Evaluation of SHAW Model in Simulating Energy Balance, Leaf Temperature, and Micrometeorological Variables within a Maize Canopy

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ABSTRACT

Understanding and simulating plant canopy conditions can assist in better acknowledgment of plant microclimate characteristics, its effect on plant processes, and the influence of management and climate scenarios. The ability of the Simultaneous Heat and Water (SHAW) model to simulate the surface energy balance and profiles of leaf temperature and micrometeorological variables within a maize canopy and the underlying soil temperatures was tested using data collected during 1999 and 2003 at Yucheng, in the North China Plain. The SHAW model simulates the near-surface heat and water movement driven by input meteorological variables and observed plant characteristic (leaf area index [LAI], height, and rooting depth). For 1999, the model accurately simulated air temperature and relative humidity in the upper one-third of the canopy, but overpredicted midday temperature in the lower canopy. For 2003, although the surface energy balance was simulated quite well, radiometric canopy surface temperature and midday leaf temperature in the upper portion of the canopy were overpredicted, by approximately 5°C. Model efficiency (the fraction of variation in observed values explained by the model) for leaf temperature in the lower two-thirds of the canopy ranged from 0.82 to 0.90, but fell to 0.38 for the uppermost canopy layer. Weaknesses in the model were identified and potentially include: the use of *K*-theory to simulate turbulent transfer within the canopy; and simplifying assumptions with regard to long-wave radiation transfer within the canopy. Model modifications are planned to address these weaknesses.

KNOWLEDGE of conditions near the soil–atmosphere interface is of key interest to many areas of research. The near-surface microclimate controls vital plant biological processes such as photosynthesis, respiration, transpiration, and crop damage from extreme temperatures. Canopy temperature reflects plant physiological conditions, not only by relating to air temperature, but also to stomatal opening, vapor diffusion resistance, and overall plant stress. Understanding processes of heat and water transfer within the plant canopy can assist in better acknowledgment of microclimate characteristics and their influence on plant processes. The ability to predict microclimatic conditions within the soil-plant-atmosphere system enhances our ability to predict plant response to microclimatic conditions and to evaluate management and climate scenarios (Gottschalck et al., 2001; Pachepsky and Acock, 2002; Yu et al., 2002, 2004).

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Published in Agron. J. 98:722–729 (2006).
Agroclimatology
doi:10.2134/agronj2005.0126

The surface energy balance describes the partitioning of net short and long wave radiation into latent, sensible, and soil heat fluxes which form the basis for simulating water and heat transfer and are the driving factors for C and N circulation. Transport of mass and energy between the land and atmosphere is an increasing area of interest as the need to better represent surface–atmosphere interactions in climate and atmospheric circulation models increases.

Researchers have struggled with describing heat and mass transfer between the atmosphere and vegetated surfaces for more than 35 yr (Waggoner and Reifsnyder, 1968) and have developed several models ranging widely in complexity (Goudriann and Waggoner, 1972; Norman, 1979; Shuttleworth and Wallace, 1985; Kustus, 1990; Massman and Weil, 1999). Comprehensive models capable of simulating microclimate within the canopy typically employ one of two theories. Gradient (or *K*-theory) models (Norman, 1979; Flerchinger et al., 1998; Mihailović et al., 2002) define heat and mass fluxes within the canopy as the product of a concentration gradient and the eddy diffusivity, *K*. Considerable effort has been expended to estimate eddy diffusivities within the canopy (Ham and Heilman, 1991; Jacobs et al., 1992; Huntingford et al., 1995; Sauer et al., 1995; Sauer and Norman, 1995). The *K*-theory has come under criticism for not predicting counter-gradient fluxes (Denmead and Bradley, 1985). Lagrangian trajectory theory (L-theory; Raupach, 1989) has been proposed as an alternate to *K*-theory, and recently several L-theory models have been developed (van den Hurk and McNaughton, 1995; Massman and Weil, 1999; Warland and Thurtell, 2000). Wilson et al. (2003) compared *K*-theory and L-theory approaches and concluded that both approaches performed equally in simulating surface energy components.

The SHAW model, which is based on *K*-theory, was originally developed by Flerchinger and Saxton (1989b) and modified by Flerchinger and Pierson (1991) to include transpiring plants and a plant canopy. Its ability to simulate heat, water, and chemical movement through plant cover, snow, residue, and soil for predicting climate and management effects on soil freezing, snowmelt, soil temperature, soil water, evaporation, transpiration, energy flux, and surface temperature has been demonstrated (Flerchinger and Hanson, 1989a; Flerchinger and Pierson, 1991; Xu et al., 1991; Flerchinger et al., 1994, 1996a,b, 1998; Hayhoe, 1994; Flerchinger and Seyfried, 1997, Kennedy and Sharratt, 1998; Duffin,

Abbreviations: IRGA, infrared gas analyzer; IRT, infrared temperature sensor; IRTS, infrared thermocouple sensor; LAI, leaf area index; MBE, mean bias error; ME, model efficiency; NCP, North China Plain; RMSD, root mean square deviation; SHAW, Simultaneous Heat and Water.

1999; Hymer et al., 2000; Nassar et al., 2000; Flerchinger et al., 2003). However, the model has not been tested in its ability to simulate profiles of meteorological variables within a canopy. The objectives of this paper are to test the ability of the SHAW model for simulating (i) the surface energy balance over a plant canopy, (ii) radiometric surface temperatures, (iii) canopy leaf temperature and (iv) the profiles of micrometeorological variables (air temperature, relative humidity, wind speed) in a maize canopy, and (v) profile of underlying soil temperature. Simulations were compared with measurements from a maize canopy at Yucheng, China.

FIELD MEASUREMENT

Site Description

The experiment was conducted at the Yucheng Comprehensive Experiment Station (36°50′ N, 116°34′ E, 28 m above sea level) of Chinese Academy of Sciences, lying on the North China Plain (NCP). Soil was a sandy loam soil. Measurements were made at the center of a 300 by 300 m, well-watered field of maize. Surrounding the experimental field was unbroken fields of maize, at similar growth stages and available water supply, extending at least 5 km in all direction. Except for the southeast wind direction where our laboratory buildings may have interfered with wind flow, the effective aerodynamic fetch was much greater than the dimension of the experimental farm.

Instruments

In 1999, meteorological variables were measured using a microclimate observation system developed by Sun et al. (2000), which included a humidity/temperature sensor (IH3602C, Honeywell, Morristown, NJ) and a hot-wire anemometer (developed by Sun et al., 2000) mounted at heights of 40, 90, 140, and 230 cm within the canopy. In 2003, meteorological variables were measured with a self-calibrating heat flux sensor (HFP01SC, Hukseflux, the Netherlands), an anemometer (A100R, Vector, UK) and a humidity probe (HMP45C, Vaisala, Helsinki, Finland) located above the canopy top.

Hourly total incoming radiation was collected using a pyranometer (CM11, Kipp & Zonen, Delft, the Netherlands) just above the top of maize canopy. Soil temperature and water content were measured by soil heat flux sensors (TCAV, Campbell Scientific, Logan, UT) and water content reflectometers (CS616_L, Campbell Scientific, Logan, UT) at specified depths.

Hourly net radiation above the canopy was collected using a four-component net radiometer (CNR-1, Kipp & Zonen, Delft, the Netherlands). Water and heat flux from the surface were measured using a three-dimensional sonic anemometer (Model CSAT3, Campbell Scientific, Inc., Logan UT) and an open path infrared gas analyzer (IRGA; Model LI-7500, LI-COR, Inc., Lincoln, NE) mounted above the canopy top. Ground heat flux was measured with a heat flux sensor (HFP01, Hukseflux, the Netherlands) installed 0.05-m deep within the soil.

Radiometric temperature of the maize canopy was measured with an infrared thermocouple sensor (IRTS-P_L50IRT, Apogee, Logan, UT) mounted above the canopy top at a 45° angle toward ground surface. Canopy leaf temperatures were collected at 20-cm increments between heights of 60 to 200 cm using a manually operated portable infrared temperature sensor (IRT, Minolta/Land Cyclops Compac 3, Land, England) with a recording frequency of 4Hz and an 8° angle of view, detecting radiation in the 8 to 14 μm wave bands. Leaf temperature was measured by rotating the sensor horizontally at each specified height. The average reading over a 10 to 20 s period at each height was used for analysis; the standard deviation of the 4Hz readings ranged from 0.15 to 0.46. Calibration of the IRT was performed before the measuring period using a commercial Everest black body surface.

Measurement

In 1999, data collected from 3 to 5 August (Day 215–217) were used to compare with model simulations of micrometeorological variables (i.e., air temperature, relative humidity, and wind speed) in the canopy. Plant height of maize was about 220 cm with a LAI of 4.50. Meteorological sensors collected hourly weather observations of air temperature, wind speed, humidity, and vapor pressure at heights of 40, 90, 140, and 230 cm from ground surface and solar radiation at 230 cm which was just above the top of the canopy. Precipitation measurements were obtained from the weather observation site approximately 100 m from the field site. Soil temperature and moisture were collected near the surface and at depths of 5, 10, 15, 20, 40, 60, and 100 cm.

In 2003, model simulation was compared with (i) surface energy balance measurements from 15 June to 9 October (Day 166–282), (ii) radiometric canopy temperatures from 6 July to 9 October (Day 187–282), (iii) profiles of leaf temperatures in different layers for clear days from 17 August to 18 September (Day 229–261) and (iv) soil temperatures measured from 15 June to 9 October (Day 166–282). Plant emergence was around 1 July. Maximum plant height of 260 cm was obtained by the maize around 17 August (Day 229) with a LAI of 5.58. Hourly weather measurements (including air temperature, wind speed, relative humidity, and solar radiation), energy balance components (including net radiation, sensible heat flux, and latent heat flux) and radiometric surface temperature were collected at a height of 280 cm from ground surface. Hourly soil temperature and moisture were measured near the surface and at depths of 2, 5, 10, 20, and 50 cm. Precipitation data were collected as the method in 1999. Leaf temperatures within the canopy were measured with a portable IRT at heights of 60, 80, 100, 120, 140, 160, 180, and 200 cm above surface hourly from 0800 to 1800 h (local standard time) as well as at 2000 h and 2200 h during clear days from 17 August to 18 September (Day 229–261). Leaf temperatures were sampled 20 times per second and averaged hourly.

Table 1. Description and definition of model performance measures.

Measure	Description	Mathematical definition†
ME	Model efficiency, that is, variation in measured values accounted for by the model	$1-\frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{N}(Y_i - \overline{Y})^2}$
RMSD	Root mean square deviation between simulated and observed values	$\left[\frac{1}{N}\sum_{i=1}^{N}(\hat{Y}_i - Y_i)^2\right]^{1/2}$
MBE	Mean bias error of model predictions compared to observed values	$\frac{1}{N}\sum_{i=1}^{N}(\hat{Y}_i - Y_i)$

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

MODEL DESCRIPTION

The SHAW model was originally developed by Flerchinger and Saxton (1989b) and modified by Flerchinger and Pierson (1991) to include transpiring plants and a plant canopy, consisting of a vertical, one-dimensional profile extending from the vegetation canopy, snow, residue, or soil surface to a specified depth within the soil. A layered system is established through the plant canopy, snow, residue, and soil, and each layer is represented by an individual node.

Weather conditions above the upper boundary and soil conditions at the lower boundary define heat and water fluxes into the system. Computed surface energy balance fluxes include absorbed solar radiation, long-wave radiation exchange, and turbulent transfer of heat and vapor. Net radiation is determined by computing solar and long-wave radiation exchange between canopy layers, residue layers, and the soil surface and considers direct, and upward and downward diffuse radiation transmitted, reflected and absorbed by each layer. Sensible and latent heat flux of the surface energy balance are computed from temperature and vapor gradients between the canopy surface and the atmosphere using a bulk aerodynamic approach with stability corrections.

Provisions for a plant canopy in the SHAW model made by Flerchinger and Pierson (1991) include heat and water transfer through the soil-plant-atmosphere continuum. The plant canopy may be divided into as many as 10 layers. Heat and water flux within the canopy include solar and long-wave radiation, turbulent transfer of heat and water vapor, and transpiration from plant leaves. Transpiration from plants is linked mechanistically to soil water by flow through the roots and leaves along a soil-plant-atmosphere continuum. Within the plant, water flow is controlled mainly by changes in stomatal resistance, which is computed as a function of leaf water potential. Gradient-driven transport, or *K*-theory, is used for transfer within the canopy. Turbulent heat and vapor transfer within the canopy are determined by computing transfer between layers of the canopy and considering the source terms for heat and transpiration from the canopy leaves for each layer within the canopy. The leaf energy balance is computed iteratively with heat and water vapor transfer equations and transpiration within the canopy. Hourly time steps were used in this study. Detailed descriptions of energy and mass transfer calculations within the canopy and residue layers are given by Flerchinger and Pierson (1991), Flerchinger et al. (1998), and Flerchinger and Saxton (1989b).

MODEL EVALUATION

The model was applied to data collected at Yucheng Station during 1999 and 2003. Leaf area index and canopy height were input to the model based on field measurements. Plant parameters of minimum stomatal resistance, stomatal resistance exponent, critical leaf potential, and albedo of plant leaves were set to 100 s m^{-1}, 5.0, −300 m, and 0.30, respectively. Minor model modifications were made to match measured wind speed profiles within the canopy based on measurements made in 1999 and the model was further tested using data from 2003. Simulated and measured values were compared using ME, mean bias error (MBE), and root mean square deviation (RMSD). Definitions of model performance measures are given in Table 1. Model efficiency (Nash and Sutcliffe, 1970) is analogous to coefficient of determination, with the exception that ME ranges from negative infinity to 1.0; negative ME values indicate that the mean observation is a better predictor than simulated values. Root mean square deviation is a measure of the squared difference between simulated and mea-

Table 2. Model efficiency (ME), root mean square deviation (RMSD), and mean bias error (MBE) for the simulated micrometeorological variables from 3 to 5 August (Day 215–217) of 1999. (a: simulation of original SHAW model; b: simulation of modified SHAW model by dividing the exponential in wind speed function by 3.5).

	Wind speed			Air temperature			Relative humidity		
Height	ME	RMSD	MBE	ME	RMSD	MBE	ME	RMSD	MBE
cm		m s^{-1}			°C			%	
a.									
40	−0.13	0.12	−0.07	0.55	3.54	2.15	0.52	12.05	−10.20
90	−0.60	0.57	−0.41	0.74	2.81	1.41	0.83	7.76	−5.36
140	−1.28	1.15	−0.97	0.91	1.77	0.56	0.93	5.32	−2.09
230	0.96	0.19	−0.16	0.95	1.20	0.08	0.97	3.75	1.34
b.									
40	−14.60	0.43	0.39	0.60	3.32	2.01	0.49	12.47	−10.12
90	0.63	0.27	0.16	0.76	2.69	1.28	0.83	7.76	−5.05
140	0.62	0.47	−0.36	0.91	1.74	0.50	0.94	5.12	−1.91
230	0.96	0.19	−0.16	0.95	1.21	0.06	0.97	3.82	1.39

sured values, while MBE is an indicator of the bias in simulated values compared to observations.

1999 Results

The original model was initialized on Day 215 (3 August) and used to estimate micrometeorological variables at heights of 40, 90, 140, and 230 cm from the ground surface. Values were simulated through Day 217 (5 August). Table 2a presents a comparison of simulated and measured hourly values of air temperature, relative humidity, and wind speed, respectively. Simulated values of the three variables agreed better with measured values in the upper canopy layers than in the lower. The simulation processed best at the top of canopy with ME exceeding 0.95. At the lower layer, ME fell to 0.55 for air temperature, 0.52 for relative humidity and was unacceptable for wind speed. Simultaneously the magnitude of the difference between simulated and measured values were larger at lower layers than upper layers except for wind speed as indicated by the values of RMSD presented in Table 2a. Mean bias error indicated that air temperature was overpredicted in all layers, and relative humidity was overpredicted at 230 cm but underpredicted at the other heights.

The bias of simulated wind speed may suggest that the assumption of an exponential decrease in wind speed with depth was excessive. Wind speed at a height z within the canopy is computed from:

$$u_c = u_{ch} \exp[a(z/h - 1)]$$

where u_{ch} is wind speed at the top of the canopy, and h is the height of the canopy. The exponent (a) is computed in the model based on LAI, so some modification was made to the model by dividing the computed exponent in wind speed function. A factor of 3.5 minimized the overall MBE for the wind speed profile. The resulting ME, RMSD, and MBE for the modified simulation are listed in Table 2b; simulated vs. measured values for wind speed, temperature, and humidity are presented in Fig. 1. There were very small changes for the three micrometeorological variables in the upper canopy. The modification made modest improvement in simulation results for air temperature in the lower canopy but simulation of relative humidity within the canopy changed only slightly. Although there are alternative expressions for describing within-canopy wind speed (Pereira and Shaw, 1980; Jacobs et al., 1995; Aiken and Nielsen, 2003), clearly the major limitation in simulating temperature and humidity more accurately was not related to the wind speed simulation within the canopy.

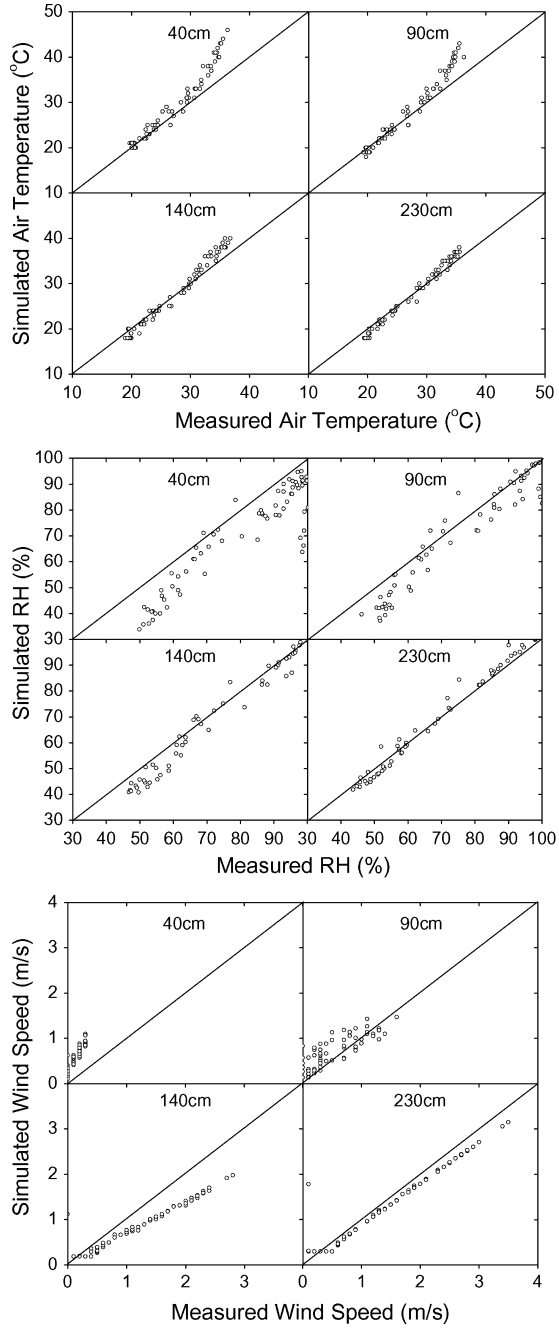

Fig. 1. Simulated vs. measured values for air temperature, relative humidity, and wind speed in each canopy layer from 3 to 5 August (Day 215–217) of 1999 after Simultaneous Heat and Water (SHAW) model modification for wind speed within the canopy. RH = relative humidity.

2003 Results

The SHAW model modified by dividing the wind speed exponent by 3.5 was run from 15 June (seeding stage of maize) to 9 October (ripening stage of maize) (Day 166–282) of 2003. Simulated and measured net radiation, latent heat flux, sensible heat flux, and ground heat flux for the entire simulation period are plotted in Fig. 2. Model efficiency, RMSD, and MBE comparing energy balance during both day and night with measured values are listed in Table 3. Simulated net radiation and measured net radiation agreed well with ME equal to 0.97 and MBE of -0.4 Wm^{-2}. Latent heat flux was overpredicted (i.e., more negative) with ME equal to 0.81 and MBE -9.1 W m^{-2}, and sensible heat flux was underestimated (i.e., less negative) with ME equal to 0.78 and MBE near 6.5 W m^{-2}. The simulation of ground heat flux whose ME was 0.17 was poor due in part to the small variation in ground heat flux. The

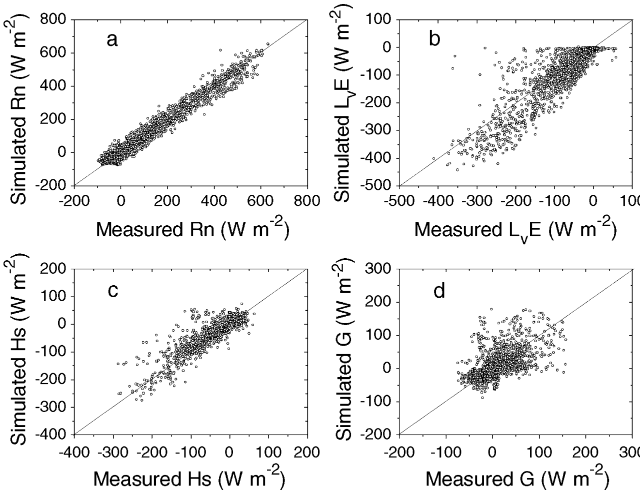

Fig. 2. Simulated vs. measured net radiation (Rn), latent heat flux (LvE), sensible heat flux (Hs), and ground heat flux (G) from 15 June to 9 October (Day 166–282) of 2003 (All fluxes are in W m^{-2} and assumed positive toward the surface).

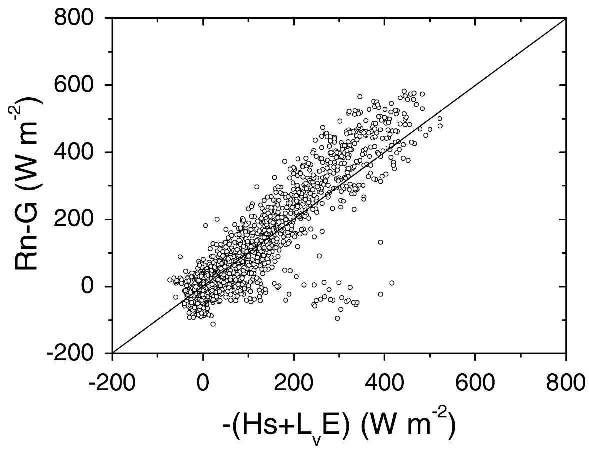

Fig. 3. The difference of net radiation and ground heat flux vs. the sum of latent and sensible heat flux from 15 June to 9 October (Day 166–282) of 2003 (all fluxes are in W m^{-2} and assumed positive toward the surface).

magnitude of difference between simulated and measured values was largest for latent heat flux (whose RMSD was 42.0 W m^{-2}) and smallest for sensible heat flux (whose RMSD equaled to 24.7 W m^{-2}). The bias between measured and simulated values above may be attributed to the general lack of energy balance closure (Wilson and Goldstein, 2002) as suggested by Fig. 3 which shows that the difference between net radiation and ground heat flux is generally greater than the absolute sum of sensible and latent heat flux measured from 15 June (seeding stage of maize) to 9 October (ripening stage of maize) (Day 166–282) of 2003.

Time series of simulated and measured components of energy balance from 15 August to 18 September (Day 227–242) is plotted in Fig. 4. They were simulated reasonably but the energy balance for rainy days indicated spikes in measured sensible, latent, and ground heat flux. The values for components of the energy balance from Day 235 to 239, 241 to 242, 244, 247 to 249, 251, and 260 to 262 were obviously lower than other days. Precipitation affects both the simulation and measurement of energy balance and may lead to erroneous measurements. To examine whether precipitation influenced model performance, ME, RMSD, and MBE from 15 August to 18 September of 2003 (Day 227–261) are presented in Table 4 for all days and only clear days.

Table 3. Average measured values, model efficiency (ME), root mean square deviation (RMSD), and mean bias error (MBE) for components of the surface energy balance from 15 June to 9 October (Day 166–282) of 2003 (all fluxes are in W m^{-2} and assumed positive toward the surface).

Measure	Average	ME	RMSD	MBE
	W m^{-2}		W m^{-2}	
Rn†	86.4	0.97	30.0	−0.4
LE	−64.8	0.81	42.0	−9.1
Hs	−23.9	0.78	24.7	6.5
G	1.3	0.17	31.9	0.0

† Rn = net radiation, LE = latent heat flux, Hs = sensible heat flux, and G = ground heat flux.

Model performance for net radiation changed little. The ME increased from 0.59 to 0.69 for latent heat flux, 0.52 to 0.69 for sensible heat flux and 0.40 to 0.54 for ground heat flux. In this simulation, net radiation was overestimated, latent heat flux was overpredicted (more negative) and sensible heat flux was underpredicted (less negative) regardless of whether cloudy days were included, while ground heat flux was underestimated for all days but overestimated for clear days as MBE shows in Table 4. The difference in MBE when considering all days (positive MBE) vs. only clear days (negative MBE; Table 4) suggests that precipitation affects the accuracy of the measurement, the model simulation, or both.

Simulated values for radiometric surface temperature agreed well overall with measurements collected from 6 July to 9 October (Day 187–282) of 2003 with ME equal 0.91 though it was overpredicted a little with MBE equal to 0.34°C. However, a plot of simulated vs. measured in

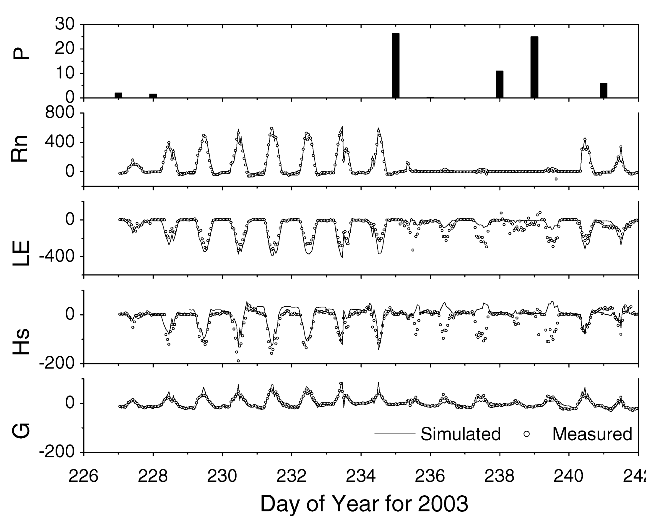

Fig. 4. Measured and simulated net radiation (Rn), latent heat flux (LvE), sensible heat flux (Hs), and ground heat flux (G) for a maize canopy in Yucheng from 15 to 30 August of 2003 (Day 227–242). (Precipitation, P, is in mm; all energy fluxes are in W m^{-2} and assumed positive toward the surface).

Table 4. Average measured values, model efficiency (ME), root mean square deviation (RMSD), and mean bias error (MBE) for components of the surface energy balance in all days and in clear days respectively from 15 August to 18 September of 2003 (Day 227–261) (all fluxes are in W m^{-2} and assumed positive toward the surface).

Measure	Average	ME	RMSD	MBE
	W m^{-2}		W m^{-2}	
		All days		
Rn	75.6	0.96	32.2	2.0
LE	−66.8	0.59	55.5	−12.6
Hs	−18.4	0.52	30.2	15.4
G	1.0	0.40	20.4	−2.5
		Clear days		
Rn	108.7	0.96	38.6	2.5
LE	−75.5	0.69	54.3	−31.4
Hs	−67.1	0.69	27.0	19.3
G	−1.0	0.54	17.9	3.1

Fig. 5 indicates much of this overprediction occurred at higher midday temperatures where simulated values are overpredicted by approximately 5°C.

During clear days between 17 August and 17 September (Day 229–260) of 2003, leaf temperatures in different canopy layers were measured. Simulated leaf temperatures vs. measured values for specified layers are plotted in Fig. 6. Comparisons indicated that leaf temperatures in all layers could not be simulated well at the same time. The simulation was better in the lower two-thirds of plant canopy (around 180 cm) than the upper layers, and better at morning and evening than at noon. This trend is also suggested by Table 5, in which ME, RMSD, and MBE calculated with those leaf temperatures in clear days from Day 229 to 260 showed good agreement between simulated and measured values in the lower two-thirds of plant canopy with ME ranging from 0.76 for 60 cm to 0.86 for 160 cm, even though the simulated values were slightly lower than observations with MBE around −1°C, and comparison at 200 cm are rather poor with ME around 0.38. These comparisons in the upper layers parallel the overprediction of radiometric surface temperature indicated previously.

The cause for overprediction in the upper layer (around 200 cm) was not understood and could arise from some limitations of the SHAW model: (i) Some

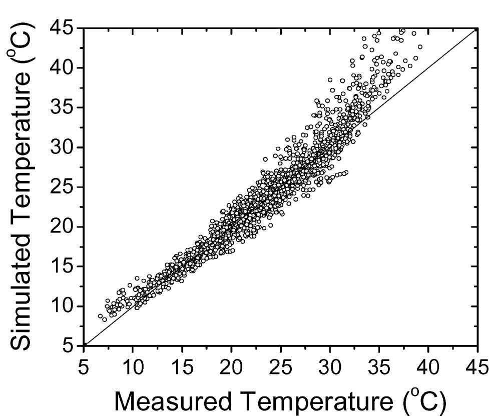

Fig. 5. Simulated vs. measured radiometric surface temperature from 6 July to 9 October (Day 187–282) of 2003.

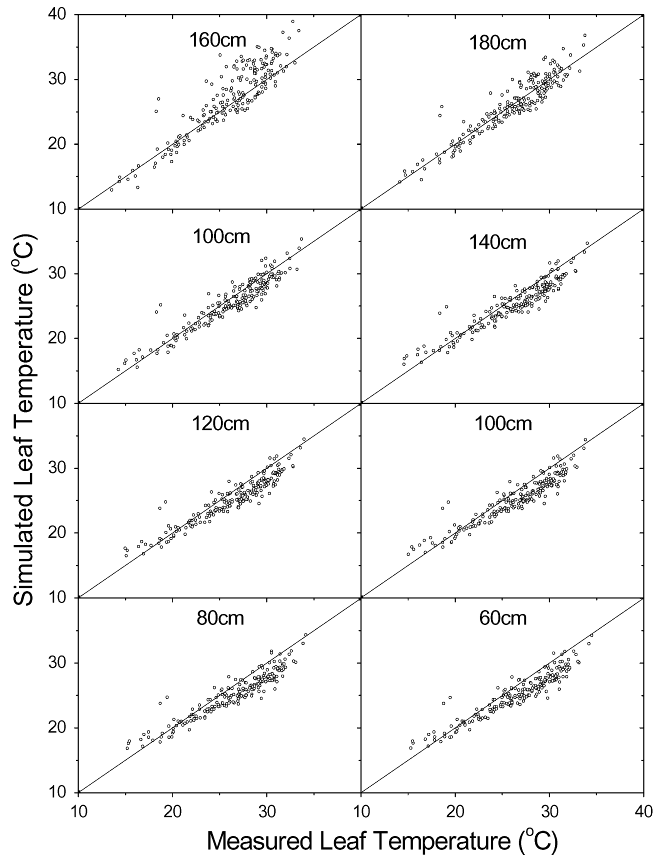

Fig. 6. Simulated vs. measured leaf temperatures in different layers on clear days from 17 August to 17 September (Day 229–260) of 2003.

studies indicated that *K*-theory used in the model is not applicable in the canopy air space (Denmead and Bradley, 1985, and Wilson et al., 2003) and found that the *K*-theory consistently overpredict canopy radiometric temperatures; (ii) For simplicity, long-wave emittance by a canopy layer is calculated using a leaf temperature for all plant species equal to air temperature within the layer, thus emitted long-wave radiation is biased by the difference between air temperature and leaf temperature; (iii) Leaf temperature for each layer within the canopy is determined from a leaf energy balance of the canopy layer in the model assuming the leaves within the canopy have negligible heat capacity; and (iv) Simulating within a one-dimensional profile, the model did not consider horizontal turbulent exchange which is more significant to the elimination of heat near the top of the canopy. Modifications to the SHAW are planned or currently underway to address items (i) through (iii) above. Additionally, data is needed to assess the simulation of within-canopy radiation dynamics as this could significantly influence temperature and humidity profiles within the canopy.

Comparison of simulated and measured soil temperature indicates that the model performed well at soil surface and at deeper depth with ME ranging from 0.80 to 0.91 (Table 6), but poorer at shallow depth with ME equal to 0.48 for 2 cm and 0.65 to 5 cm. The time series of air temperature, simulated and measured radiometric canopy surface temperature and soil surface tempera-

Table 5. Average measured values, model efficiency (ME), root mean square deviation (RMSD), and mean bias error (MBE) for leaf temperature of different canopy layers during clear days from 17 August to 17 September (Day 229–260) of 2003.

Height, cm	60	80	100	120	140	160	180	200
Average (°C)	26.66	26.67	26.50	26.43	26.35	26.22	26.12	26.05
ME	0.76	0.77	0.79	0.81	0.83	0.86	0.85	0.38
RMSD (°C)	2.05	1.97	1.90	1.79	1.73	1.53	1.60	4.40
MBE (°C)	−1.38	−1.26	−1.17	−1.06	−0.93	−0.57	0.06	1.67

ture from 9 to 14 September (Day 252–257) in Fig. 7 provides a description of temperature from canopy top to underlying soil. Soil temperature was underpredicted at the surface with MBE equal to −0.18°C and overpredicted at the deeper depths. Increasing RMSD from 50 cm to soil surface indicated the error of simulation was larger at shallower depths. Inspection of the soil temperature from Day 252 to 257 plotted in Fig. 7 suggests likewise.

SUMMARY AND CONCLUSIONS

The SHAW model was used to simulate the profiles of micrometeorological variables, energy balance, radiometric surface temperature of canopy and profiles of leaf temperature and soil temperature within a maize canopy in Yucheng, China. The micrometeorological variables were simulated well in the upper layers of canopy but not satisfactorily near the soil surface. Model modifications to improve simulated wind speed within the canopy did little to improve simulated temperature and humidity within the canopy.

Net radiation was mimicked by the SHAW model with ME reaching 0.97 and MBE equaling to −0.4 W m^{-2} for the entire simulation in 2003. Latent and sensible heat fluxes were simulated well with ME around 0.80. Latent heat was overpredicted (more negative) with MBE about −9.1 W m^{-2}; sensible heat flux was underpredicted (less negative) with MBE equaling to 6.5 W m^{-2}. Measured ground heat flux was not simulated well for the entire simulation period. The simulation did not compare well with measured values at night and on rainy days.

While the surface energy balance was simulated well by the model, improvements could be made in simulating the microclimate within the canopy profile. Model efficiency for simulated radiometric canopy surface temperature was 0.91, but the model overpredicted midday temperatures by approximately 5°C. Leaf temperatures at different layers could not be predicted well at the same time. The simulated temperature was increasingly better and MBE became smaller with increasing height within the canopy. It was simulated best at approximately two-thirds of the plant height, under which it was underpredicted by 0.57 to 1.38°C and above which it was overpredicted. Above 200 cm, the simulation was rather poor (ME = 0.38). Simulation in morning and evening was better than midday. Soil temperatures were predicted adequately near soil surface and increasingly well with depth.

Based on simulation results, the SHAW model can reasonably simulate the surface energy balance, but transfer processes within the canopy could be improved to better simulate the canopy microclimate. Weaknesses identified within the model that may account for less than ideal microclimatic simulation within the canopy include: the use of *K*-theory to simulate turbulent transfer within the canopy; and simplifying assumptions with regard to long-wave radiation transfer within the canopy. Model modifications are underway to address these weaknesses identified in the model.

Table 6. Average measured values, model efficiency (ME), root mean square deviation (RMSD), and mean bias error (MBE) for soil temperature of each depth from 15 June to 9 October (Day 166–282) of 2003.

Depth	Average	ME	RMSD	MBE
cm	°C		°C	
0	24.44	0.82	2.67	−0.18
2	23.61	0.48	2.28	0.53
5	23.55	0.65	1.79	0.48
10	23.43	0.80	1.26	0.42
20	23.15	0.91	0.73	0.31
50	22.04	0.85	0.64	0.35

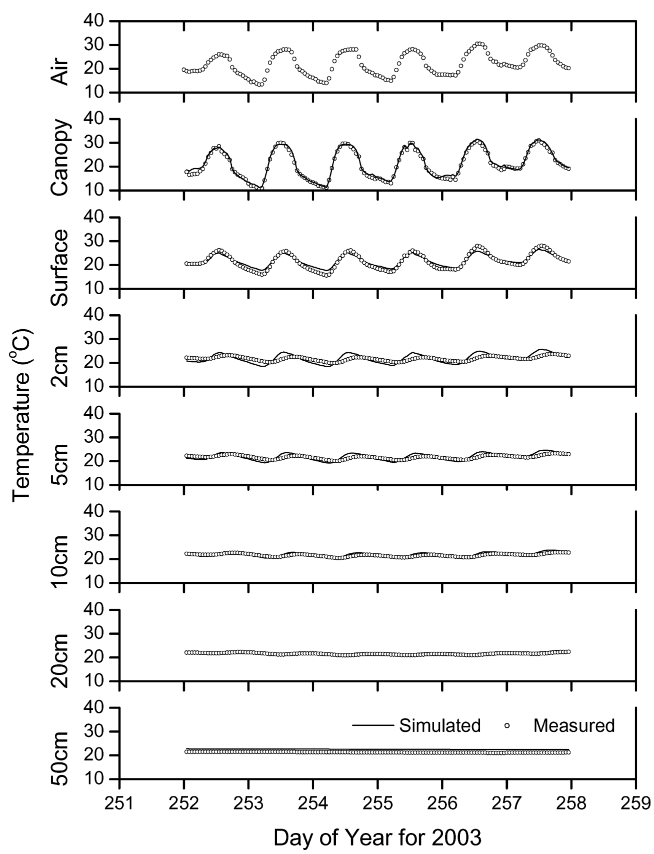

Fig. 7. Profile of temperatures from canopy top to underlying soil from 9 to 14 September (Day 252 through 257) of 2003 (——, simulated values; ……, measured values).

ACKNOWLEDGMENTS

This work is supported by National Natural Science Foundation of China (Grant 40328001).

REFERENCES

Aiken, R.M., and D.C. Nielsen. 2003. Scaling effects of standing crop residues on the wind profile. Agron. J. 95:1041–1046.

Denmead, O.T., and E.F. Bradley. 1985. Flux-gradient relationships in a forest canopy. p. 412–442. *In* B.A. Hutchison and B.B. Hicks (ed.) The forest–atmosphere interaction. D. Reidel Publ. Co., Hingham, MA.

Duffin, E.K. 1999. Evaluating snowmelt runoff, infiltration, and erosion in a sagebrush-steppe ecosystem. Master's thesis. Watershed Science Program, Utah State Univ., Logan.

Flerchinger, G.N., J.M. Baker, and E.J.A. Spaans. 1996a. A test of the radiative energy balance of the SHAW model for snowcover. Hydrol. Processes 10:1359–1367.

Flerchinger, G.N., K.R. Cooley, and Y. Deng. 1994. Impacts of spatially and temporally varying snowmelt on subsurface flow in a mountainous watershed: I. snowmelt simulation. Hydrol. Sci. J. 39: 507–520.

Flerchinger, G.N., and C.L. Hanson. 1989a. Modeling soil freezing and thawing on a rangeland watershed. Trans. ASAE 32:1551–1554.

Flerchinger, G.N., C.L. Hanson, and J.R. Wight. 1996b. Modeling of evapotranspiration and surface energy budgets across a watershed. Water Resour. Res. 32:2539–2548.

Flerchinger, G.N., W.P. Kustas, and M.A. Weltz. 1998. Simulating surface energy fluxes and radiometric surface temperatures for two arid vegetation communities using the SHAW model. J. Appl. Meteorol. 37:449–460.

Flerchinger, G.N., and F.B. Pierson. 1991. Modeling plant canopy effects on variability of soil temperature and water. Agric. For. Meteorol. 56:227–246.

Flerchinger, G.N., T.J. Sauer, and R.A. Aiken. 2003. Effects of crop residue cover and architecture on heat and water transfer at the soil surface. Geoderma 116:217–233.

Flerchinger, G.N., and K.E. Saxton. 1989b. Simultaneous heat and water model of a freezing snow-residue-soil system: I. Theory and development. Trans. ASAE 32:573–578.

Flerchinger, G.N., and M.S. Seyfried. 1997. Modeling soil freezing and thawing and frozen soil runoff with the SHAW model. p. 537–543. *In* I.K. Iskandar et al. (ed.) Proc. of the Int. Symp. on Physics, Chemistry, and Ecology of Seasonally Frozen Soils, Fairbanks, AK. 10–12 June 1997. CRREL Spec. Rep. 97-10. U.S. Army Cold Regions Res. and Engineering Lab., Hanover, NH.

Gottschalck, J.C., R.R. Gillies, and T.N. Carlson. 2001. The simulation of canopy transpiration under doubled CO_2: The evidence and impact of feedbacks on transpiration in two 1-D soil–vegetation–atmosphere transfer models. Agric. For. Meteorol. 106:1–21.

Goudriann, J., and P.E. Waggoner. 1972. Simulating both aerial microclimate and soil temperature from observations above the foliar canopy. Neth. J. Agric. Sci. 20:104–124.

Ham, J.M., and J.L. Heilman. 1991. Aerodynamic and surface resistances affecting energy transport in a sparse crop. Agric. For. Meteorol. 53:267–284.

Hayhoe, H.N. 1994. Field testing of simulated soil freezing and thawing by the SHAW model. Can. Agric. Eng. 36:279–285.

Huntingford, C., S.J. Allen, and R.J. Harding. 1995. An intercomparison of single and dual-source vegetation–atmosphere transfer models applied to transpiration from Sahelian savannah. Boudary-Layer Meteorol. 74:397–418.

Hymer, D.C., M.S. Moran, and T.O. Keefer. 2000. Soil water evaluation using a hydrologic model and calibrated sensor network. Soil Sci. Soc. Am. J. 64:319–326.

Jacobs, A.F.G., J.H. van Boxel, and R.M.M. El-Kilani. 1995. Vertical and horizontal distribution of wind speed and air temperature in a dense vegetation canopy. J. Hydrol. 166:313–326.

Jacobs, A.F.G., J.H. van Boxel, and R.H. Shaw. 1992. The dependence of canopy layer turbulence on within-canopy thermal stratification. Agric. For. Meteorol. 58:247–256.

Kennedy, I., and B. Sharratt. 1998. Model comparisons to simulate frost depth. Soil Sci. 163:636–645.

Kustus, W.P. 1990. Estimates of evaporation with a one- and two-layer model of heat transfer over partial canopy cover. J. Appl. Meteorol. 29:704–715.

Massman, W.J., and J.C. Weil. 1999. An analytical one-dimensional second-order closure model of turbulence statistics and the Lagrangian time scale within and above plant canopies of arbitrary structure. Boundary-Layer Meteorol. 91:81–107.

Mihailović, D.T., B. Lalić, I. Arsenić, J. Eitzinger, and N. Dusanić. 2002. Simulation of air temperature inside the canopy by the LAPS surface scheme. Ecol. Model. 147:199–207.

Nash, J.E., and J.V. Sutcliffe. 1970. River flow forecasting through conceptual models: I. A discussion of principles. J. Hydrol. 10: 282–290.

Nassar, I.N., R. Horton, and G.N. Flerchinger. 2000. Simultaneous heat and mass transfer in soil columns exposed to freezing/thawing conditions. Soil Sci. 165:208–216.

Norman, J.M. 1979. Modeling the complete crop canopy. p. 249–277. *In* B.J. Barfield and J.F. Gerber (ed.) Modification of the aerial environment of plants. Am. Soc. of Agric. Eng., St. Joseph, MI.

Pachepsky, L.B., and B. Acock. 2002. A model 2DLEAF of leaf exchange: Development validation, and ecological application. Ecol. Modell. 93:1–18.

Pereira, A.R., and R.H. Shaw. 1980. A numerical experiment on the mean wind structure inside canopies of vegetation. Agric. For. Meteorol. 22:303–318.

Raupach, M.R. 1989. A practical Lagrangian method for relating scalar concentrations to source distributions in vegetation canopies. Q. J. R. Meteorol. Soc. 115:609–632.

Sauer, T.J., and J.M. Norman. 1995. Simulated canopy microclimate using estimated below-canopy soil surface transfer coefficients. Agric. For. Meteorol. 75:135–160.

Sauer, T.J., J.M. Norman, C.B. Tanner, and T.B. Wilson. 1995. Measurement of heat and vapor transfer coefficients at the soil surface beneath a maize canopy using source plates. Agric. For. Meteorol. 75:161–189.

Shuttleworth, W.J., and J.S. Wallace. 1985. Evaporation from sparse crops—An energy combination theory. Q. J. R. Meteorol. Soc. 111:839–855.

Sun, X., Q. Yu, Y. Luo, and X. Xie. 2000. The design and application of an observation instrument of microclimate within crop canopy. Chin. J. Eco-Agric. 8:76–79.

van den Hurk, B.J.J.M., and K.G. McNaughton. 1995. Implementation of near-field dispersion in a simple two-layer surface resistance model. J. Hydrol. 166:293–311.

Waggoner, P.E., and W.E. Reifsnyder. 1968. Simulating of the temperature, humidity and evaporation profiles in a leaf canopy. J. Appl. Meteorol. 7:400–409.

Warland, J.S., and G.W. Thurtell. 2000. A Lagrangian solution to the relationship between a distributed source and concentration profile. Boundary-Layer Meteorol. 96:453–471.

Wilson, K., and A. Goldstein. 2002. Energy balance closure at FLUXNET sites. Agric. For. Meteorol. 113:223–243.

Wilson, T.B., J.M. Norman, W.L. Bland, and C.J. Kucharik. 2003. Evaluation of the importance of Lagrangian canopy turbulence formulations in a soil–plant–atmosphere model. Agric. For. Meteorol. 115:51–69.

Xu, X., J.L. Nieber, J.M. Baker, and D.E. Newcomb. 1991. Field testing of a model for water flow and heat transport in variably saturated, variably frozen soil. p. 300–308. *In* Transp. Res. Record, Vol. 1307. Transp. Res. Board, Natl. Res. Council, Washington, DC.

Yu, Q., Y.L. Liu, J.L. Liu, and T. Wang. 2002. Simulation of leaf photosynthesis of winter wheat on Tibetan Plateau and in North China Plain. Ecol. Modell. 155:205–216.

Yu, Q., Y. Zhang, Y. Liu, and P. Shi. 2004. Simulation of the stomatal conductance of winter wheat in response to light temperature and CO_2 changes. Ann. Bot. (London) 93:435–441.