DEVELOPMENT OF THE ROOT ZONE WATER QUALITY MODEL (RZWQM) FOR OVER-WINTER CONDITIONS

G. N. Flerchinger, R. M. Aiken, K. W. Rojas, L. R. Ahuja

ABSTRACT. *Soil temperature and water conditions through the winter and early spring drive many important physical, chemical and biological processes. Impacts of management practices on these complex processes are often difficult to predict. The primary objective of this study was to incorporate routines for snow, soil heat, and soil freezing from the Simultaneous Heat and Water (SHAW) model into the process based RZWQM to extend its applicability to winter conditions. Routines from SHAW for simulating transfer through flat and standing residue layers were also included. The RZWQM's solution of the Richards' equation was retained, making it necessary to decouple the SHAW model's simultaneous solution of the heat and water equations. The modified RZWQM was applied to varying tillage and residue conditions using data from Pullman, Washington, and Akron, Colorado, and compared to the original SHAW model. Statistical comparisons indicated that the two models simulated soil temperature similarly for most plots, showing successful implementation of the SHAW routines. Differences in simulated soil temperatures and ice contents between the two models were related to differences in computing soil water transfer and solution of Richards' equation. Model efficiency for soil temperature simulated by the modified RZWQM, defined as the fraction of variability in measured temperature accounted for by the model, ranged from 0.71 to 0.92 within the top 25-cm at the Pullman site; simulated snow and soil frost depths were similar to previous simulations from the SHAW model. Model efficiency for simulated temperature at the Akron sites ranged from 0.87 to 0.98. Dynamic response of soil water potential was simulated reasonably well, with model efficiencies ranging from 0.61 to 0.86 for the Akron site. This modified version of the RZWQM, that includes frozen soil and boundary conditions representative of varying surface conditions, makes the model more responsive to management of soil and water resources in northern latitudes.*
Keywords. *Crop residue, RZWQM, SHAW Model, Snow, Soil freezing, Soil frost.*

Effective agricultural management requires an understanding of complex interactions between chemical, physical, hydrological, biological, and meteorological processes. Land managers need to address these important interactions in the near surface, but often lack the necessary means. An efficient way to evaluate the effectiveness of different management strategies is with the use of modeling tools. The Root Zone Water Quality Model (RZWQM), first reported by Rojas et al. (1988) and later by DeCoursey and Rojas (1990), was developed to help manage the use of agrochemicals and tillage/no-tillage practices by assessing environmental impacts of alternative management strategies. The model consists of modules to address six primary processes to be considered in evaluating any agricultural management system: physical processes, nutrient cycling, soil chemical processes, pesticide processes, plant growth, and management. Physical processes, which largely include heat and water transfer in the near-surface soil environment, drive other important processes, including pesticide and nutrient transport, runoff, plant germination and growth, and residue decomposition. The ability to accurately predict temperature and water conditions enables better modeling of these complex processes and improves evaluation of agricultural management options.

Hydrologic and physical processes in the RZWQM have been tested under a variety of conditions. Ahuja et al. (1993), Johnsen et al. (1995), Singh and Kanwar (1995a,b), Cook (1996), Walker (1996) and Kumar et al. (1998) tested the soil water transport and drainage components in Oklahoma, North Carolina, Minnesota, Illinois, and Iowa. Evapotranspiration simulations were evaluated by Farahani and Bausch (1995), Farahani and Ahuja (1996), and Ma et al. (1998b). More recently, the RZWQM has been evaluated and applied in the Management Systems Evaluation Area (MSEA) projects in several Midwestern states of the United States. (Watts et al., 1999). Extensive testing of other components of the RZWQM has also been conducted, including organic matter and nitrogen cycling (Hansen et al., 1995, Ma et al., 1998b), pesticide processes (Azevedo et al., 1997; Ahuja et al., 1995, 1996; Ma et al., 1995, 1996), plant growth (Nokes et al., 1996), and management (Ahuja et al., 1998; Singh and Kanwar 1995b). A review of applications of the RZWQM was given by Ma et al. (1998a).

Snow and soil freezing components were not included in the first RZWQM model (RZWQM Team, 1992), which

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has restricted its application during non-winter periods. More recently, simple routines for snow accumulation and melt were implemented in the RZWQM (Flerchinger et al., 1999), but these did not include soil freezing. However, snow and frozen soil are key factors influencing agricultural management and hydrology in many areas. Frozen soil is the leading cause of runoff and erosion in many of the northern latitudes of the United States and elsewhere.

One of the more detailed models of snow and freezing soil is the Simultaneous Heat and Water (SHAW) Model, originally developed by Flerchinger and Saxton (1989a) specifically to address tillage and residue affects on soil freezing, thawing and runoff from frozen soils. The model was expanded to consider vegetation canopies by Flerchinger and Pierson (1991) and Flerchinger et al. (1996b). The ability of the SHAW model to simulate wintertime phenomena of snow and frozen soil has been extensively tested (Flerchinger and Hanson, 1989; Flerchinger and Saxton, 1989b; Xu et al., 1991; Hayhoe, 1994; Flerchinger et al., 1994; Flerchinger et al., 1996a; Flerchinger and Seyfried, 1997; Kennedy and Sharratt, 1997).

Incorporating snow and frozen soil routines from the SHAW model into the RZWQM is a natural enhancement of the RZWQM, enabling the model to address wintertime processes and soil freezing. Simulation of heat and water transfer through canopy, stubble and residue layers, previously not addressed by the RZWQM, were also incorporated in this study. This study's primary objective was to couple the RZWQM with the heat transfer and soil freezing routines of the SHAW model, henceforth termed the RZ-SHAW coupling. The RZ-SHAW coupling was applied to sites with varying residue configurations to illustrate the ability of the model to simulate soil temperature, snow depth, and soil frost.

MODEL COUPLING

SOIL PROCESSES

The state equation for vertical temperature distribution in soil, considering convective heat transport by liquid and latent heat transfer by vapor for a layer of freezing soil, is given by:

$$C_s \frac{\partial T}{\partial t} - \rho_i L_f \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z}\left[k_s \frac{\partial T}{\partial z}\right] - \rho_l c_l \frac{\partial q_l T}{\partial z} - L_v\left(\frac{\partial q_v}{\partial z} + \frac{\partial \rho_v}{\partial t}\right) \quad (1)$$

where the terms (W m^{-3}) represent, respectively: specific heat term for energy stored due to a temperature increase; latent heat required to freeze water; net thermal conduction into a layer; net thermal advection into a layer due to water flux; and net latent heat of evaporation within the soil layer. In the above equation, C_s and T are volumetric heat capacity (J kg^{-1}C^{-1}) and temperature (C) of the soil, t is time (s), ρ_i is density of ice (kg m^{-3}) , L_f is latent heat of fusion (J kg^{-1}), θ_i is volumetric ice content (m^{3}m^{-3}), z is soil depth (m), k_s is soil thermal conductivity (W m^{-1} C^{-1}), ρ_l is density of water (kg m^{-3}), c_l is specific heat capacity of water (J kg^{-1} C^{-1}), q_l is liquid water flux (m/s), L_v is latent heat of vaporization (J kg^{-1}), q_v is water vapor flux (kg m^{-2} s^{-1}), and ρ_v is vapor density (kg m^{-3}) within the soil.

The water flux equation for frozen soil is written as:

$$\frac{\partial}{\partial z}\left[K\left(\frac{\partial \psi}{\partial z} + 1\right)\right] + \frac{1}{\rho_l}\frac{\partial q_v}{\partial z} + U = \frac{\partial \theta_l}{\partial t} + \frac{\rho_i}{\rho_l}\frac{\partial \theta_i}{\partial t} \quad (2)$$

where the terms (m^3 m^{-3} s^{-1}) represent, respectively: net liquid flux into a layer; net vapor flux into a layer; a source/sink term for water extracted by roots; change in volumetric liquid content; and change in volumetric ice content. In this equation, K is unsaturated hydraulic conductivity (m s^{-1}), ψ is soil matric potential (m), and U is a source/sink term for water flux (m^{3}m^{-3} s^{-1}), e.g., water extracted by plant roots.

Expressions for volumetric heat capacity, thermal conductivity, vapor flux, and liquid flux in the above equations are discussed in Flerchinger and Saxton (1989a) and RZWQM Team (1992). The relation assumed for the soil water characteristic equation in the SHAW model is (Campbell, 1974):

$$\psi = \psi_e \left(\frac{\theta_l}{\theta_s}\right)^{-b} \quad (3)$$

where ψ_e is air entry potential (m), b is a pore size distribution parameter, and θ_s is saturated water content (m^{3}m^{-3}). The RZWQM uses a more generic form of this equation, given by (Brooks and Corey 1966):

$$\psi = \psi_e \left(\frac{\theta_l - \theta_r}{\theta_s - \theta_r}\right)^{-b} \quad (4)$$

where θ_r is residual water content. Unsaturated hydraulic conductivity in the SHAW model is computed from (Campbell, 1974):

$$K = K_s \left(\frac{\theta_l}{\theta_s}\right)^{2b+3} \quad (5)$$

where K_s is saturated hydraulic conductivity (m s^{-1}). The RZWQM uses the following expression:

$$K = \begin{cases} K_s(-\psi)^{-N_1} & \text{for } \psi > \psi_K \\ C(-\psi)^{-N_2} & \text{for } \psi < \psi_K \end{cases} \quad (6)$$

where C, N_1, and N_2 are empirical coefficients, and ψ_K is the air-entry potential (m) for the conductivity function.

Unknowns in equations 1, 2, and 4 are temperature, water content, ice content, and matric potential so an additional equation is needed for a solution. This is provided by a simplification of the Clausius-Clapeyron equation given by Fuch's et al. (1978). Due to matric and osmotic potentials, soil water exists in equilibrium with ice at temperatures below the normal freezing point of bulk water and over the entire range of soil freezing temperatures normally encountered. When ice is present, total water potential (m) is related to temperature by (Fuchs et al., 1978):

$$\phi = \pi + \psi = \frac{L_f}{g}\left(\frac{T}{T_K}\right) \quad (7)$$

where g is the acceleration of gravity (m s^{-2}), T is temperature (C), and T_K is absolute temperature (K). Osmotic potential (π in m) within the soil is computed from:

$$\pi = \frac{-cRT_K}{g} \quad (8)$$

where c is solute concentration (eq kg^{-1}) in the soil solution, and R is the universal gas constant (8.3143 J $mole^{-1}K^{-1}$). Given the solute concentration, soil temperature defines the matric potential and, therefore, liquid water content when ice is present. Thus, as temperature drops, water potential becomes more negative, creating a gradient in water potential and causing moisture movement toward the freezing front. From equations 4, 7, and 8, liquid water content is defined by temperature below freezing; soil water content greater than that computed from these relations is assumed to be ice. If total water content is known, the change in ice content in equations 1 and 2 and the latent heat term in equation 1 can be determined.

Transfer Above the Soil Surface

Prior to the RZ-SHAW coupling, the RZWQM assumed surface soil temperature was equal to average daily air temperature. However, heat transfer to the soil surface can be modified by the presence of a canopy, standing stubble, snow, and residue. Thus, routines from the SHAW model for net radiation, surface energy balance, and transfer through canopy, snow and residue layers were also incorporated into the RZ-SHAW coupling. During non-winter periods, the user may select to use the SHAW routines above the soil surface, or opt for a simpler Penman-type algorithm described by Aiken et al. (1997a).

The surface energy balance in the SHAW model includes solar and long-wave radiation exchange, sensible and latent heat transfer at the surface, and vapor transfer within the canopy, snow, and residue. Absorbed solar radiation, corrected for local slope, is based on measured incoming short-wave radiation and includes reflection and back-scattering within the canopy and residue layers. Long-wave radiation emitted by the atmosphere is estimated from the Stefan-Boltzman law and adjusted for cloud cover (estimated from measured solar radiation). Surface sensible and latent heat transfer is estimated using a bulk aerodynamic approach with stability corrections.

Detailed descriptions of energy and mass transfer calculations within the canopy, snow, and residue layers are given by Flerchinger and Pierson (1991), Flerchinger et al. (1994, 1996a) and Flerchinger and Saxton (1989a), respectively. Convective heat and water transfer within standing stubble are computed much the same as within a transpiring canopy, except that the source for vapor transfer from the stubble elements is a function of water content. An energy balance in computed for each layer of a multi-layer snowpack. Liquid water is routed through the snowpack using attenuation and lag coefficients; effects of metamorphic changes of compaction, settling, and grain size on snow density and albedo are included. Heat is transferred through the residue layer by conduction through the residue elements and convection through the air voids. Evaporation and convective vapor transfer through the residue layer is described by Flerchinger and Saxton (1989a).

Numerical Solution

Solution of equations 1 and 2 is obtained through an implicit finite-difference approach using a Newton-Raphson iteration technique for each time step. In the SHAW model, the solution involves alternating back and forth between a Newton-Raphson iteration for the heat flux equations and one for the water flux equations. An iteration is conducted for the heat flux equations (eq. 1) and temperature estimates for the end of the time step are updated. For soil layers with ice present, matric potential and liquid water content are defined by equations 4, 7, and 8; all additional water is assumed to be ice. This is followed by an iteration for the water flux equations (eq. 2) where updated matric potential in unfrozen soil layers and ice content in frozen soil layers are determined. Upon completion of the iteration for the water flux equations, the solution reverts back to an iteration for the heat flux equations with the updated values. Iterations continue until all subsequent iterations of both heat and water flux equations for each layer are within a prescribed tolerance. Thus, the heat and water flux equations are solved simultaneously, maintaining a correct balance between the two coupled equations.

Because of the interactions of the soil water redistribution routines with other components of the RZWQM, it was desirable to retain these routines within the RZ-SHAW coupling. This necessitated decoupling the soil heat and water routines within the SHAW model prior to implementing the energy routines from the SHAW model into the RZWQM; routines from the SHAW model for both heat and water vapor transfer above the soil surface were implemented within the RZ-SHAW coupling. Upon solving the water flux equation and updating of the matric potentials assuming constant ice content in each layer, heat flux routines from the SHAW model are used to solve soil temperatures and ice contents. Above the soil surface, the RZ-SHAW routines for heat and water vapor transfer within the canopy, snow, and residue layers are coupled and solved much the same way as in the SHAW model. Surface soil matric potential supplied by the RZWQM soil water redistribution routine is used as a lower boundary for water vapor transfer through the canopy, snow and residue layers. With total water content of each soil layer assumed constant, temperature, matric potential and ice content are solved for each layer using a Newton-Raphson iterative solution of the heat flux equations. After an iteration of the heat flux equations for the entire profile, an iteration for water vapor transfer above the soil surface is conducted, and vapor density in the canopy and residue are updated. When subsequent iterations for each layer are within a prescribed tolerance (set to 0.01°C and 1% change in vapor density), the state variables for temperature, water, and ice are returned to the RZWQM routines. Water vapor transfer computed by the SHAW routines is subsequently used as an evaporative flux by the RZWQM soil redistribution routines, lagged by one time step.

Interaction with plant routines within the RZWQM requires that a minimum soil water matric potential be defined in the solution of the Richards' equation. This is typically set between –15 to –20 bars (approximately –150 to –200 m). However, limiting soil matric potential during the winter period significantly curtailed the amount of ice formed within the soil layers. This limitation is not present in the SHAW model and was therefore removed from the RZ-SHAW coupling during winter periods. This would not affect plant transpiration routines since the plants are not active during these periods.

Site Conditions

Data were collected for various tillage and residue treatments during the winter of 1986-1987 at Pullman, Washington, and during 1995-1996 at Akron, Colorado. The RZ-SHAW coupling was applied to the Pullman site and compared to previous simulations of the SHAW model. Both models were applied to the Akron data to assess the accuracy of the models and to test the routines for standing residue.

Pullman Site

Data collected for the 1986-1987 winter at the Pullman site were described by Flerchinger and Saxton (1989b), who used it to test the SHAW model. Data were collected for six tillage-residue conditions for winter wheat. The extremes in plot conditions were heavy residue, no-till (plot H-NT), and a light residue cover tilled with a rotary hoe to represent a conventionally tilled plot (plot L-CT).

The site was located on a south-facing Palouse silt loam (fine-silty mixed mesic *Pachic Ultic Haploxeroll*) soil on the USDA Palouse Conservation Field Station. Measured atmospheric data for the site included hourly air temperature, wind speed, humidity, solar radiation and precipitation. Manual measurements of snow depth were taken throughout the winter season. Soil temperatures were measured near the surface and at depths of 7.5, 15, 25, 38, 53, 69, 84, 107, 137, and 168 cm. Soil frost depth was estimated from soil gypsum blocks read every three hours. Soil water content measurements were collected approximately weekly using a combination of gravimetric samples for depths less than 25 cm and neutron probe readings for deeper depths. Neutron probe readings were converted to water content based on previous calibration exercises at the field station. Residue amount on the surface was determined from residue samples collected from 25 cm × 25 cm random samples. A summary of residue cover characteristics for the Pullman and Akron sites is given in table 1.

Akron Site

Data collected at the Akron site were described by Aiken et al. (1997b), where soil temperature and moisture measurements were collected during the 1995-1996 winter for stubble mulched wheat, no-till wheat, millet, corn, and sunflower. Stubble mulch wheat (wheat-SM), no-till millet (millet-NT), and no-till wheat (wheat-NT) represented a progression from an essentially bare soil surface, to a flat residue layer, to residue cover with standing stubble; these three treatments therefore were selected for model application. (The corn and sunflower fields had negligible standing residue remaining on the surface.)

Table 1. Residue properties for the simulated field conditions

Site / Treatment	Residue Loading (kg/ha)	Residue Cover (%)	Stem Area Index	Stem Height (cm)
Pullman, Washington				
Rotary hoe wheat	0	0	0.0	0.0
No-till wheat	10 415	91	0.0	0.0
Akron, Colorado				
Stubble mulch	0*	0	0.01	0.05
No-till millet	2500*	57	0.05	0.11
No-till wheat	5600*	85	0.31	0.23

* Estimated values.

The study site was located on a level Weld silt loam (fine montmorillonitic, mesic *Aridic Paleustoll*) soil. Hourly weather measurements included air temperature, wind speed, humidity, and solar radiation; hourly soil temperatures were measured near the surface and at depths of 3, 7, 15, and 25 cm. Soil water potential observations corrected for temperature were estimated from gypsum soil moisture blocks installed at depths of 3, 7, 15, and 25 cm. Break-point precipitation observations were collected from a shielded, weighing precipitation gauge. Surface residue cover and standing stems (height, frequency, and diameter) were quantified using a 100-point line intercept method. Standing stem observations were used to estimate the stem area index, taken as the vertical projected area of standing stems per unit area of ground surface.

Model Simulations

The model was applied to one winter season for the two plots at the Pullman site, which serves as a benchmark data set to evaluate the ability of the RZ-SHAW coupling to simulate a data set previously used to test the SHAW model. The model was parameterized for identical residue and soil conditions simulated by Flerchinger and Saxton (1989b). The models were initialized with soil temperature and water content profiles measured on day 308 of 1986 (4 November) and values were simulated through February of 1987 using measured weather data and assuming a unit gradient in soil water potential (i.e., free drainage) at the bottom of the 180-cm simulated profile.

For further comparison of the RZ-SHAW coupling with the SHAW model and to test the standing residue equations, both models were applied to the data from the Akron site. Residue conditions simulated by both models are listed in table 1; standing residue for the wheat-SM and millet-NT was negligible and these treatments were simulated without any standing residue. Albedo of the residue and soil was assumed constant and set to 0.40 and 0.25, respectively. Soil hydraulic properties were estimated from soil textural information. The models were initialized using soil moisture profiles measured on day 331 of 1995 (27 November) and estimated soil temperatures below the measured 25 cm profile. Values were simulated through day 156 of 1997 (5 June) using measured weather data and assuming a unit gradient in soil water potential at the bottom of the 135-cm simulated profile.

Simulated and measured values of soil temperatures and matric potentials were compared using model efficiency (ME), root mean square difference (RMSD) and mean bias error (MBE). Definitions for each are given in table 2 (Nash and Sutcliffe, 1970; and Green and Stephenson, 1986).

MODEL RESULTS

DECOUPLING OF THE ENERGY AND WATER FLUX EQUATIONS

A decoupled solution to equations 1 and 2 was implemented in an experimental version of the SHAW model similar to that in RZ-SHAW to examine the effect of a decoupled or non-simultaneous solution. Decoupling the energy and water flux equations had a minimal effect on temperature, water and ice contents simulated by the SHAW model using hourly time steps. (Maximum time step in the RZWQM is 1 h). Differences in temperature between the two solutions were less than 0.1°C, and ice contents were within 0.005 cm^3cm^{-3}. Run-time for the non-coupled solution in the SHAW model was approximately 15% less than the full simultaneous solution of equations 1 and 2. This savings in run-time was not a prime concern in this study but may be important in developing a simplified version of the SHAW model. (Run-time for an annual simulation with hourly time-steps may take RZ-SHAW approximately 7 min on a 266 MHz processor; SHAW routines may account for up to 25% of this run-time.)

Differences in simulated soil temperature and water between the SHAW model and RZ-SHAW were minimal, but not trivial. Examination of table 3 indicates the similarity in simulated temperatures between the models for all plots at the Pullman and Akron sites. The MBE for the models are within 0.2°C of each other for all plots and, with the exception of near-surface temperature for the Akron wheat-NT plot, the RMSD for the models are within 0.2°C of each other. The overall similarity in the performance of the two models would suggest a successful coupling of the two models, but there was some concern for the 1.0°C difference in RMSD for the near-surface temperatures of the wheat-NT plot. Because this is the only plot with standing residue, the immediate assumption might be that the standing residue routines were not implemented correctly. However, further inspection related differences in simulated temperature to differences in simulated soil water transport between the two models.

Table 2. Description and definition of model performance measures

Measure	Description	Mathematical Definition*
ME	Model Efficiency, i.e., variation in measured values accounted for by the model.	$1-\dfrac{\sum_{i=1}^{N}\left(Y_i-\hat{Y}_i\right)^2}{\sum_{i=1}^{N}\left(\overline{Y}_i-\hat{Y}\right)^2}$
RMSD	Root Mean Square Difference between simulated and observed values.	$\left[\dfrac{1}{N}\sum_{i=1}^{N}\left(\hat{Y}_i-Y_i\right)^2\right]^{1/2}$
MBE	Mean Bias Error of model predictions compared to observed values.	$\dfrac{1}{N}\sum_{i=1}^{N}\left(\hat{Y}_i-Y_i\right)$

* $\hat{Y}_i$ = simulated values; Y_i = observed values; $\overline{Y}$ = mean of observed values; N = number of observations.

Table 3. Comparison of simulated soil temperatures to measured soil temperatures for the SHAW model and the RZ-SHAW coupling*

Site / Treatment	Depth (cm)	ME RZ-SHAW	ME SHAW	MBE RZ-SHAW	MBE SHAW	RMSD RZ-SHAW	RMSD SHAW
Pullman, Washington							
L-CT	Surface	0.74	0.70	–0.6	–0.8	1.3	1.4
	15	0.74	0.72	–0.8	–0.7	1.0	1.0
	25	0.71	0.76	–0.8	–0.5	1.0	0.9
H-NT	Surface	0.81	0.80	+0.4	+0.3	0.9	0.9
	15	0.92	0.90	–0.1	0.0	0.4	0.5
	25	NA	NA	NA	NA	NA	NA
Akron, Colorado							
Wheat-SM	Surface	0.95	0.94	+0.1	+0.2	2.9	3.0
	15	0.91	0.91	+0.4	+0.3	1.9	1.9
	25	0.93	0.93	+0.2	+0.1	1.6	1.5
Millet-NT	Surface	0.87	0.86	–0.2	–0.1	3.6	3.8
	15	0.90	0.91	0.0	0.0	1.4	1.3
	25	0.91	0.94	–0.1	–0.1	1.2	1.0
Wheat-NT	Surface	0.90	0.83	–0.5	–0.7	3.4	4.4
	15	0.97	0.96	0.0	–0.2	1.0	1.2
	25	0.98	0.97	–0.2	–0.3	0.8	1.0

* NA : Measured soil temperatures at the 25-cm depth for the H-NT site were not available due to sensor malfunction.

The wheat-NT site was the wettest plot (0.303 cm^3cm^{-3} surface water content compared to 0.195 cm^3cm^{-3} for the wheat-SM plot) at the Akron site, which experienced more diurnal freeze/thaw cycles prior to deep frost penetration than the Pullman site. Such conditions create the potential for moisture migration in response to freezing, and minor differences in computing water flow can accumulate. Under drier conditions, there is insufficient water transport and differences in water flux computations are not as pronounced. Upon simulating the wheat-NT site with a drier soil water profile identical to that of the wheat-SM plot, the difference in RMSD for the two models decreased to 0.3°C, with values of 2.8 and 3.1°C. In further support that differences in computing water transport caused the observed differences in the models, the RMSD for near-surface temperature was the same for both models (4.5°C) when simulating a profile with soil hydraulic conductivities set to zero. Additionally, when the wheat-SM plot was simulated with a wetter soil profile, the difference in RMSD between the models increased from 0.1°C to 0.6°C. The possibility that these differences can be attributed to latent heat of evaporation at the surface was negated since simulated cumulative evaporation for the two models was within 2 mm for the 196-day simulation.

Differences in simulated total water content between the two models for the wheat-NT plot were largest in the near surface soil layers (fig. 1). The divergence in simulated surface water content on day 352 occurred as the soil surface thawed after several diurnal freeze/thaw cycles. Total water and ice content of the 2-cm depth simulated by the RZ-SHAW coupling were somewhat lower during this thaw event than those for the SHAW model, as shown in figure 1, allowing the water to drain to layers below; whereas, elevated ice content in the underlying layer prohibited drainage in the SHAW model. This difference in ice content of the surface layer after day 352 created a difference in soil thermal properties of the surface layer,

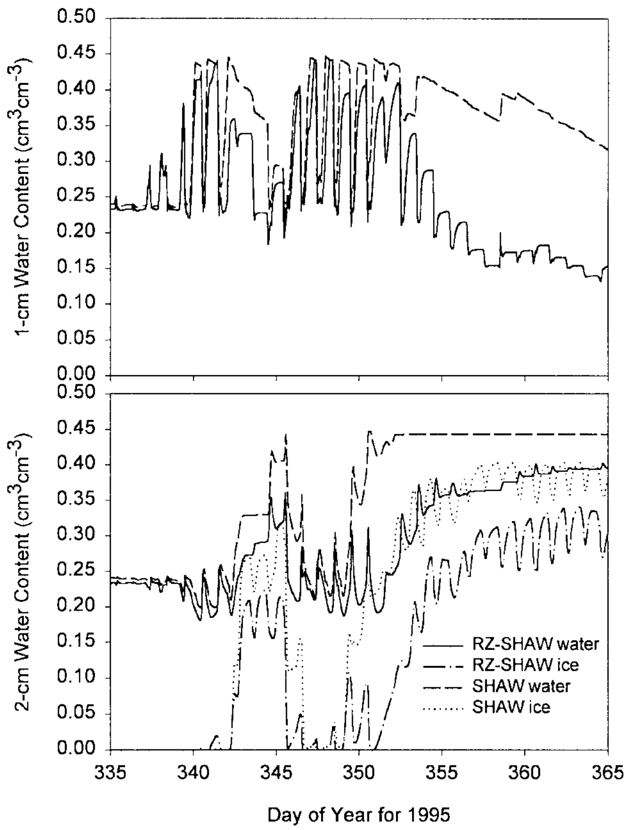

Figure 1–Comparison of output from the RZ-SHAW coupling and the SHAW model for surface 1-cm total water content and 2-cm total water content and ice content during December 1995 for the wheat-NT plot at Akron, Colorado. (Oscillations in ice content are due to diurnal freezing and thawing.)

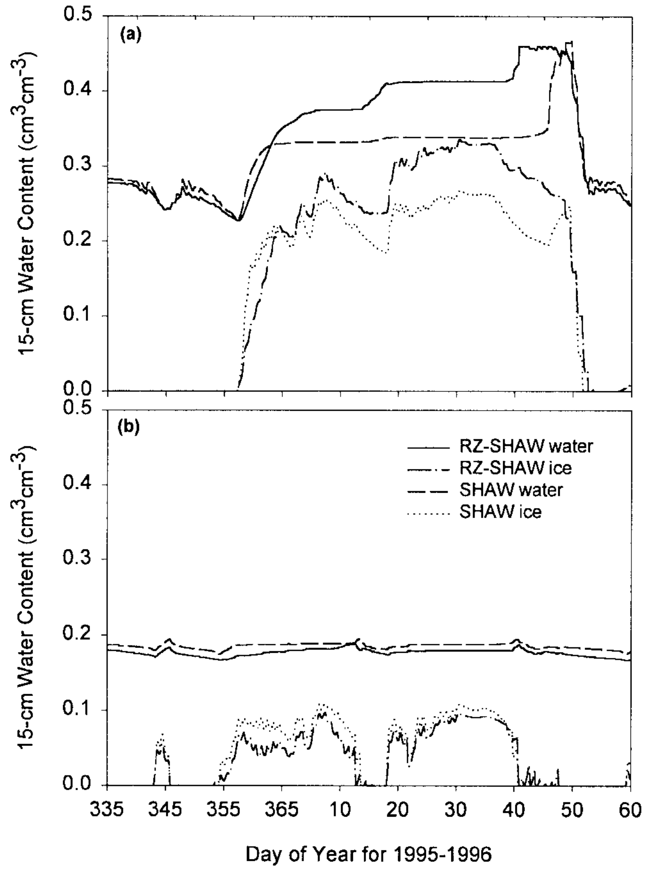

Figure 2–Comparison of output from the RZ-SHAW coupling and the SHAW model for 15-cm total soil water content and ice content for (a) the wheat-NT plot, and (b) the wheat-SM plot at Akron, Colorado, from December through March.

resulting in differences in simulated soil temperature for this depth.

Total water content and ice content for the 15-cm depth for the entire season is plotted in figure 2 for the wheat-NT and wheat-SM plots. The differences between the two models in computed soil water transport with wetter soils is illustrated here as well. Liquid water content simulated by the two models was quite similar, but greater ice accumulation resulted in higher total water content. This difference is more pronounced with wetter soils, such as the wheat-NT plot, where there is more opportunity for water transport.

Differences in the simulated ice content between SHAW and RZ-SHAW during the first freeze-thaw cycle for plot L-CT at the Pullman site can be seen in figure 3. At the 1-cm depth, the models have ice contents that are typically within 0.04 cm^{3}cm^{-3} of each other. Differences for the 1-cm depth were minimal here compared to the Akron wheat-NT site because this depth froze quickly, offering little opportunity for moisture migration. However, differences at the 3-cm depth are comparable to the Akron site, with the SHAW model accumulating more ice and total water content. Because the 3-cm water content was slightly higher in the SHAW simulation, unsaturated conductivity was higher. As a result, more water was able to migrate into the layer as it froze, which resulted in higher ice and total water contents for the SHAW simulation.

PULLMAN SITE

Simulated and measured snow and frost depths for the RZ-SHAW coupling are plotted with measured values for plot H-NT in figure 4 and for plot L-CT in figure 5. The effect of tillage and residue on frost depth was simulated quite well by the model. Predictions, such as those shown in figures 4 and 5, were not possible in the RZWQM prior to implementation of the RZ-SHAW coupling. Snow depth calculated from measured precipitation was underestimated in both cases, perhaps due in part to inefficient catch of the shielded precipitation gauge. Flerchinger and Saxton (1989b) obtained better comparison for snow depth in their simulations by specifying the density of the snow to match the observed snow depth.

Simulated and measured soil temperature for the surface, 7.5 cm and 15 cm soil depths during January are plotted in figure 6 for plot H-NT and in figure 7 for plot L-CT. Snow insulated the soil for much of the time period, resulting in very little diurnal variation in soil temperature. After the snow melted, considerably more diurnal variation occurred in plot L-CT, the bare soil surface, compared to plot H-NT. Statistical comparisons between simulated and measured soil temperatures in the top 25-cm are presented in table 3. Temperature simulations were slightly better for H-NT, as the simulated temperatures for L-CT were underpredicted by approximately 0.8°C.

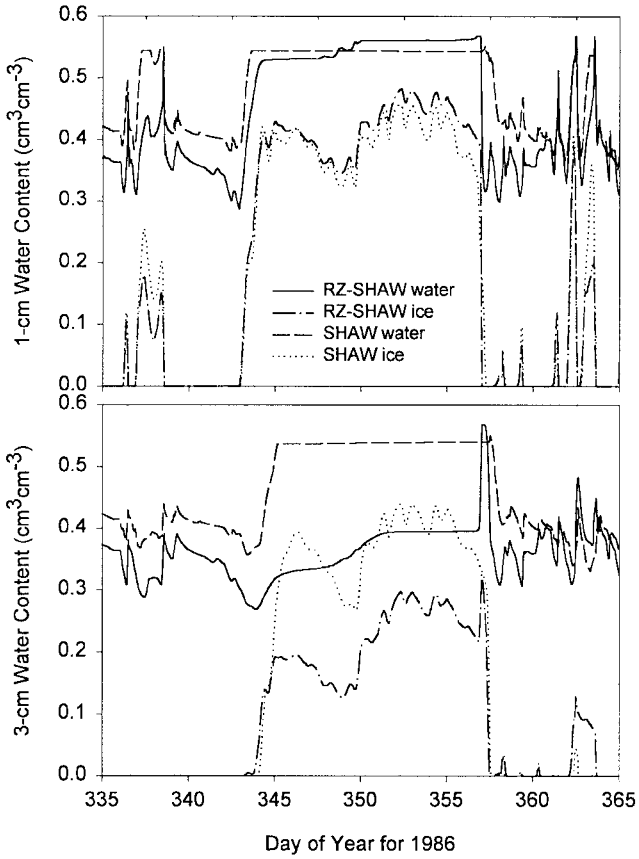

Figure 3–Comparison of output from the RZ-SHAW coupling and the SHAW model for total water content and ice content at the 1-cm and 3-cm depths during the first freeze thaw cycle of December 1986 for plot L-CT at Pullman, Washington.

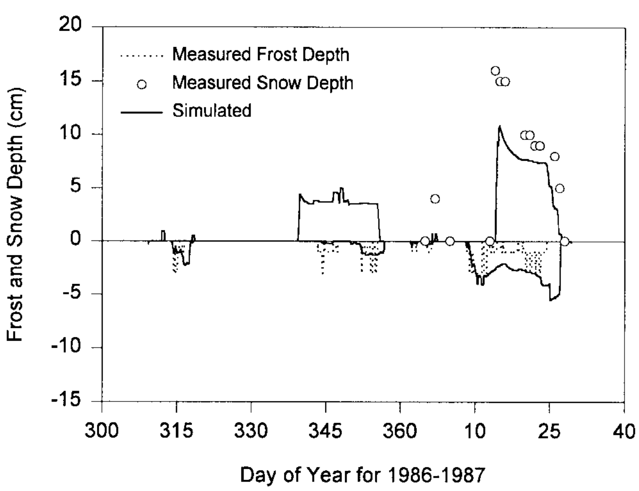

Figure 4–Comparison of measured and simulated frost and snow depth for the RZ-SHAW coupling during 1987 for plot H-NT, a no-till plot with heavy residue cover at Pullman, Washington.

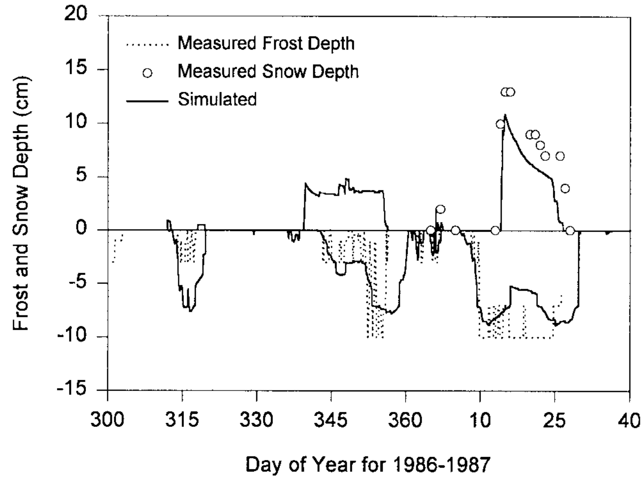

Figure 5–Comparison of measured and simulated frost and snow depth for the RZ-SHAW coupling during 1986-87 for plot L-CT, a tilled bare soil surface at Pullman, Washington.

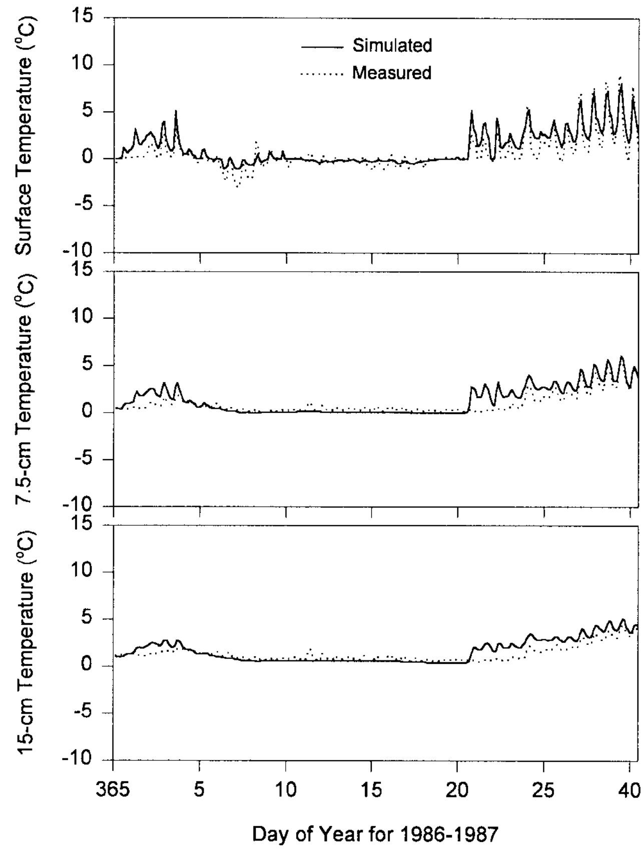

Figure 6–Comparison of measured and simulated soil temperature for the RZ-SHAW coupling during January 1987 for plot H-NT, a no-till plot with heavy residue cover at Pullman, Washington.

Volumetric water content was also predicted somewhat better for H-NT. The RMSD of volumetric water content simulated for H-NT by the RZ-SHAW coupling compared to the nine sampling dates throughout the season ranged from 0.02 to 0.06 cm^3cm^{-3} for the top 25 cm of the profile; RMSD for L-CT ranged from 0.04 to 0.07 cm^3cm^{-3} for the 7, 15, and 25 cm depths. The RMSD for the near-surface water content for L-CT, which tends to be more variable because of the bare soil surface, was 0.12 cm^3cm^{-3}. Water content simulated by the SHAW model was similar to that for the RZ-SHAW coupling.

Akron Site

The RZ-SHAW coupling model efficiencies for simulated temperature at the Akron site are slightly better

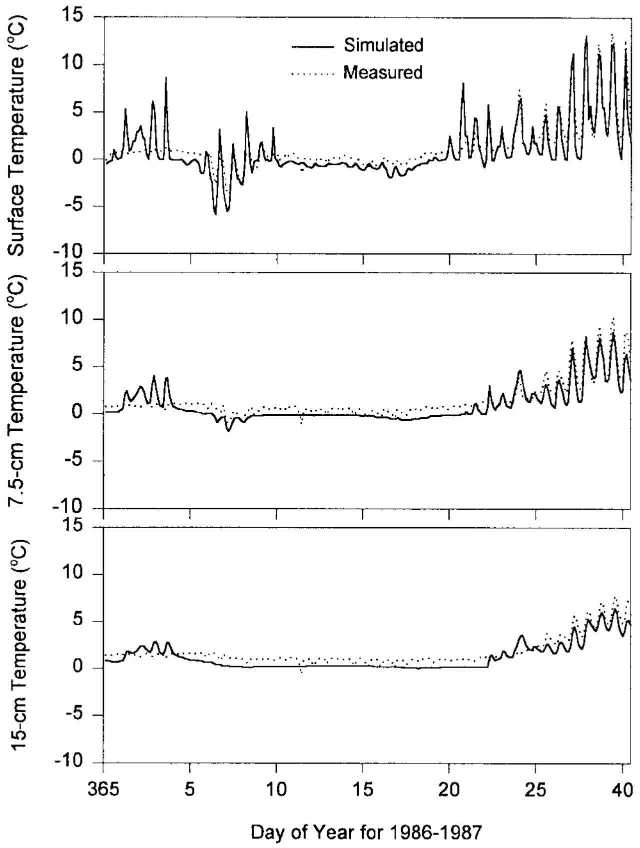

Figure 7–Comparison of measured and simulated soil temperature for the RZ-SHAW coupling during January 1987 for plot L-CT, a tilled bare soil surface at Pullman, Washington.

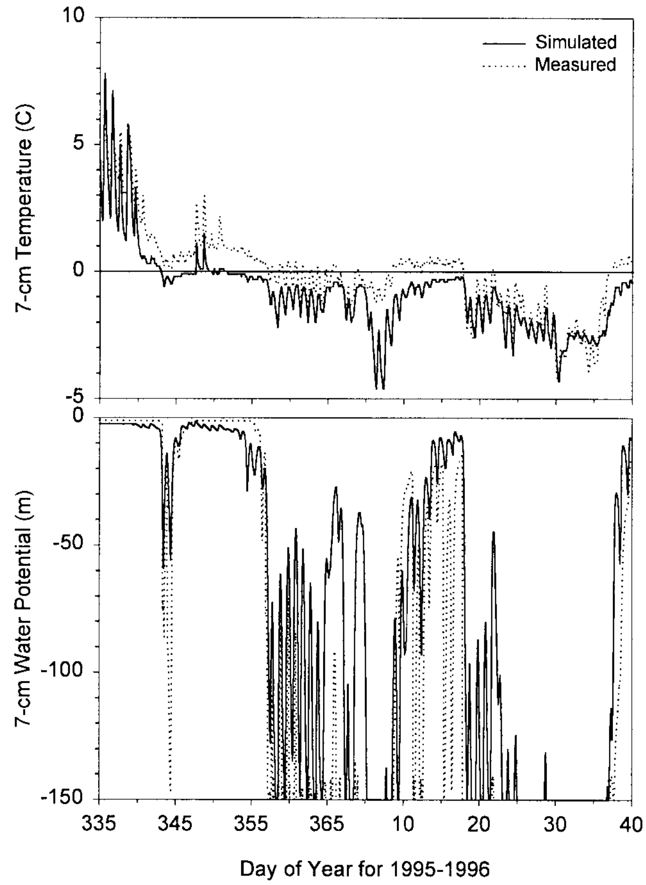

Figure 8–Comparison of measured and simulated 7-cm soil temperature and 7-cm matric potential (truncated to –150 m or approximately –15 bars) for the RZ-SHAW coupling from December through March for the wheat-NT plot at Akron, Colorado.

than those for the SHAW model (table 3). However, with the exception of near-surface temperature for the wheat-NT plot as discussed previously, simulated soil temperatures for the two models were similar. Based on ME and RMSD, both models simulated the surface temperature somewhat better for the wheat-SM plot, but deeper depths were simulated best for the wheat-NT plot. Results from the wheat-NT plot, which represent a first test of the routines in the models for standing stubble, are encouraging and support the approach used in these routines.

The Akron site was virtually free of snow for most of the winter except for a small accumulation which covered the ground during the first week in February and another which lasted for a few days in the latter part of March. Measured soil temperature and matric potentials indicate that frost depth exceeded the 25-cm measured profile, and it was simulated to approximately 60 cm. The dynamic response of the 7-cm matric potential (truncated to –150 m) to soil freezing and thawing in the wheat-NT plot is plotted in figure 8 along with the corresponding soil temperature. Both simulated and measured matric potentials indicate a dramatic drop in matric potential around day 355 of 1995 associated with soil water freezing. As simulated soil temperature dropped further below 0°C, more water froze, and the simulated and measured matric potential continued to drop. Inspection of figure 8 reveals the sensitivity of soil matric potential to small changes in soil temperature slightly below 0°C. The rise in matric potential on day 9 of 1996 is associated with a brief thaw period as soil temperatures rose and ice in the soil began to thaw, even though simulated soil temperatures at the 7-cm depth did not rise above –0.4°C. The soil froze very solidly again between days 20 and 35 as air temperatures dropped below –15°C.

Model efficiency for the wheat-NT 7-cm matric potential plotted in figure 8 is 0.83. ME of simulated matric potential for other plots at this depth were 0.78 for millet and 0.76 for wheat-SM. The worst performance for both models (0.61 for RZ-SHAW and 0.40 for SHAW) was the 3-cm matric potential in wheat-SM, perhaps due in part to the extreme temporal variability in near-surface matric potential for this bare soil surface. However, one must bear in mind the problems associated with using soil moisture blocks near the soil surface, and that they are not a particularly accurate measurement of matric potential. With this exception, ME for simulated matric potential in the top 25 cm ranges from 0.72 to 0.86 for RZ-SHAW and 0.59 to 0.89 for SHAW.

Summary and Conclusions

Soil heat routines with detailed provisions for soil freezing and thawing from the SHAW model were implemented into the RZWQM (herein termed the RZ-SHAW coupling) along with routines for heat and water transfer through flat and standing residue and snow above the soil surface. The RZWQM solution to the Richards' equation was retained to preserve interactions with other portions of the model, making it necessary to decouple the simultaneous solution to the soil heat and water flux equations used in the SHAW model. Thus, an experimental version of the SHAW model was developed to examine the effects of solving the two sets of equations separately. In preliminary comparisons, decoupling the equations in the SHAW model had minimal effect on the solution and reduced runtime by approximately 15%. This can have important implications in developing a simplified version of the SHAW model, as reduced runtimes will make it more feasible to incorporate the SHAW model into other models where efficient runtimes might be a concern. Further investigation is needed to examine the effects of decoupling the heat and vapor flux equations for the residue layers as well.

Based on simulations for a variety of residue configurations, the SHAW routines were successfully implemented into the RZWQM. Application of the RZ-SHAW coupling and the SHAW models to the wheat-NT plot represents the first test of the routines for standing residue. Based on comparisons of simulated temperature and matric potential with field measurements, these routines simulated heat and water transfer through the standing stubble with reasonable accuracy. Statistical comparisons of the RZ-SHAW coupling and the SHAW model to measured data were quite similar, and in some instances, RZ-SHAW compared better with field measurement than the SHAW model. Minor differences in model performance for near-surface temperature and water content between the two models were attributed to differences in soil water flux computations and the solution of the Richards' equation. Measurements of near-surface water content with sufficient detail to assess which of the models was more accurate were lacking. Simulated temperature and water content at depth were very similar between the two models.

The addition of routines for frozen soil and surface boundary conditions from the SHAW model enables this modified version of the RZWQM to better represent varying surface conditions and management scenarios in northern latitudes. These modifications provide land managers with a means to address the important and complex interactions in the near surface. With these provisions to address wintertime processes and soil freezing, the RZWQM should provide more accurate and reliable year-around and multi-year simulations.

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