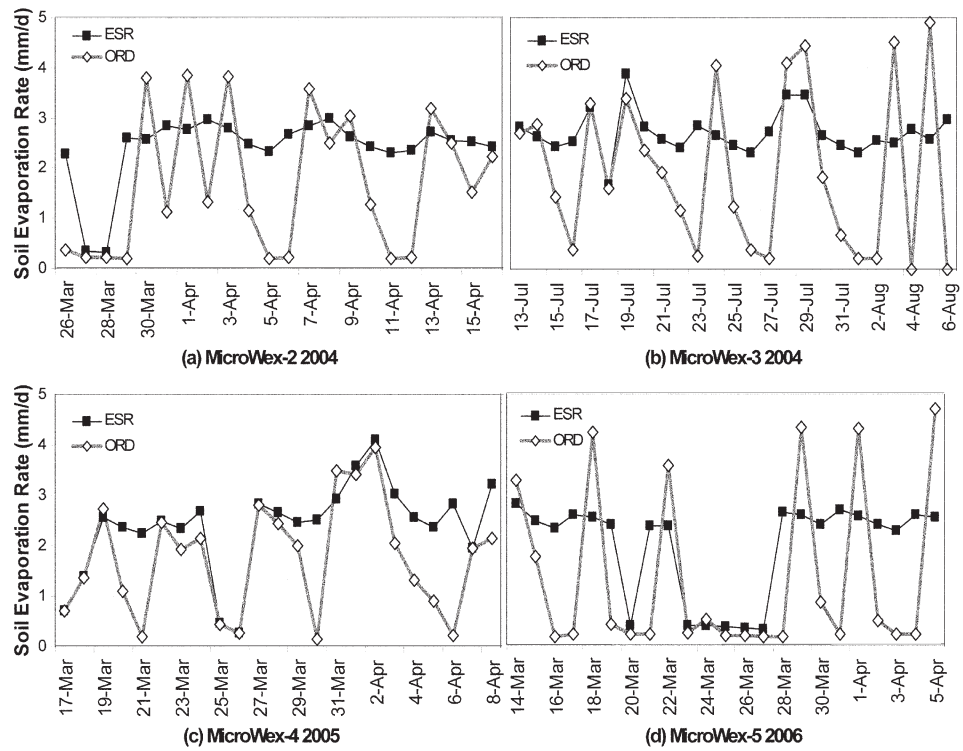

Fig. 7. Simulated daily soil evaporation rates for four Microwave, Water, and Energy Balance Experiments (MicroWEXs), for Original Ritchie DSSAT (ORD), and for Extended Suleiman and Ritchie (ESR) soil evaporation models.

The Willmott-D index showed improved model performance for the 0- to 5-cm layer, and approximately equal performance for the 5- to 15-cm layer. As with the model efficiency, the MicroWex-3 and MicroWex-5 simulations compared more favorably.

The MSE component analysis, shown in Fig. 10, indicated much better performance for the ESR model compared to the ORD model for the 0- to 5-cm layer. In this analysis, the mean

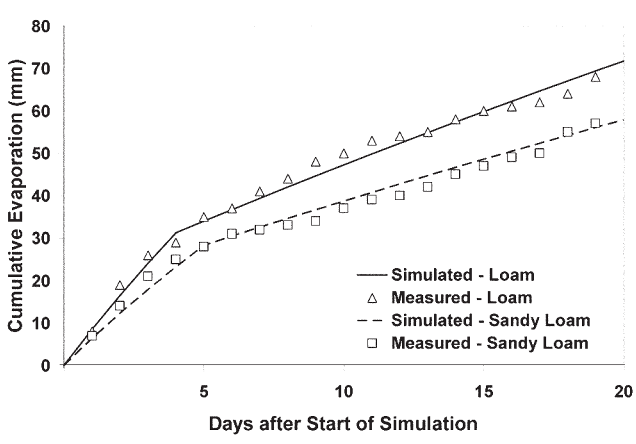

Fig. 8. Simulated and measured cumulative evaporation from top 75 cm of soil for Suleiman and Ritchie (2003; SR) laboratory wet soil column with two soil types.

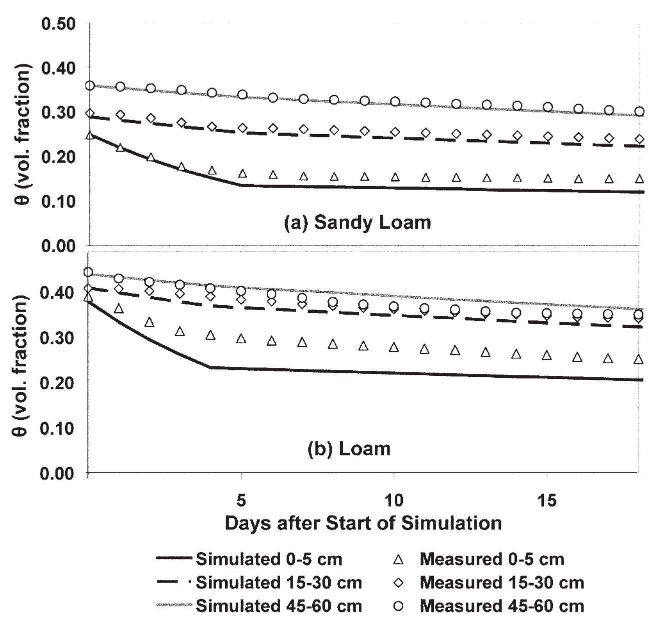

Fig. 9. Simulated and measured soil water content at several depths from (a) sandy loam soil and for (b) loam soil for the Suleiman and Ritchie laboratory wet soil column studies.

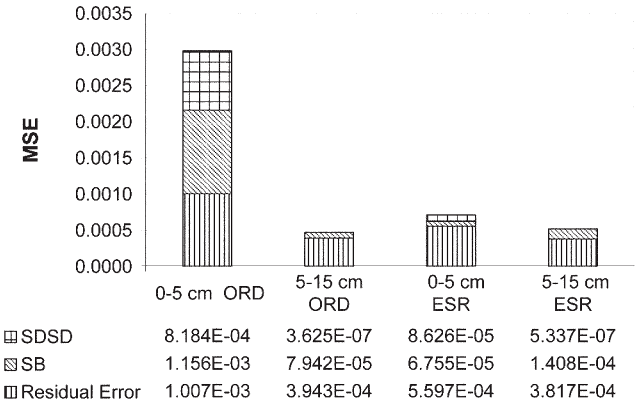

Fig. 10. Components of mean squared error estimate for Original Ritchie DSSAT (ORD) and Extended Suleiman and Ritchie (ESR) soil evaporation models and top two soil layers.

squared error was separated into components of error. The ESR model resulted in decreased squared bias over the ORD model by a factor of 3.6 for the 0- to 5-cm soil layer. The second component of MSE is squared difference of standard deviations. A reduced squared difference of standard deviation indicated that the ESR model provided a better simulation of the magnitude of fluctuations in simulated soil water content as compared to the fluctuations of the measured data. As shown in Fig. 10, the ESR soil evaporation model improved simulation of squared difference of standard deviations by an order of magnitude for the 0- to 5-cm layer. No improvement in model prediction is gained by the ESR model for the 5- to 15-cm soil layer.

CONCLUSIONS

A procedure was developed that extends the SR soil evaporation model to wetter conditions for general use in a dynamic soil–crop model. The procedures added to the SR model retain a daily time step, as used in the DSSAT model system although there are rapid changes in the soil water content following a rain or irrigation. The cumulative soil water changes, after taking drainage into account, estimate the evaporation from bare soil with reasonable accuracy. This ESR procedure has fewer equations and simpler logic than the ORD model previously used in DSSAT-CSM. Despite the simpler logic and input, the ESR soil evaporation algorithm predicted near surface soil evaporation as well as, or better than, the ORD model. The prediction of soil water redistribution near the surface, where large fluxes occur, is a major improvement over the previous method. Thus, these modeling procedures should be highly useful for improving the near surface soil water content calculations for daily incrementing models. Such near surface water dynamics should also be useful in models with tillage and other near surface soil management.

This analysis also revealed that there is no clear distinction between the so-called first and second stages of evaporation. With the presence of water tables or slowly draining upper surface layers, the evaporation rate is higher than estimated with a two-stage system used in the Ritchie (1972) model. Water loss from the soil by evaporation can be higher than a usual second stage estimate but lower than the potential evaporation because of the restriction of water flowing through unsaturated soil near the surface a few days after rainfall or irrigation. The procedures developed herein do not require a first-second stage analysis and are simpler in equations and logic than the previous methods used in DSSAT.

ACKNOWLEDGMENTS

This paper was partially supported by the Office of Natural Resources Management and Office of Agriculture in the Economic Growth, Agriculture, and Trade Bureau of the U.S. Agency for International Development, under terms of Grant No. LAG-G-00-97-00002-00. The observations during the MicroWEXs used for this study were funded by the NSF-Hydrology Program (EAR-0337277) and the NASA New Investigator Program (NASA-NIP-00050655). The authors would like to thank the anonymous reviewers and the editors for providing constructive suggestions to improve the manuscript.

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Table 5. Summary of statistical model evaluation analyses.

Statistic	ORD Model† All experiments			ESR Model† All experiments			ESR Model (0–5 cm) Individual experiments			
	Complete Data Set (n = 178)	0–5 cm (n = 89)	5–15 cm (n = 89)	Complete Data Set (n = 178)	0–5 cm (n = 89)	5–15 cm (n = 89)	MicroWEX-2 (n = 22)	MicroWEX-3 (n = 25)	MicroWEX-4 (n = 19)	MicroWEX-5 (n = 23)
Bias	0.0215	0.0340	0.0089	0.0018	–0.0082	0.0119	–0.0200	–0.0025	–0.0181	0.0051
MAE‡	0.0314	0.0482	0.0145	0.0177	0.0190	0.0164	0.0214	0.0205	0.0216	0.0131
RMSE	0.0417	0.0549	0.0216	0.0248	0.0267	0.0227	0.0294	0.0273	0.0303	0.0193
RRMSE	0.355	0.510	0.170	0.211	0.248	0.179	0.319	0.222	0.274	0.186
ME		–3.003	0.022		0.051	–0.081	–0.673	0.281	–0.442	0.514
D-index		0.604	0.738		0.808	0.725	0.697	0.845	0.768	0.884

† Original Ritchie DSSAT (ORD) and Extended Suleiman and Ritchie (ESR) soil evaporation models.

‡ Mean average error (MAE), root mean square error (RMSE), relative root mean square error (RRMSE), model efficiency (ME), and Willmott index of agreement (D-index).

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