TECHNICAL NOTE:

SIMULATING THE SURFACE ENERGY BALANCE IN A SOYBEAN CANOPY WITH THE SHAW AND RZ-SHAW MODELS

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ABSTRACT. *Correct simulation of surface energy balance in a crop canopy is critical for better understanding of soil water balance, canopy and soil temperature, plant water stress, and plant growth. One existing effort is to incorporate the surface energy balance in the Simultaneous Heat and Water (SHAW) model into the Root Zone Water Quality Model (RZWQM). In this study, an improved version of the RZ-SHAW (RZWQM-SHAW) hybrid model was tested for energy balance components, canopy and soil temperature, evapotranspiration (ET), and soil water content against eddy covariance data measured in a soybean canopy and against predictions of the original SHAW and RZWQM models. The experiment was first used previously to test the SHAW model for radiation energy fluxes within the canopy without examining the energy balance components, soil water balance, and soil temperature. The same parameters from that study were used in both the SHAW model and RZ-SHAW hybrid model without any modification in this study. In terms of root mean squared error (RMSE), both RZ-SHAW and SHAW simulated net radiation, sensible heat, and latent heat well. However, the ground heat flux simulated by RZ-SHAW was less accurate, with RMSE of 28.9 W m^{-2} compared to 22.6 W m^{-2} with SHAW, which could be due to differences in simulated soil evaporation. Simulated soil temperature at both 1.5 cm and 4.5 cm depths with RZ-SHAW was comparable to that of SHAW, with RMSE of 2.18°C and 2.23°C, respectively, compared to 2.13°C and 2.20°C with SHAW. Similarly, simulated canopy temperature was essentially the same, with RMSE values of 1.77°C with RZ-SHAW and 1.69°C with SHAW. Simulated surface soil water content was reasonable for both models. Simulated ET had an RMSE of 0.069 cm d^{-1} with RZ-SHAW and 0.074 cm d^{-1} with SHAW. The new RZ-SHAW model was an improvement over the original RZWQM model in simulating soil temperature and moisture, in addition to its ability to provide complete energy balance and canopy temperature.*

Keywords. *Canopy temperature, Energy balance, Evapotranspiration, RZWQM.*

Correct simulation of the surface energy balance is important in cropping system models because partitioning of solar energy determines not only crop evapotranspiration (ET) but also the canopy and soil surface temperatures. Including surface energy balance in system models should also improve soil water simulation (Wang et al., 2010). However, in general, most crop system models do not simulate detailed surface energy balances. As a result, ET is generally simulated using the Penman equation or its later improvements, and surface soil temperature is assumed equal to air temperature (Farahani and DeCoursey, 2000). This shortcoming was recognized early in the development of the Root Zone Water Quality Model (RZWQM) and inspired the effort to develop a linkage to the SHAW (Simultaneous Heat And Water) full energy balance model (RZ-SHAW or RZWQM-SHAW) (Ahuja et al., 2000a; Flerchinger et al., 2000). This hybrid model added the capability of simulating surface energy balance and winter frozen soil condition to the original RZWQM model, which was designed to simulate the effects of agricultural management practices on soil water quality and crop production.

RZ-SHAW has been evaluated for over-winter conditions (Flerchinger et al., 2000), crop residue (Kozak et al., 2007), and crop canopy (Yu et al., 2007; Kozak et al., 2006). Flerchinger et al. (2000) successfully tested the RZ-SHAW linkage for simulating soil water content, ice content, frost depth, and soil temperature in comparison with the original SHAW model at two locations having varying tillage and residue conditions. Yu et al. (2007) further evaluated RZ-SHAW for energy balance simulation in a wheat canopy and found that both RZ-SHAW and SHAW gave similar simulation errors for surface energy balance. Using RZ-SHAW, Kozak et al (2006) investigated several plant water stress options in simulating corn and soybean yield and biomass responses to irrigation, and found that plant growth needed to be recalibrated when water stress factors were defined from canopy and stomatal resistances in RZ-SHAW.

However, the previous evaluations of RZ-SHAW focused mainly on surface energy balance components (total radiation, latent heat, sensible heat, and ground heat flux) without evaluating ET, soil water content, and soil and canopy tem-

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peratures. Flerchinger et al. (2009) tested the SHAW model for within-canopy radiation fluxes using data from a soybean canopy from Iowa, but they did not examine the total energy balance and soil water balance. The objectives of this technical note are to compare the SHAW-simulated energy balance components, ET, soil water content, and soil and canopy temperatures against the eddy covariance data collected in the same experiment used by Flerchinger et al. (2009), and to compare the SHAW simulation results with those simulated by the recently improved RZ-SHAW model using the same model parameters as in Flerchinger et al. (2009). Simulated ET and soil water content were also compared against simulations by the original RZWQM.

Materials and Methods

Incorporation of SHAW into RZWQM

The SHAW model was described by Flerchinger and Saxton (1989) and Flerchinger and Pierson (1991), with further improvements for within-canopy energy balance by Flerchinger and Yu (2007) and Flerchinger et al. (2009). In this study, version 2.4 of SHAW, previously evaluated by Yu et al. (2007), was improved and used. RZWQM has been documented by Ahuja et al. (2000a). In RZWQM, the extended Shuttleworth-Wallace potential evapotranspiration (PET) (Farahani and DeCoursey, 2000) is used as the upper boundary condition for ET, with actual evaporation (E) estimated by solving the Richards equation and actual transpiration (T) computed from the Nimah-Hanks equation (Nimah and Hanks, 1973; Ahuja et al., 2000b). Soil water is simulated during infiltration by the Green-Ampt equation and during redistribution by the Richards equation (Ahuja et al., 2000b). The RZ-SHAW model employs the energy balance, canopy transpiration, and heat transfer routines of SHAW while retaining the soil water balance routines of RZWQM. The SHAW routines are called at the same time step as the Richards equation, hourly or sub-hourly only during soil water redistribution; ET during rainfall or irrigation events is assumed zero. Plant parameters required by the SHAW routines, such as rooting depth, leaf area index (LAI), plant height, and aboveground biomass (live and dead), are supplied from the plant growth modules in RZWQM. The SHAW routines in RZWQM also take care of soil heat transport but not the soil water balance. In addition, the SHAW routines provide RZWQM with frozen soil conditions (i.e., soil ice content and frozen depth) and soil surface and canopy temperature.

Plant water uptake in SHAW is calculated by assuming a soil-plant-atmosphere continuum and is driven by leaf water potential and leaf stomatal resistance (Flerchinger and Pierson, 1991). This potential-driven plant water uptake for each canopy layer forms a set of sequential equations and is solved iteratively with the leaf energy balance of each canopy layer. Therefore, it is essential to use SHAW transpiration so that the energy and water balances are correctly coupled in RZ-SHAW.

In the previous RZ-SHAW version (Yu et al., 2007), soil surface evaporation, as calculated by the Richards equation in RZWQM, was used only as a limit to the upper boundary evaporation in SHAW, which could result in a discrepancy between RZWQM-simulated soil evaporation (Ahuja et al., 2000b) and SHAW-simulated soil evaporation (Flerchinger and Pierson, 1991). Furthermore, SHAW-simulated transpiration was not fed back to the Richards equation in RZWQM as a sink term. As a result, RZ-SHAW-simulated ET was different from SHAW-simulated ET. The latter was the latent heat (LE) component of the energy balance. In this study, the actual evaporation from RZWQM is passed to the SHAW module to replace the original evaporation in SHAW so that the latent heat from evaporation in SHAW matches the soil surface evaporation in RZWQM. On the other hand, RZWQM uses plant transpiration from SHAW as its plant water uptake instead of its original plant water uptake routine using the Nimah-Hanks equation. Therefore, the total actual ET used in RZ-SHAW for water balance matches the latent heat calculated in SHAW for energy balance.

Experimental Data

The Brooks Field study site (41° 41′ N, 93° 41′ W, 313 m a.s.l.) in Iowa was in a 45 ha field on a Canisteo silty clay loam. Soybean [*Glycine max* (L.) Merr.] was planted on May 8, 2004 (DOY 129) in north-south rows spaced 38 cm apart and harvested on September 28, 2004 (DOY 272). Total leaf area index of the soybean was measured approximately every 7 to 10 days using an LAI-2000 (Li-Cor, Lincoln, Neb.). Leaf area index of green leaves only was also measured within a day of total LAI measurement by hand-sampling ten plants and measuring the leaf area of the individual leaves using a leaf area meter (Sauer et al., 2007; Flerchinger et al., 2009). Leaf area index of senesced leaves was obtained by subtracting the observed leaf area index from the maximum observed leaf area index for the season. Total measured dry biomass was divided into green and senesced biomass based on their respective leaf areas.

An eddy covariance (EC) system was used to measure turbulent fluxes starting on DOY 170. The EC system consisted of a three-dimensional sonic anemometer (model CSAT3, Campbell Scientific, Inc., Logan Utah) and an open-path infrared gas analyzer (IRGA; model LI-7500, Li-Cor, Inc., Lincoln, Neb.) sampled at 10 Hz, located 1.6 m above the soil surface. Shortwave and longwave radiation, air temperature, and humidity were collected every 15 min using a four-component net radiometer (CNR-1, Kipp & Zonen, Delft, The Netherlands) and a temperature and humidity probe (HMP45C, Vaisala, Helsinki, Finland). Soil heat flux was measured with up to five heat flux sensors (HFT1, Radiation Energy Balance Systems, Seattle, Wash.) installed 0.06 m deep within the soil and five sets of thermocouples installed 0.015 and 0.045 m deep. Volumetric water content was measured daily from 20 gravimetric 6 cm soil cores. Soil heat flux (G) measured at 0.06 m was corrected for heat storage above the heat flux plates using measured soil temperature and water content interpolated between soil water sampling dates. Detailed measurements are given by Sauer et al. (2007).

The experiment was used by Flerchinger et al. (2009) to test modifications to the SHAW model for within-canopy radiation exchange without plant growth simulation (plant height, LAI, plant biomass, and rooting depth are model inputs), but they did not study total energy balance, soil and canopy temperatures, and soil water content. In this study, both SHAW and RZ-SHAW were run with parameters from Flerchinger et al. (2009) without any modification. A uniform soil profile was used to a depth of 1.0 m, with a saturated hydraulic conductivity of 0.63 cm h^{-1}, bulk density of 1.16 g cm^{-3}, and saturated soil water content of 0.55 cm^3 cm^{-3}. Soil and canopy albedo were assumed to be 0.15 and 0.3, respectively. The plant rooting depth was also approximated based on plant height. Plant LAI, biomass, and rooting depth were inputs from experimental measurements for RZ-SHAW, as was done for SHAW, in order to compare directly with results from SHAW. All simulations were started on June 9, 2004 (DOY 161) when field measurements of plant growth commenced.

Results and Discussion

As shown in table 1, daily total net radiation (Rn), latent heat (LE), sensible heat (H), and ground flux (G) simulated by the SHAW model matched the measurements reasonably well, with root mean squared error (RMSE) of 43.6, 38.5, 36.8, and 22.6 W m^{-2}, respectively. These statistics are comparable to those reported by Yu et al. (2007) and are within the measured energy balance closure error of 45.5 W m^{-2}. Therefore, the parameters used by Flerchinger et al. (2009) for energy fluxes within the canopy worked well for total energy balance, and no further calibration was needed. The corresponding RMSE values of the energy components simulated by RZ-SHAW were 43.9, 37.9, 34.4, and 28.9 W m^{-2}, respectively (table 1). RZ-SHAW simulated all the energy components comparably to SHAW except for ground heat flux (G). The difference in G simulation was probably due to differences in simulated soil evaporation between RZ-SHAW and SHAW and might also be due to interception and evaporation of rain from the plant canopy simulated in SHAW but not in RZ–SHAW. Simulated surface evaporation was slightly higher in RZ-SHAW (4.6 cm) than in SHAW (4.1 cm) from DOY 171 to 246. Nonetheless, the simulated results were comparable between the two models, as shown by the model efficiency (ME), mean difference (MD), and coefficient of determination (r^2) (table 1).

Both SHAW and RZ-SHAW underestimated sensible heat (H) and overestimated latent heat (LE) in the early growing season (fig. 1) but matched observations better later in the growing season. In addition, both SHAW and RZ-SHAW slightly overestimated G later in the growing season. Ground heat flux (G) was more affected by rainfall events in RZ-SHAW because the SHAW subroutine in RZWQM was not called during rainfall events and might cause unrealistic ground heat flux.

A main reason for incorporating SHAW into RZWQM is to improve soil surface temperature simulation. Based on statistics used in the study, SHAW and RZ-SHAW models provided the same goodness-of-prediction for soil temperature at 1.5 and 4.5 cm depths (table 2). However, both models simulated slightly higher soil temperatures throughout the growing season. During the middle of the growing season, RZ-SHAW provided slightly better simulation of soil temperature than SHAW. Although there were simulation errors in surface soil temperature, these simulated temperature values were reasonable compared to the measured air temperature in the sense that soil temperature did not respond instantaneously to air temperature, as assumed in RZWQM. As shown in figure 2, RZWQM-simulated surface temperatures fluctuated more than those simulated by SHAW and RZ-SHAW and was mainly affected by air temperature. Simulated soil temperature by RZWQM had ME values of 0.52 at 1.5 cm and 0.44 at 4.5 cm, with corresponding RMSE values of 2.93 °C and 2.59 °C, respectively. The MD was -1.15 °C and -1.41 °C at 1.5 cm and 4.5 cm, respectively. Due to diurnal variation in measured temperature, both r^2 and ME are less sensitive in describing goodness-of-prediction than the other statistics. The poor prediction by RZ–SHAW around DOY 217 was due to extensive rainfall duration on DOY 216 and 217, during which the SHAW model was not called. Further improvement may be needed for rainy days.

Table 1. Comparison of energy balance components, net radiation (Rn), sensible heat (H), latent heat (LE), and ground heat flux (G), measured using eddy covariance to those simulated by SHAW and RZ-SHAW.

Statistics[a]	Energy Balance Component	SHAW	RZ-SHAW
Coefficient of determination (r^2)	Rn	0.98	0.98
	H	0.67	0.67
	LE	0.95	0.96
	G	0.89	0.80
Mean difference (MD) (W m^{-2})	Rn	3.6	8.7
	H	2.9	4.0
	LE	5.3	2.8
	G	-4.6	1.8
Root mean squared error (RMSE) (W m^{-2})	Rn	43.6	43.9
	H	38.5	37.9
	LE	36.8	34.4
	G	22.6	28.9
Model efficiency (ME)	Rn	0.97	0.96
	H	0.57	0.54
	LE	0.93	0.94
	G	0.86	0.78

[a]
$$r^2 = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(P_i - O_i)^2 + \sum_{i=1}^{N}(P_i - O_{avg})^2}, \quad MD = \frac{\sum_{i=1}^{N}(P_i - O_i)}{N}$$

$$ME = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(O_i - O_{avg})^2}, \text{ and } RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2}$$

where P_i and O_i are paired simulated and observed results, O_{avg} is the average observed value, and N is the number of data pairs.

Predicting canopy temperature is another important reason for developing RZ-SHAW. Canopy temperatures simulated by both models were very close to each other (fig. 3). RZ-SHAW was slightly worse in predicting canopy temperature than SHAW (table 2). Good simulation of canopy temperature was consistent throughout the growing season (fig. 3).

Evapotranspiration was simulated equally well by RZ-SHAW and SHAW (table 2, fig. 4). Total simulated ET from DOY 171 to 246 was 28.4 cm and 29.6 cm with RZ-SHAW and SHAW, respectively, compared to the estimated value of 28.5 cm by eddy covariance during the same period. The difference between RZ-SHAW and SHAW was mainly due to plant water uptake (25.4 cm for SHAW and 23.8 cm for RZ-SHAW), which might be attributed to the inability of the Richards equation to meet the water uptake demand when the

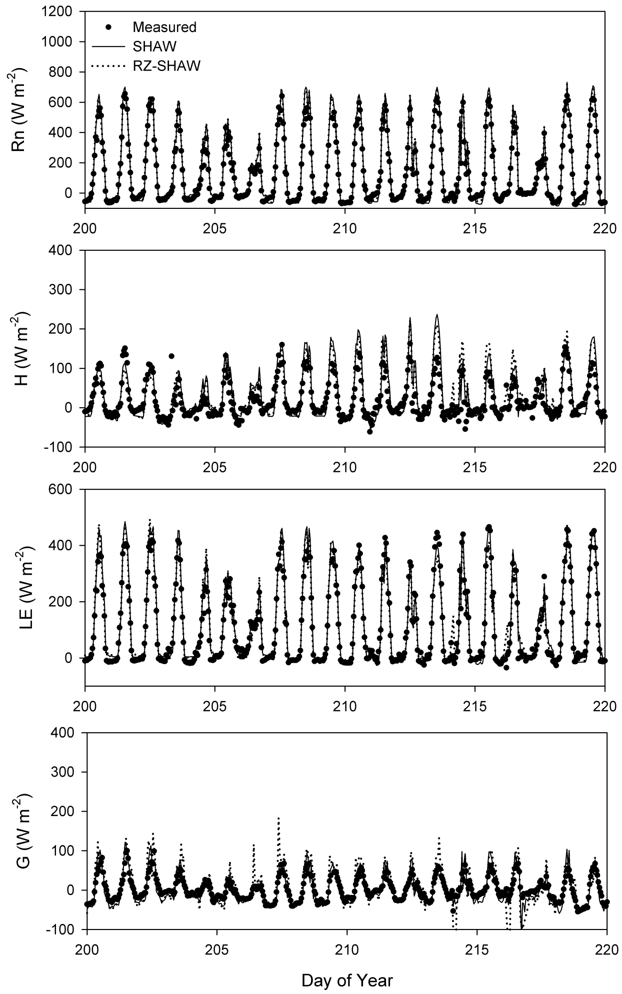

Figure 1. Measured and simulated net radiation (Rn), sensible heat (H), latent heat (LE), and ground heat flux (G) with SHAW and RZ-SHAW from DOY 200 to 220 as an example.

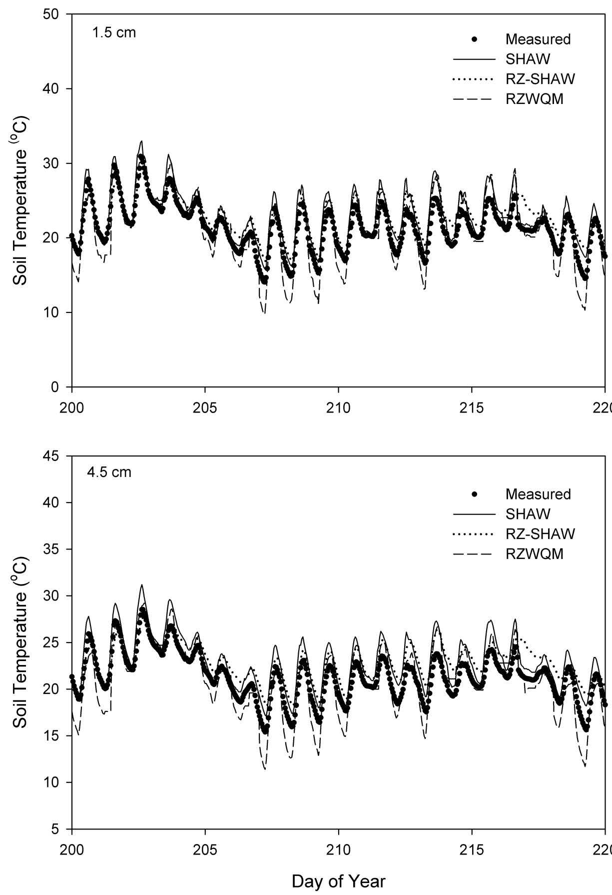

Figure 2. Measured and simulated soil temperature with SHAW, RZ-SHAW, and RZWQM at 1.5 cm and 4.5 cm from DOY 200 to 220 as an example.

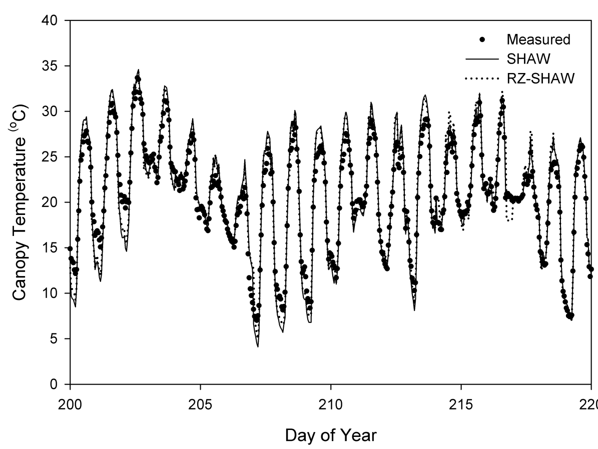

Figure 3. Measured and simulated canopy temperature with SHAW and RZ-SHAW from DOY 200 to 220 as an example.

Table 2. Comparison of measured soil and canopy temperatures and evapotranspiration with those simulated by SHAW and RZ-SHAW.

Statistics	Simulated Variable	SHAW	RZ-SHAW
Coefficient of determination (r^2)	Soil temperature at 1.5 cm (°C)	0.99	0.99
	Soil temperature at 4.5 cm (°C)	0.99	0.99
	Canopy temperature (°C)	0.99	0.99
	Evapotranspiration (cm d^{-1})	0.95	0.96
Mean difference (MD)	Soil temperature at 1.5 cm (°C)	1.50	1.40
	Soil temperature at 4.5 cm (°C)	1.68	1.61
	Canopy temperature (°C)	0.31	0.47
	Evapotranspiration (cm d^{-1})	0.014	-0.001
Root mean squared error (RMSE)	Soil temperature at 1.5 cm (°C)	2.13	2.18
	Soil temperature at 4.5 cm (°C)	2.20	2.23
	Canopy temperature (°C)	1.69	1.77
	Evapotranspiration (cm d^{-1})	0.074	0.069
Model efficiency (ME)	Soil temperature at 1.5 cm (°C)	0.75	0.74
	Soil temperature at 4.5 cm (°C)	0.60	0.59
	Canopy temperature (°C)	0.90	0.89
	Evapotranspiration (cm d^{-1})	0.54	0.60

soil was extremely dry. Compared to the PET from the Shuttleworth-Wallace equation for the same period, SHAW and RZ-SHAW simulated ET accounted for 64% and 67% of PET (44.2 cm). The relatively low actual ET during this period was mainly due to dry weather, especially from DOY 200 to 215. However, RZ-SHAW simulated ET much better than the original RZWQM. The latter had an RMSE of 0.139 cm

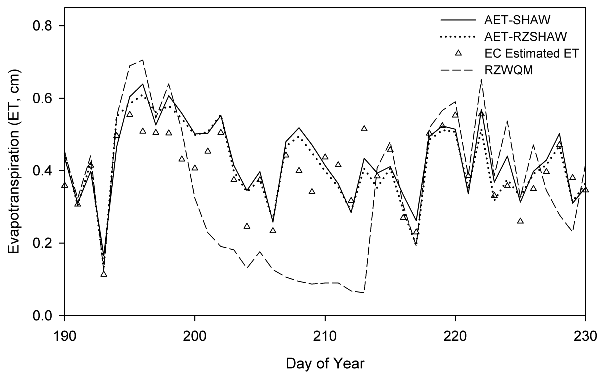

Figure 4. Estimated evapotranspiration (ET) from latent heat as measured from eddy covariance data and as simulated with SHAW, RZ-SHAW, and RZWQM from DOY 190 to 230 as an example.

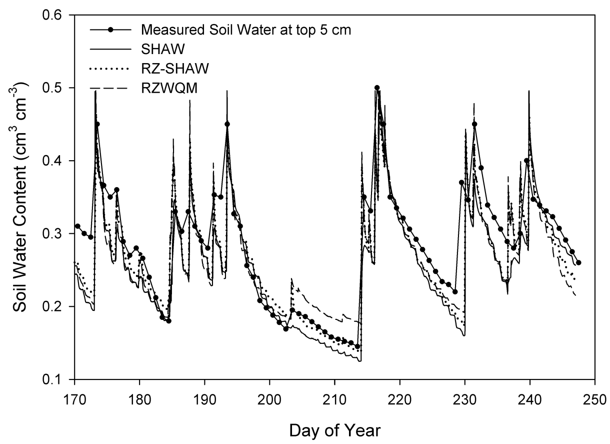

Figure 5. Measured and simulated surface soil water content (0 to 5 cm) with SHAW, RZ-SHAW, and RZWQM from DOY 170 to 250.

for simulated ET and an ME of -0.60. In addition, RZWQM underpredicted ET, with an MD of -0.018 cm and r^2 of 0.87. Such a poor simulation of ET by RZWQM was mainly due to low ET simulation during the dry period from DOY 200 to 213 (fig. 4).

Since the exact time of the day when soil water was measured is unknown, figure 5 plots daily soil water within the top 5 cm at noon each day. However, due to the large variation of surface soil water within a day, it is recommended to record the exact sampling time when measured soil water content is to be compared with simulation results at an hourly time step. Nonetheless, simulated soil water was comparable for both RZ-SHAW and SHAW, with a relative difference of only 4% in soil water content between the two models. In addition, both models correctly simulated the seasonal dynamics of surface water content (fig. 5). Although RZWQM simulated soil water content correctly during most of the growing season, it failed to further reduce soil moisture during the dry period of DOY 203 to 213, which may be related to the lower ET simulation during this dry period.

CONCLUSION

This study evaluated the new RZ-SHAW hybrid model for surface energy balance, soil and canopy temperature, evapotranspiration, and surface soil water content. Results showed that RZ-SHAW and SHAW were statistically comparable in simulating net radiation, sensible heat, latent heat, ground heat flux, soil and canopy temperature, and soil water content. Results also demonstrated that, although SHAW was called only during water redistribution in RZWQM, such an approach is adequate for simulating surface energy balance and soil surface conditions. The new RZ-SHAW model improved the simulation of soil surface temperature and ET compared to RZWQM, especially during dry soil conditions.

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