Agricultural and Forest Meteorology 194 (2014) 218–229

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Modeling evapotranspiration and energy balance in a wheat–maize cropping system using the revised RZ-SHAW model

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ARTICLE INFO

Article history:
Received 15 May 2013
Received in revised form 2 January 2014
Accepted 17 April 2014

Keywords:
RZWQM
SHAW
Modeling
Agricultural systems
Energy balance

ABSTRACT

Correctly simulating evapotranspiration (ET) and surface energy balance is essential to simulating crop growth under water and heat stress conditions in agricultural systems. The revised hybrid model (RZ-SHAW), combining the Root Zone Water Quality Model (RZWQM) and Simultaneous Heat and Water (SHAW) model, was evaluated for simulating ET and surface energy balance components against observed data from an eddy covariance system in a wheat–maize double cropping system in the North China Plain (NCP), after it was calibrated for soil water content and crop growth. The average daily ET was slightly under-simulated by 0.05 mm in the wheat seasons and over-simulated by 0.23 mm in the maize seasons, compared with the observed latent heat flux (LE) from 2003 to 2005. The root mean squared error (RMSE) and model efficiency (ME) of simulated daily ET were 0.59 mm and 0.86 for the three years. The goodness of simulation for Rn (net radiation), LE, H (sensible heat flux) and canopy temperature was better in the middle crop seasons than in the early crop seasons. The RMSE values for simulated Rn, H, LE, G (ground heat flux), and canopy temperature were 31.9, 37.2, 37.9, 21.8 W m^{-2}, and 1.37 °C, respectively, for middle wheat seasons and were 29.2, 27.1, 29.7, 19.7 W m^{-2}, and 1.22 °C, respectively, for middle maize seasons. These simulation results were comparable with previous modeling studies, indicating that the revised hybrid model is reasonable for simulating ET, surface energy balance as well as crop growth in the double cropping system.

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1. Introduction

Surface energy balance determines the transfer of water and heat between soil surface and atmosphere, especially evapotranspiration (ET), which in turn influences nutrient cycling and plant growth. Most crop system models do not simulate the detailed surface energy balance, or couple the soil water balance (such as ET) with the soil surface energy balance (such as soil temperature and canopy temperature). Wang et al. (2010) found that including soil surface energy balance in the Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM) improved soil water simulations. Coupling land surface and crop growth models can also be used to assess the effect of crop growth on energy balance and water use (Maruyama and Kuwagata, 2010). A hybrid model RZ-SHAW, coupling Root Zone Water Quality Model (RZWQM, Ahuja et al., 2000) with the Simultaneous Heat and Water model (SHAW, Flerchinger and Saxton, 1989), was developed for simulating energy balance, along with soil water and crop growth in agricultural systems. The hybrid model enables RZWQM to simulate the influences of surface energy balance and winter frozen soil conditions on crop growth (Flerchinger et al., 2000; Ma et al., 2012).

The hybrid RZ-SHAW model has been evaluated for estimating the energy balance (net radiation, latent heat, sensible heat, and ground heat flux) under different surface conditions (Flerchinger et al., 2000, 2009; Yu et al., 2007). Recently, this model was improved and tested for simulating soil water balance and soil surface and crop canopy temperature (Li et al., 2012; Ma et al., 2012). This hybrid model was also used to simulate crop water stress under different irrigation management, and soil temperature and evapotranspiration under different tillage managements (Kozak et al., 2006, 2007). These studies showed better or comparable model performances of the hybrid model against the original RZWQM, suggesting a correct linkage between RZWQM and SHAW.

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http://dx.doi.org/10.1016/j.agrformet.2014.04.009
0168-1923/Published by Elsevier B.V.

However, in the previous studies, the hybrid model used RZWQM simulated evaporation and SHAW simulated plant transpiration to calculate ET or the latent heat flux (Li et al., 2012; Ma et al., 2012). This linkage may influence plant growth simulations in RZWQM since the crop transpiration was calculated by SHAW, which presumably leads to a further recalibration of crop growth parameters in RZWQM. For example, Kozak et al. (2006) found that the crop parameters required recalibration when water stress was defined from canopy and stomatal resistances in the RZ-SHAW model. In the current version of the hybrid model, both plant transpiration and soil evaporation were calculated in RZWQM, which were then fed to SHAW for calculating equivalent latent heat and other energy balance components. Therefore, the same ET was used for estimating soil water balance and its effect on crop growth in RZWQM and soil surface energy balance components in SHAW. In this study, the simulated actual ET from RZWQM was evaluated against observed latent heat flux from the eddy covariance method. The simulated potential ET based on Shuttleworth–Wallace method (Farahani and DeCoursey, 2000) in RZWQM was also evaluated against observed data from a large-scale weighing lysimeter experiment with adequate irrigation.

Furthermore, the previous evaluations of the hybrid model were carried out with short-term data sets within one crop season, and simulation of plant growth was usually not calibrated (Yu et al., 2007; Ma et al., 2012; Li et al., 2012). Also, these model evaluations were conducted under a low canopy height condition, such as in winter wheat and soybean (Yu et al., 2007; Ma et al., 2012). A high crop canopy (such as in maize) greatly influences the sensible heat flux and other soil surface energy balance components, which is of special interest in this study. The main objective of this study was to test the new revised RZ-SHAW hybrid model for simulating ET, soil surface energy balance, and soil and canopy temperature against observed data from an eddy covariance system and the potential ET observed with a large weighing lysimeter in a typical wheat–maize double cropping system in the North China Plain (NCP).

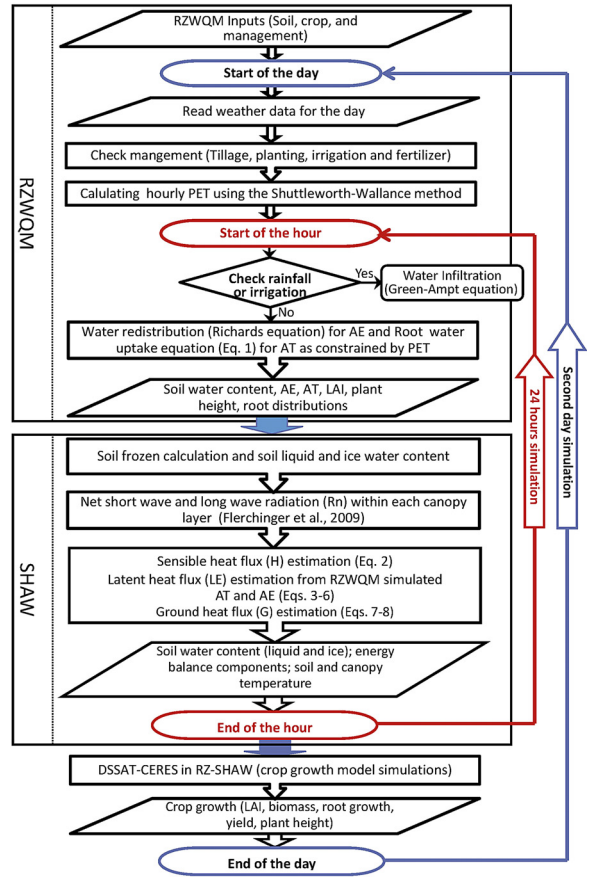

Fig. 1. The flow chart of daily and hourly executions of the revised hybrid RZ-SHAW model (root zone water quality model (RZWQM) and simulations heat and water (SHAW)) (AE and AT are actual evaporation and transpiration; PET is potential evapotranspiration; LAI is leaf area index).

2. Materials and methods

2.1. The revised hybrid RZ-SHAW model

Fig. 1 shows the daily and hourly execution in the RZ-SHAW model. At beginning of each day, the model calculates potential ET (PET) using the extended Shuttleworth–Wallace method (Farahani and DeCoursey, 2000). Specifically, the extended Shuttleworth–Wallace method separates total PET into transpiration from the canopy (PT), and evaporation (PE) from bare soil (PE_s) and residue covered soil (PE_r) ($PE = PE_s + PE_r$). Detailed estimation processes of the three components of PET can be found in Farahani and DeCoursey (2000). The calculated PE and PT are used as the upper limits for actual evaporation (AE) and transpiration (AT) constrained by soil water supply.

After estimating PET, RZWQM checks for rainfall or irrigation event (Fig. 1). If there is rainfall or irrigation, infiltration is estimated via the Green–Ampt equation. If there is no rainfall or irrigation, soil water redistribution is estimated using the Richards equation. The modified Brooks–Corey equations are used to describe relationships between volumetric soil water content and matric suction head, the soil water retention curve (Brooks and Corey, 1964; Ahuja et al., 2000). The key soil hydraulic parameters for the Brooks–Corey equations, soil bulk density (related to soil saturated water content), soil water content at 33 kPa ($\theta_{1/3}$), and saturated hydraulic conductivity (K_{sat}), were calibrated using the parameter estimation software (PEST, Doherty, 2005) and shown in Table 1.

Actual evaporation (AE) is estimated by the capability of the soil to deliver water as determined by the Richards equation. Actual transpiration (AT) is computed by an empirical root water uptake equation of the DSSAT crop models (Ritchie, 1998) (Eq. (1)).

$$\mathrm{RWU(L)} = \frac{k_1 * e^{k_2 * (\mathrm{SW(L)} - \mathrm{LL(L)})}}{k_3 - \ln(\mathrm{RLV(L)})} \tag{1}$$

where RWU(L) is potential root uptake per unit root length for soil layer L (cm^3 water per cm root); RLV(L) is the root length density in the soil layer (cm root per cm^3 soil); SW(L) and LL(L) are current soil water content and the lower limit of plant available water in the soil layer ($cm^3\,cm^{-3}$), respectively; and $k_1 = 1.32 \times 10^{-3}$, $k_2 = 120–250 \times \mathrm{LL(L)}$, and $k_3 = 7.01$. RLV(L) is simulated daily and adjusted for soil layers according to the soil root growth factor (SRGF, Table 1) in each soil layer (Ritchie, 1998).

The Richards equation is solved at sub-hourly time step using a mass conservative numerical solution (Celia et al., 1990). At each time step, RZWQM calls the SHAW routines for soil surface and canopy energy balance estimations using RZWQM simulated soil water content, AE, AT, leaf area index (LAI), plant height and root distributions (Fig. 1). The SHAW model is not called during infiltration because ET during rainfall or irrigation events is assumed zero (Yu et al., 2007; Ma et al., 2012).

The SHAW model first calculates liquid and ice water content using the freezing point depression equation (Fuchs et al., 1978). Then net short wave radiation and net long wave radiation within each canopy layer ($R_{n,i}$) are estimated for the multi-layer canopy using algorithms described by Flerchinger and Yu (2007) and Flerchinger et al. (2009).

Table 1
Initial soil hydraulic parameter values, boundaries and optimized final values used by parameter estimation software (PEST).[a] BD, soil bulk density ($g\,cm^{-3}$); $\theta_{1/3}$, soil water content at 33 kPa ($cm^3\,cm^{-3}$); K_{sat}, saturated hydraulic conductivity ($cm\,h^{-1}$); SRGF, soil root growth factor.

Layer	BD				$\theta_{1/3}$				K_{sat}				SRGF				
	Initial	Lower	Upper	Final	Initial	Lower	Upper	Final	Initial	Lower	Upper	Final	Initial	Lower	Upper	Final wheat	Final maize
0–8	1.28	1.22	1.45	1.269	0.19	0.150	0.250	0.230	5.50	0.50	10.00	8.40	1.00	1.00	1.00	1.00	1.00
8–15	1.39	1.22	1.45	1.269	0.23	0.150	0.280	0.216	1.32	0.50	10.00	5.50	0.75	0.50	1.00	0.90	0.66
15–45	1.39	1.26	1.48	1.341	0.23	0.200	0.280	0.247	1.32	0.50	10.00	5.50	0.54	0.10	0.75	0.58	0.37
45–90	1.40	1.26	1.48	1.399	0.29	0.200	0.350	0.307	0.68	0.10	10.00	5.25	0.32	0.05	0.50	0.27	0.16
90–107	1.40	1.26	1.48	1.410	0.29	0.200	0.350	0.326	0.68	0.10	10.00	5.50	0.14	0.01	0.20	0.10	0.01
107–150	1.39	1.26	1.46	1.450	0.29	0.200	0.350	0.262	0.32	0.10	10.00	1.50	0.01	0.00	0.10	0.01	0.01

[a] The initial parameter values were based on previous studies at the experiment site (Yu et al., 2007; Fang et al., 2008, 2010a).

Next as shown in Fig. 1, the sensible heat flux (H) is estimated by SHAW based on Campbell (1977)

$$H = -\rho_a c_a \frac{(T - T_a)}{r_H} \tag{2}$$

where ρ_a, c_a and T_a are density ($kg\,m^{-3}$), specific heat ($J\,kg^{-1}\,K^{-1}$) and temperature (°C) of air at the measurement reference height; T is the temperature (°C) of the exchange surface, and r_H is the resistance to surface heat transfer ($s\,m^{-1}$) corrected for atmospheric stability. The exchange surface is either the top of the canopy, residue layer, the snow surface or the soil surface depending on the system profile.

Plant transpiration (AT) from RZWQM is divided among the different canopy layers in SHAW based on the proportion of leaf area within each canopy layer, which is used as a source term in water vapor flux through the canopy and to compute leaf temperature from the leaf energy balance. SHAW uses a Newton–Raphson approach (Campbell, 1985) to solve the leaf energy balance to minimize the error term in the leaf energy balance within a given canopy layer, where the error term is given by:

$$\Delta = R_{n,i} + L_v AT_i - \rho_a c_a LAI_i \frac{T_{l,i}^{n+1} - T_i}{r_{h,i}} - W_{c,i} c_r \frac{T_{l,i}^{n+1} - T_{l,i}^{n}}{dt} \Rightarrow 0 \tag{3}$$

where L_v is latent heat of vaporization ($J\,kg^{-1}$), ρ_a, c_a and $T_{l,i}$ are the density ($kg\,m^{-3}$), heat capacity ($J\,kg^{-1}\,°C^{-1}$) and temperature (°C) of the ambient air within the canopy layer i; $T_{l,i}^{n}$ and $T_{l,i}^{n+1}$ are leaf temperature (°C) at the beginning and end of the time step; LAI_i is the leaf area index in canopy layer i, which is computed by dividing the canopy into layers with LAI no more than 0.5 $cm^2\,cm^{-2}$ (maximum i value is 10); $R_{n,i}$ is net radiation ($W\,m^{-2}$) for the leaves in canopy layer i, which is estimated by multilayer canopy models (Flerchinger and Yu, 2007; Flerchinger et al., 2009); AT_i is transpiration ($kg\,m^{-2}\,s^{-1}$) from the leaves (LAI_i) in the canopy layer i, which is proportioned to their LAI_i values as follows:

$$AT_i = AT \frac{LAI_i}{LAI} \tag{4}$$

$r_{h,i}$ is the resistance ($s\,m^{-1}$) to heat transfer from the leaf to the surrounding air computed as (Campbell, 1977)

$$r_{h,i} = 307 \left(\frac{d}{u_i} \right)^{1/2} \tag{5}$$

d is leaf width (m), u_i is wind speed in canopy layer i, $W_{c,i}$ is the canopy mass (kg) within the layer, c_r is the heat capacity ($J\,kg^{-1}\,°C^{-1}$) of the canopy elements, and dt is the time step.

Because AT_i is a function of stomatal resistance, leaf temperature and leaf water potential, the SHAW model and previous versions of RZ-SHAW requires an iterative procedure to solve for $T_{l,i}^{n+1}$ within each iteration of the heat and water balance equations for the entire soil–plant–atmosphere continuum. However, with AT_i supplied by the RZWQM routines in this version, an updated leaf temperature at the end of the time step can be computed explicitly by dividing the leaf energy balance error in the Eq. (3) by its derivative, i.e.,

$$T_{l,i}^{n+1'} = T_{l,i}^{n+1} + \Delta_i \left[8(1 - \tau_{d,i})\varepsilon_c (T_{l,i}^{n+1} + 273.16)^3 - \frac{\rho_a c_a L_{AI,i}}{r_{h,i}} - \frac{W_{c,i} c_r}{dt} \right]^{-1} \tag{6}$$

where $T_{l,i}^{n+1'}$, is the updated leaf temperature at the end of the time step. $\tau_{d,i}$ is the transmissivity of the canopy layer to diffuse radiation, ε_c is emissivity of canopy elements, and the coefficient 8 is used (instead of the 4 that arises from the derivative of long-wave emittance) to reflect the fact that leaves emit long-wave radiation upward as well as downward.

The updated temperature, $T_{l,i}^{n+1'}$, from Eq. (6) is used in the sensible heat term in Eq. (3) as a source term for the energy balance for the canopy layer, whereas AT_i is used as a source term in the water balance equation for the canopy layer. Additionally, turbulent transfer within the canopy for this hybrid version of the model has been updated based on the K-theory described in Flerchinger et al. (2012).

Soil evaporation (AE) supplied by the RZWQM is used in SHAW to compute the energy balance of the surface soil layer by forcing water vapor flux from the soil surface, and therefore latent heat flux, to equal the soil evaporation. Soil heat flow and temperature in the soil matrix, considering convective heat transfer by liquid and latent heat transfer by vapor for freezing soil is given by

$$C_s \frac{\partial T}{\partial t} - \rho_i L_f \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z} \left[K_{t(s)} \frac{\partial T}{\partial z} \right] - \rho_l c_l \frac{\partial q_l T}{\partial z} - L_v \left(\frac{\partial q_v}{\partial z} + \frac{\partial \rho_v}{\partial t} \right) \tag{7}$$

where C_s and T are volumetric heat capacity ($J\,kg^{-1}\,K^{-1}$) and temperature (°C) of the soil, ρ_i is density of ice ($kg\,m^{-3}$), θ_i is volumetric ice content ($m^3\,m^{-3}$), $K_{t(s)}$ is soil thermal conductivity ($W\,m^{-1}\,K^{-1}$), ρ_l is density of water, c_l is specific heat capacity of water ($J\,kg^{-1}\,K^{-1}$), θ_i is liquid water flux ($m\,s^{-1}$), q_v is water vapor flux ($kg\,m^{-2}\,s^{-1}$), L_f is latent heat of fusion (335,000 $J\,kg^{-1}$) and ρ_v is vapor density ($kg\,m^{-3}$) within the soil. The soil thermal conductivity and heat capacity are quantified using the theory of de Vries (1963). SHAW also uses a Newton–Raphson algorithm (Campbell, 1985) to solve finite difference expressions of the energy balance equation for soil temperature profiles. Soil surface temperature is solved through this iteration process by balancing radiation, sensible and latent heat fluxes from above with the soil heat flux (G) into the soil. G is calculated by rearranging Eq. (7) as the sum of gradient and storage terms for a soil slab thickness (Δz_s, m) as follows

$$G = \left[\frac{K_{s(t)}}{\Delta Z_s} + c_l q_l \right] (T_{s(t)} - \hat{T}_{z(t)}) - \frac{\Delta z_s}{2\Delta t} [C_s (T_{s(t)} - T_{s(t-\Delta t)}) - \rho_i L_f (\theta_{i(t)} - \theta_{i(t-\Delta t)})] + L_v q_v \tag{8}$$

where Δt is time increment (s), $T_{s(t)}$ is surface soil temperature at time t (°C), $T_{s(t-\Delta t)}$ is previous surface soil temperature at time $t - \Delta t$ (°C), $\hat{T}_{z(t)}$ is soil temperature expected at soil slab lower boundary z at time t (°C).

Table 2
Initial crop genetic parameter values, optimization boundaries and optimized final parameter values used by parameter estimation software (PEST).

Parameter[a]	Initial[b]	Lower	Upper	Final
Wheat				
P1V	50	25	70	40.0
P1D	60	25	70	28.3
P5	430	400	490	480.0
G1	27	18	60	22.4
G2	25	20	38	30.4
G3	1	0.5	2	0.6
PHINT	85	80	90	90.0
Maize				
P1	230	230	280	230.0
P2	0.4	0.3	0.7	0.4
P5	830	620	850	679.7
G2	760	720	850	796.0
G3	6	5	10.5	7.9
H_{max}	220	200	250	227
Stem_half	50	40	60	45
PHINT	39	30	50	41.0

[a] PIV: Relative amount that development is slowed for each day of unfulfilled vernalization, assuming that 50 days of vernalization is sufficient for all cultivars. P1D: Relative amount that development is slowed when plants are grown in a photoperiod 1 h shorter than the optimum (which is considered to be 20 h). P5: Relative grain filling duration based on thermal time (degree days above a base temperature of 1 °C), where each unit increase above zero adds 20 degree days to an initial value of 430 degree days. G1: Kernel number per unit weight of stems (less leaf blades and sheaths) plus spike at anthesis (1/g). G2: Kernel filling rate under optimum conditions (mg/day). G3: Non-stressed dry weight of a single stem (excluding leaf blades and sheaths) and spike when elongation ceases (g). PHINT: Phyllochron interval (°C). P1: Thermal time from seedling emergence to the end of juvenile phase during which the plants are not responsive to changes in photoperiod (degree days). P2: Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development is at maximum rate, which is considered to be 12.5 h (days). P5: Thermal time from silking to physiological maturity (degree days). G2: Maximum possible number of kernels per plant. G3: Grain filling rate during the linear grain filling stage and under optimum conditions (mg/day). PHINT: Phyllochron interval (degree days). H_{max}: the maximum canopy height at maturity (cm). *Stem_half*: plant stem biomass at half of maximum canopy height (g).

[b] These initial parameter values were based on previous studies at the experiment station (Fang et al., 2008, 2010a).

At the end of time step (Fig. 1), SHAW provides RZWQM with hourly frozen soil conditions (i.e., soil ice content and frozen depth, soil water content) and soil surface temperature for calculating crop growth (DSSAT-CERES in RZ-SHAW, Fig. 1), which includes updated LAI, plant height, biomass, and root distribution to be used for estimating PET and energy balance by RZ-SHAW for the following day (Fig. 1).

The CERES-Wheat and CERES-Maize models are selected for simulating crop growth in RZ-SHAW (Fig. 1), which were incorporated into RZWQM by Ma et al. (2006). The CERES models uses the radiation use efficiency approach for biomass growth which is partitioned among leaves, stems, roots, ears, and grains based on the crop stage of development and growing conditions (such as soil water and nitrogen conditions) (Ritchie, 1998). All the cultivar parameters (Table 2) control the crop growth and grain yield which are modified by the environmental factors (such as soil water and nitrogen conditions). The detailed processes and equations can be found in the literature (Ritchie, 1998; Jones and Ritchie, 1991; Jones et al., 2003). In this study, these cultivar parameters were initialized based on previous studies at the experiment site (Yu et al., 2007; Fang et al., 2008, 2010a) and were further calibrated to obtain reasonable crop growth and grain yield simulations.

To better simulate wheat height, we used a maximum canopy height of 85 cm based on the measured plant height from 2003 to 2006 at the experimental site for CERES-Wheat. Since plant height is not calculated in the CERES-Maize model, we used a simple exponential equation based on stem biomass as follows (Ma et al., 2011):

$$\text{Height} = H_{max}(1 - e^{-\alpha \times \text{stem}/(2*H_{max})}) \quad (9)$$

$$\alpha = \frac{-2H_{max} \times \ln(0.5)}{Stem\_half} \quad (10)$$

where H_{max} is the maximum canopy height at maturity (cm) and *Stem_half* is plant stem biomass at half of maximum canopy height (g); *stem* is stem biomass (g). We found that H_{max} = 227 cm and *Stem_half* = 45 g provided good simulation of maize canopy height.

2.2. Site and experiment descriptions

The field experiments were conducted at Yucheng Integrated Agricultural Experimental Station in the North China Plain (36°50′ N, 116°34′ E, 28 m above mean sea level) from 2003 to 2005. It is one of the 36 agricultural ecosystem stations of the Chinese Ecological Research Network (CERN). The soil type in the experimental area was silt loam, and detailed information can be found in Yu et al. (2007) and Li et al. (2010). The typical cropping system is from early October to early June the following year for wheat and from early June to late September for maize. Influenced by the monsoon climate, the area is characterized by high temperature and high rainfall in the summer (about 70–80% of the annual rainfall occurs from July to late September in the maize season), and only 20–30% occurs from October to early June in the wheat season.

Measurements of meteorological variables, the soil surface energy balance, soil water content, and soil or canopy temperature were made in the middle of a 300 m × 300 m from 2003 to 2005. The winter wheat variety, Zhixuan No. 1, was planted in October (Oct 15 in 2002, Oct 23 in 2003 and Oct 18 in 2004) and the maize variety, Yedan 22, was planted in June (Jun 18 in 2003, June 20 in 2004 and June 18 in 2005) for the three years. Irrigation before planting was applied for both wheat and maize for the three years, and supplemental irrigation was also applied at jointing (early March), booting stage (early April) or flowering stage (early May) for wheat depending on rainfall distributions. No supplemental irrigation was applied for maize due to the adequate seasonal rainfall. During the growing seasons, plant height, leaf area index (LAI), and aboveground biomass were measured weekly, and final grain yield were observed at harvest. The meteorological variables included wind direction and speed, humidity, temperature, soil heat flux, air pressure, total and net radiation data; detailed information on above measurements can be found in Yu et al. (2007).

Latent and sensible heat fluxes (LE and H) over the crop canopy, soil heat flux (G) and net radiation (Rn) were measured by an eddy covariance system at 2.1 m above ground during wheat seasons and 3.3 m above ground during maize seasons from 2003 to 2005. The system consisted of a fast response infrared gas analyzer (LI7500, LI-COR Inc., Lincoln, NE, USA) and a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA). More detailed information about the eddy covariance system and data collections can be found in Li and Yu (2007) and Yu et al. (2007). Crop canopy temperature was also measured with an infrared thermometer (IRT) installed on a bracket of the eddy covariance system (Li et al., 2010).

The three dimensional wind velocity, vapor, and CO_2 concentrations were sampled at a frequency of 10 Hz. Monitoring results were averaged in 30 min intervals and processed with Eddypro (LI-COR) and TK2 software for quality control (Mauder et al., 2006). According to a previous study at the site (Li et al., 2006), the threshold of wind friction velocity (u^*) is 0.15 m s^{-1}. The flux data on rainy days or in the morning when dew appeared were discarded (Falge et al., 2001). The missing data due to the malfunction of instruments or

power failure were filled using the linear interpolation for short gaps (less than 2 h) or using the Mean Diurnal Variation method for larger gaps (larger than 2 h) (Falge et al., 2001). Part of these measured data in 2003 were used to test the RZ-SHAW and SHAW models (Xiao et al., 2006; Yu et al., 2007). Lee and Yu (2004) also analyzed and tested the quality of the data and found no systematic bias between the ET measured with the Bowen ratio/energy balance (BREB) method and the eddy covariance systems. The ratio of total sensible and latent heat fluxes (Hs + LE) to available energy (Rn − G) was 72% based on the observed hourly data from 2003 to 2005. The energy balance closure observed in this study was within the range of 22 FLUXNET sites reported by Wilson et al. (2002). The ratio was higher for wheat season (73%) than for maize season (70%). Before comparing measured values with simulated fluxes, the turbulent fluxes were adjusted to force energy balance closure while maintaining the Bowen ratio (Twine et al., 2000). According to Yu et al. (2007), the above method was problematic when the Bowen ratio approached −1.0, and the error was divided equally between the two components whenever the magnitude of H + LE was lower than the error in the energy balance.

A large-scale weighing lysimeter close to the eddy covariance system was planted with same crop and adequately irrigated to measure the daily potential ET from 2003 to 2005. Daily PET measured by the adequately irrigated lysimeter was used to compare the simulated PET from Shuttleworth–Wallace method in the RZ-SHAW model, similar to the approach used by others (e.g., Makkink, 1957; Allen et al., 1989; Steiner et al., 1991; Grismer et al., 2002). A detailed description of the large-weighing lysimeter experiment was given by Yang et al. (2007). Across the three years, three flood irrigations were applied at planting, jointing and booting stages (more than 300 mm in total) for wheat and one irrigation was applied at planting (about 80 mm) for maize since rainfall was generally enough for maize growth. The irrigation amount plus rainfall was enough for crop water requirement but intermittent soil water deficit may occur between rainfall or irrigation events.

2.3. Model calibration and evaluation

As shown in Fig. 1, the RZ-SHAW simulated soil water content and plant growth (such as LAI and plant height) are very important for simulating ET and soil surface energy balance. So, we first calibrated the soil hydraulic parameters and crop cultivar parameters against the observed data of daily soil water content, crop height, LAI and aboveground biomass, and final crop yield from 2003 to 2005. The parameter estimation software (PEST) (Doherty, 2005) was used to calibrate these parameters. A detailed description on RZWQM optimizations with PEST can be found in Fang et al. (2010b). Initial soil hydraulic parameters and crop parameters were based on Yu et al. (2007) and Fang et al. (2008, 2010a) at the same experiment site. Other soil parameters, such as soil nutrient parameters and albedo information were set according to Fang et al. (2008) at the same experiment site. These initial and calibrated soil and crop genetic parameters are presented in Tables 1 and 2.

The optimized soil and plant parameters that produced better soil water content and crop growth from 2003 to 2005 were chosen for evaluating the simulations of soil surface energy balance, ET, soil and canopy temperature during this period against measured data from eddy covariance systems and large-scale weighing lysimeter. The statistical measures of Root Mean Squared Error (RMSE), Mean Difference (MD), coefficient of determination (R^2), and the Nash–Sutcliffe model efficiency (ME, Nash and Sutcliffe, 1970) were also used to evaluate model performance. Graphic presentation of some results for certain growth stages as examples is also included.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{11}$$

$$MD = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \tag{12}$$

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}\left(O_i - O_{avg}\right)\left(P_i - P_{avg}\right)}{\left[\sum_{i=1}^{n}\left(O_i - O_{avg}\right)^2\right]^{0.5}\left[\sum_{i=1}^{n}\left(P_i - P_{avg}\right)^2\right]^{0.5}} \right\}^2 \tag{13}$$

$$ME = 1.0 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2} \tag{14}$$

where P_i is the ith simulated value, O_i is the ith observed value, O_{avg} and P_{avg} are the average of observed and simulated values, respectively, and n is the number of data pairs.

3. Results and discussion

3.1. Model calibration for soil water content and plant growth

The simulated daily soil water content showed similar trends with the measured values at the 10 cm and 30 cm depths, with RMSE and MD values of 0.036 $cm^3\ cm^{-3}$ and −0.001 $cm^3\ cm^{-3}$ from 2003 to 2005 (Fig. 2a and Table 3). Soil water content was over-simulated during the winter (December–February) in 2003–2004 and 2004–2005 and under-simulated in January–February in 2003 due to the under-simulated soil water contents after planting (October–December) in 2002. In general, better soil water simulations were obtained for 2003 than for 2004 and 2005 (Table 3). Soil water content was over-simulated in the wheat season of 2004 and under-simulated in March–June (wheat season) of 2005 (Fig. 2a). The statistical results for the current calibration were comparable to previous RZWQM evaluations at the experiment site (Fang et al., 2008; Yu et al., 2006, 2007).

The simulated LAI was better for wheat than for maize (Fig. 2b). The overall RMSE, MD and ME values were 0.95 $cm^2\ cm^{-2}$, 0.40 $cm^2\ cm^{-2}$ and 0.69 from 2003 to 2005, respectively (Table 3). LAI was under-simulated only in the maize season of 2003, with a MD value of −0.63 $cm^2\ cm^{-2}$, and was over-simulated in the other five crop seasons (Fig. 2b and Table 3). The worst simulation for LAI occurred in the 2004 maize season, with RMSE and ME values of 1.07 $cm^2\ cm^{-2}$ and −0.46. During late wheat growth seasons (end of May), the LAI was also slightly over-simulated across the three years.

Crop height simulations were improved by using a new maximum canopy height for wheat (85 cm instead of 100 cm), with RMSE values of 6.90 cm, 8.73 cm and 9.19 cm for the three wheat seasons, respectively (Fig. 2c and Table 3). Maize canopy height was adequately simulated using Eqs. (9) and (10), with RMSE values of 24.33 cm, 17.89 cm, and 19.94 cm for the three seasons, respectively. The overall MD, RMSE and ME values for both wheat and maize from 2003 to 2005 were 0.57 cm, 14.41 cm and 0.96 (Table 3), respectively.

The simulated aboveground biomass was close to the measured data, with MD, RMSE and ME values of 700 $kg\ ha^{-1}$, 1538 $kg\ ha^{-1}$ and 0.90 from 2003 to 2005 (Fig. 2d and Table 3). The model under-simulated aboveground biomass in 2003, with MD values of −612 $kg\ ha^{-1}$ for wheat and −114 $kg\ ha^{-1}$ for maize, but over-simulated in 2004 and 2005 with MD values of 583 $kg\ ha^{-1}$ to 2458 $kg\ ha^{-1}$. The obviously over-simulated crop biomass in 2004

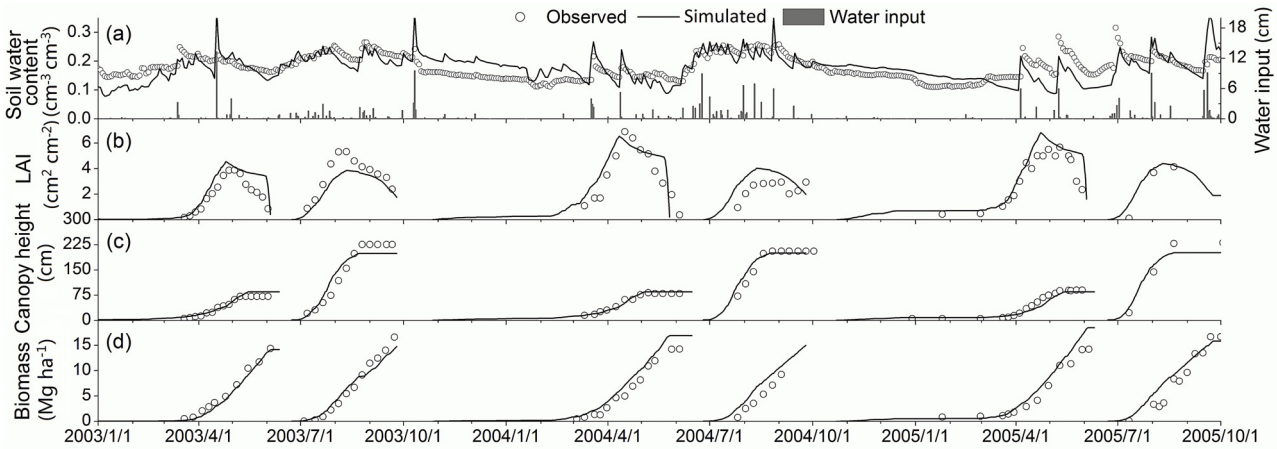

Fig. 2. Comparisons between observed and simulated daily soil water content averaged from 10 cm and 30 cm depths, leaf area index (LAI), canopy height, and aboveground biomass by RZ-SHAW in the wheat (January–June) and maize (July–October) rotation system from 2003 to 2005 (Water input includes rainfall and irrigation).

Table 3
Mean difference (MD), root mean square error (RMSE), coefficient of determination (R^2) and model efficiency (ME) for the simulated soil water content ($cm^3\ cm^{-3}$), leaf area index (LAI, $cm^2\ cm^{-2}$), crop height (cm), aboveground biomass ($kg\ ha^{-1}$), and grain yield ($kg\ ha^{-1}$) by the RZ-SHAW in a wheat–maize rotation system from 2003 to 2005.

Item	Soil water content	LAI	Canopy height	Biomass	Crop yield
2003–2005					
MD	−0.001	0.40	0.57	700	−26
RMSE	0.036	0.95	14.41	1538	455
ME	0.203	0.69	0.96	0.90	0.96
R^2	0.625	0.88	0.98	0.96	0.98
2003 wheat					
MD	−0.013	0.55	4.09	−612	−867
RMSE	0.031	0.71	6.90	731	
ME	−0.586	0.69	0.93	0.97	
R^2	0.809	0.97	0.99	1.00	
2003 maize					
MD	−0.014	−0.63	1.28	−114	504
RMSE	0.024	1.03	24.33	1170	
ME	0.036	0.53	0.91	0.95	
R^2	0.694	0.86	0.96	0.99	
2004 wheat					
MD	0.023	0.59	−1.19	1447	440
RMSE	0.040	1.06	8.73	1659	
ME	−2.263	0.65	0.97	0.88	
R^2	0.542	0.88	0.99	1.00	
2004 maize					
MD	−0.005	0.71	6.38	2458	55
RMSE	0.028	1.07	17.89	2776	
ME	−0.018	−0.46	0.89	−0.53	
R^2	0.585	0.71	0.97	0.99	
2005 wheat					
MD	−0.003	0.62	−5.27	583	−124
RMSE	0.040	0.90	9.19	1099	
ME	−0.320	0.75	0.97	0.91	
R^2	0.263	0.96	0.99	0.99	
2005 maize					
MD	−0.018	0.50	1.83	1228	−164
RMSE	0.038	0.69	19.94	1761	
ME	−0.715	0.78	0.93	0.83	
R^2	0.626	1.00	0.97	0.97	

maize season was consistent with over-simulated LAI for the maize season.

The crop yield was slightly under-simulated with a MD value of −26 $kg\ ha^{-1}$, and a RMSE value of 455 $kg\ ha^{-1}$, from 2003 to 2005. The wheat yields were under-simulated by 19% and 9% in 2003 and 2005, respectively, while maize yield were over-simulated by 8% and 1% in 2003 and 2004, respectively, and under-simulated by 2% in 2005. The under-simulated wheat yield in 2003 was mainly caused by the under-simulated soil water content from January to April (Fig. 2a), which resulted in higher simulated water stress during the early wheat season. Across the six crop seasons, the simulated crop yield showed a similar trend to measured data with a ME value of 0.96.

In general, better simulations of soil water content, plant height and biomass were obtained for 2003 than for 2004 and 2005, and better simulations of LAI and plant height were obtained for wheat than for maize. The overall model performance was comparable to previous simulations at the experiment site (Yu et al., 2006; Fang et al., 2008) and other locations (Ma et al., 2012; Kozak et al., 2007).

3.2. Model evaluation for daily and seasonal PET simulations

Compared to observed PET from the large weighing lysimeter with adequate irrigation (Fig. 3b), the Shuttleworth–Wallace method simulated PET was higher than observed during early growth stages, but was lower for the middle to late growth stages. However, the average daily PET was under-simulated by only 0.08 mm across the three years (Table 4). The lower ET observed by the lysimeter during early crop season (October–March for wheat and June for maize) was mainly due to the lower soil water content with little rainfall and supplemental irrigations (Fig. 2a), which suggested that maximum ET was not maintained during early crop growth periods. The high measured PET by lysimeter during the middle wheat seasons can be contributed to several environmental factors (such as so-called "bloom effect") as discussed by Allen et al. (1991, 2011), who also argued that the effective evaporation or radiation absorption area should be larger than the physical lysimeter area, especially during the middle crop season, which can result in over-calculated PET. The simulated total seasonal PET and observed PET by large-scale weighting lysimeter were positively correlated ($y = 1.0x$, $R^2 = 0.85$, $n = 6$), with average values of 437.5 mm and 445.9 mm, respectively, for the wheat seasons, and 330.6 mm and 336.0 mm, respectively, for maize seasons (Fig. 4).

3.3. Model evaluation for daily and seasonal AET simulations

As shown in Fig. 3a, both eddy covariance observed and RZ-SHAW simulated daily AET increased with crop growth (e.g., LAI), and peaked in April–May in the wheat seasons and in July–August in the maize seasons from 2003 to 2005. The corresponding MD,

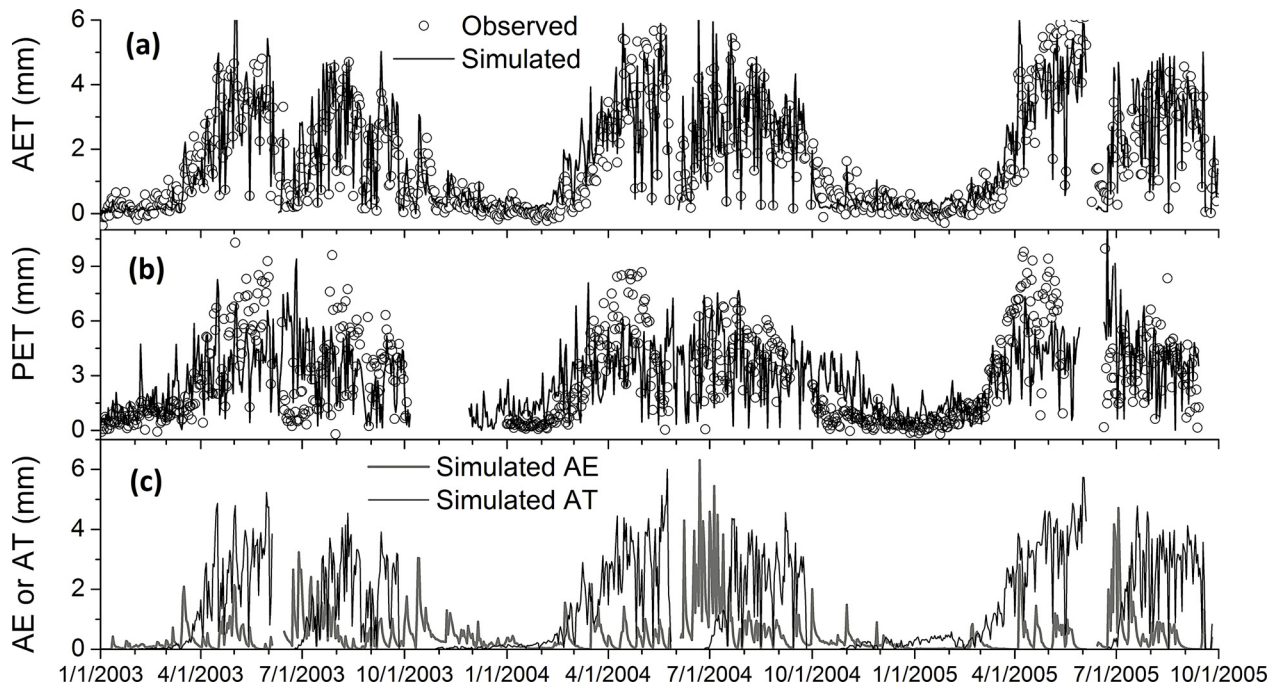

Fig. 3. Comparisons between simulated actual evapotranspiration (AET (a)) and potential evapotranspiration (PET (b)) and simulated actual evaporation (AE) and transpiration (AT) (c) by the hybrid RZ-SHAW model and observed ET by eddy covariance and PET from large weighing lysimeter in wheat (October–June next year) and maize season (June–September) from 2003 to 2005.

RMSE, ME and R^2 values for the simulated daily AET were 0.10 mm, 0.59 mm, 0.86 and 0.93 across the three years (Table 4). Daily AET was better simulated in 2003 than in 2004 and 2005, which was consistent with the soil water content and crop growth simulation results (Table 3). Compared with the observed data from eddy covariance measurements (Table 4), the simulated daily AET was slightly lower than measured values in the wheat seasons of 2003 (MD = −0.05 mm) and 2005 (MD = −0.07 mm) but higher than measured AET (MD = 0.17 mm) during the early seasons from February to March in 2004 (Figs. 3a and 5a) due to the over-simulated soil water content (Fig. 1a) and LAI (Fig. 1b). The daily AET was over-simulated with MD values of 0.23 mm for the maize seasons from 2003 to 2005 (Table 4), which was not consistent with the under-simulated soil water content (Table 3). The accuracy of daily ET simulations was comparable with a previous study in Iowa, USA (RMSE = 0.69 mm for simulations across 20 days) (Ma et al., 2012).

During early wheat (October–March next year) and early maize (June–July) seasons, the simulated AET (mainly soil evaporation as shown in Fig. 3c) by RZ-SHAW depended on the ability of soil water to deliver the potential rate determined by the Richards equation. As shown in Figs. 3a and 5a, b, the model over-simulated AET with MD value of 0.08 mm for wheat and MD value of 0.31 mm for maize during these periods from 2003 to 2005. The over-simulated AET for maize was partly associated with over-simulated soil water content during this period, such as in 2003 and 2004 (Fig. 2a). The under-simulated daily AET (MD = −0.12 mm) during early wheat season (January–February, Fig. 3a) in 2003 were consistent with the under-simulated soil water content during this period (Fig. 2a).

During the middle and late crop seasons (April–May for wheat and August–September) for maize, plant transpiration is the main component of AET (Fig. 3c). As shown in Figs. 5c–f and 3a, simulated AET was improved in the middle and late growth stages

Table 4
Mean difference (MD, mm), root mean square error (RMSE, mm), coefficient of determination (R^2) and model efficiency (ME) for simulated daily potential evapotranspiration (mm) and actual ET (mm) by the hybrid model, compared with observed data from large weighing lysimeter and eddy covariance system in a wheat–maize rotation system from 2003 to 2005.

Crop season	Mean observed	Mean simulated	MD	RMSE	ME	R^2
Daily ET						
2003 wheat	1.55	1.50	−0.05	0.14	0.92	0.96
2003 Maize	1.89	2.14	0.25	0.65	0.72	0.92
2004 wheat	1.23	1.40	0.17	0.58	0.85	0.93
2004 Maize	2.52	2.73	0.21	0.72	0.58	0.85
2005 wheat	1.48	1.41	−0.07	0.54	0.92	0.96
2005 Maize	2.22	2.47	0.24	0.70	0.69	0.90
2003–2005	1.67	1.77	0.10	0.59	0.86	0.93
Daily potential ET						
2003 wheat	2.65	2.58	−0.08	1.84	0.47	0.68
2003 Maize	3.40	3.31	−0.09	2.25	−0.43	0.23
2004 wheat	2.84	2.87	0.03	1.84	0.09	0.40
2004 Maize	4.14	3.85	−0.30	1.91	−1.41	0.06
2005 wheat	2.20	2.34	0.15	1.80	0.48	0.70
2005 Maize	3.53	4.11	0.58	2.64	−1.81	−0.15
2003–2005	2.90	2.95	0.05	1.88	0.17	0.37

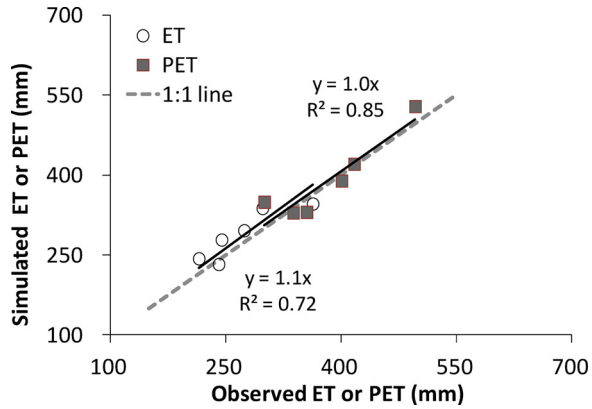

Fig. 4. Comparisons between observed seasonal potential evapotranspiration (PET) by large weighing lysimeter, seasonal actual evapotranspiration from latent heat flux (ET) and simulated seasonal PET and ET in the RZ-SHAW model across the six crop seasons from 2003 to 2005.

of wheat and maize, and was comparable with the observed data from 2003 to 2005, with MD, RMSE and ME values of −0.17 mm, 0.64 mm and 0.92 for wheat seasons and 0.27 mm, 0.53 mm and 0.68 for maize seasons. The under-simulated AET for wheat in 2004 (MD = −0.15 mm) and 2005 (MD = −0.38 mm) (Figs. 3a and 5c, e) was mainly due to the under-simulated soil water content (Fig. 2a). The over-simulated AET for maize (Fig. 5d and f) was partly attributed to over-simulated LAI in 2004 and 2005 during these periods (Fig. 2b).

As shown in Fig. 4, significant positive relations were found between the simulated seasonal AET by RZ-SHAW and observed data based on latent heat flux across the six crop seasons ($y = 1.1x$, $R^2 = 0.72$, $n = 6$). The measured and simulated average seasonal AET from 2003 to 2005 were 300.1 mm and 305.1 mm for the wheat seasons, and 244.1 mm and 272.2 mm for the maize seasons, respectively. Both measured and simulated AET for the maize seasons were lower than AET obtained from other methods at this experimental site (Fang et al., 2010a). Shen et al. (2013) reported the measured AET value of 275 mm for maize seasons (2008–2011) by eddy covariance system at Luancheng Experimental Station in Shandong province, 200 km northwest to the Yucheng Experimental Station, which was lower than ET observed from field experiments at the site based on soil water balance measurements (Zhang et al., 2004, 2006).

3.4. Model evaluation for energy balance in the wheat seasons

During early wheat seasons from October to March next year, Rn was over-simulated with relative MD (MD/mean) values of 15% for 2003, 43% for 2004 and 29% for 2005 (Table 5), mainly due to its over-simulation at night (e.g., Fig. 6a in 2004). The over-simulated

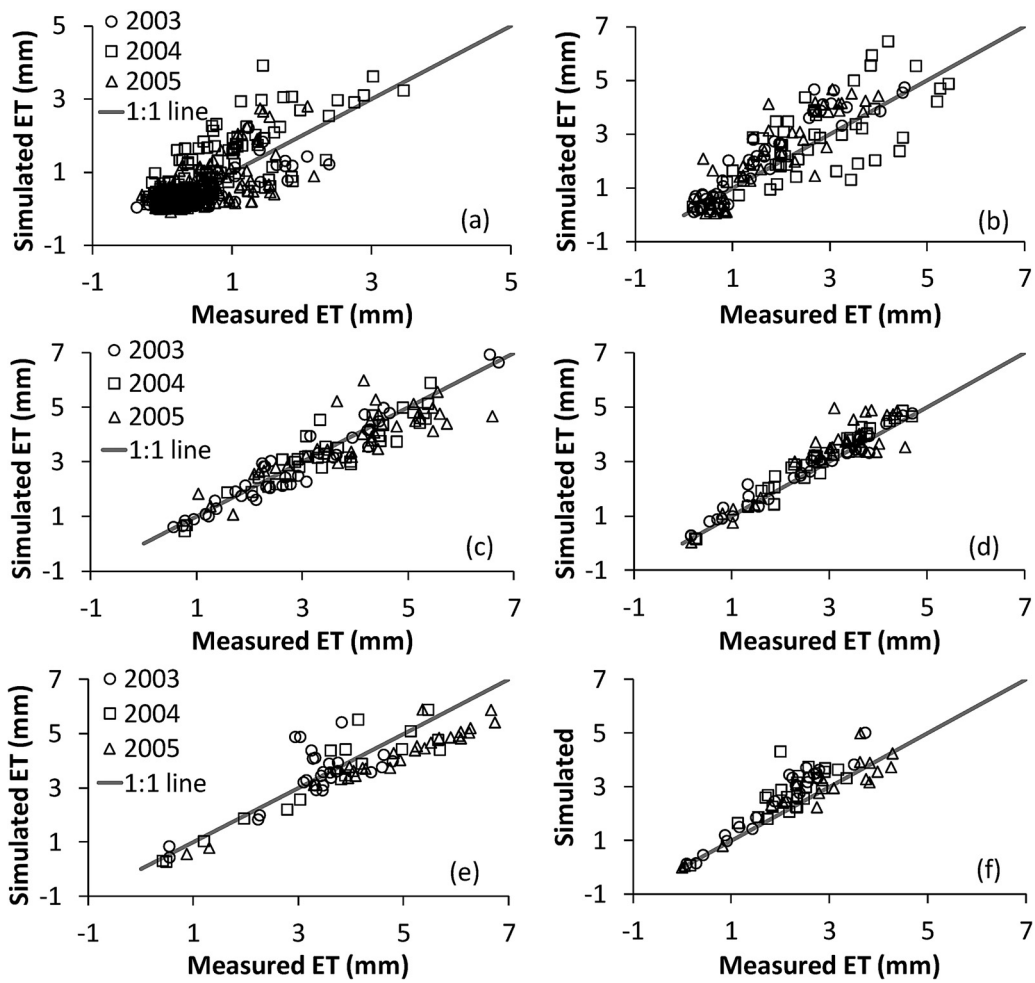

Fig. 5. Comparisons between observed daily evapotranspiration (ET) from latent heat (LE) and simulated daily ET by RZ-SHAW at early growth stage (10/10–3/31) for wheat (a) and (6/20–7/31) for maize (b), middle growth stage (4/1–5/8) for wheat (c) and (8/1–8/31) for maize (d), and late stage (5/9–6/5) for wheat (e) and (9/1–9/30) for maize (f), from 2003 to 2005.

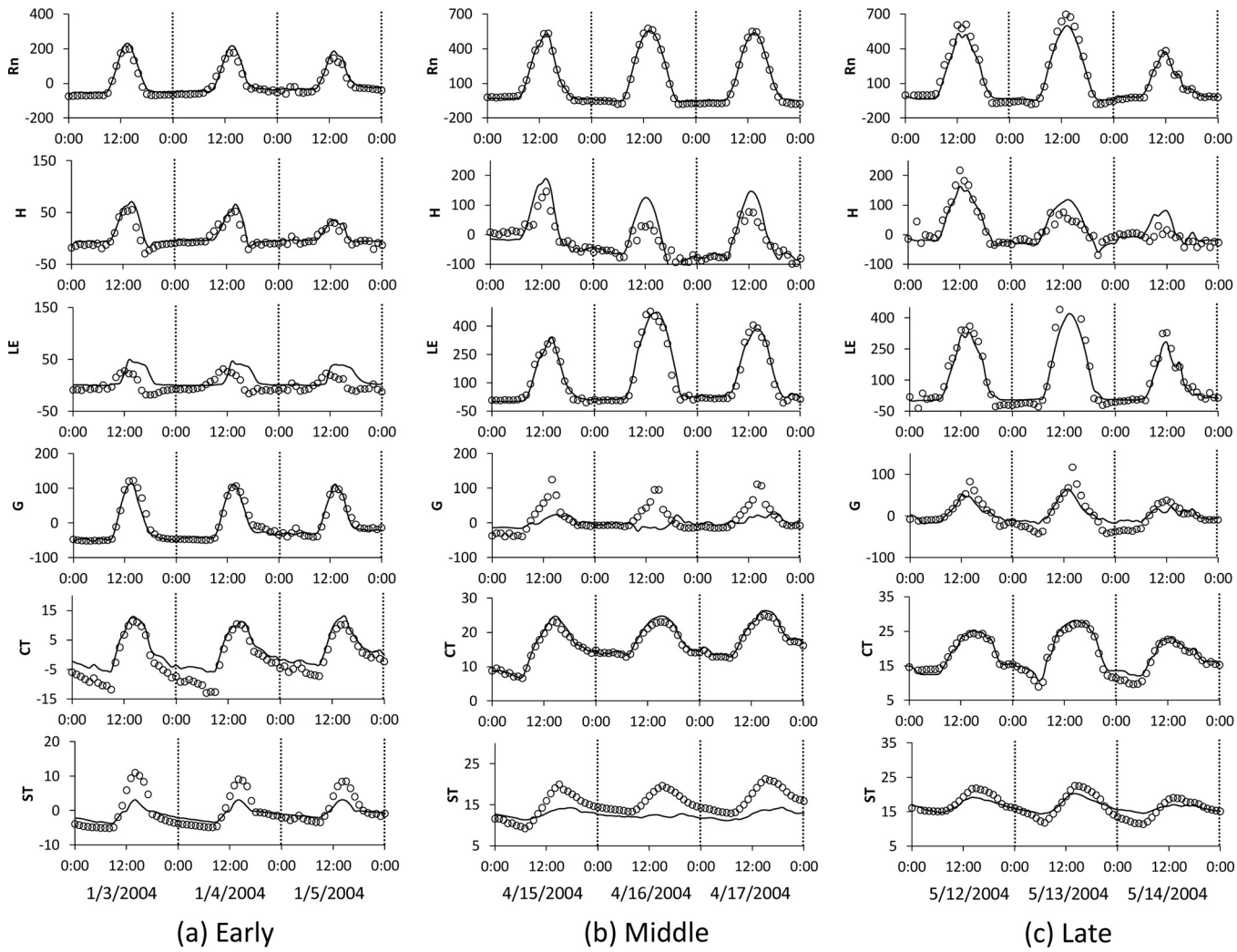

Fig. 6. Observed and simulated diurnal net radiation (Rn, W m^{-2}), sensible heat (H, W m^{-2}), latent heat (LE, W m^{-2}), ground heat flux (G, W m^{-2}), crop canopy temperature (CT, °C) and soil temperature at 5 cm depth (ST, °C) by the hybrid RZ-SHAW during early (a), middle (b) and late (c) wheat seasons in 2004.

Rn resulted in over-simulated H (mainly during nighttime as shown in Fig. 6a in 2004) with relative MD values of 77% for 2003, 80% for 2004 and 67% for 2005. The LE was also simulated with high relative MD values of −25% for 2003, 58% for 2004 and 13% for 2005 (Table 5). The obviously over-simulated LE during this period in 2004 (during hours 12:00–0:00 in Fig. 6a) was mainly due to the over-simulated soil water content and soil evaporation in 2004 (Figs. 2a and 3a). These results indicated that further improvement in simulating energy balance during the early wheat season with less canopy cover was needed. The over-simulated LE (mainly soil evaporation as shown in Fig. 3c) resulted in under-simulated soil temperature and G (e.g., Fig. 6a in 2004). The simulated canopy temperature was close to the observed data, and showed little response to simulation errors in LE (mainly soil evaporation) (e.g., Fig. 6a in 2004).

During middle (April) and late (May) wheat seasons with LAI > 3 cm^2 cm^{-2} and plant height >70 cm (Fig. 2a and b), plant transpiration was the main component of ET (Fig. 3c) and greatly influenced canopy energy balance. For these periods, the Rn and LE simulations were generally improved from early seasons with low relative MD values (−12% to 8%) for the three crop seasons (Table 5). This result was consistent with better simulations of daily ET (mainly plant transpiration) during middle growth stage than early growth stage (Fig. 5a vs. Fig. 5c) and indicated that the hybrid model was reasonable for simulating ET during these periods in the NCP. Better simulations of LE resulted in better canopy temperature simulations (Fig. 6a vs. Fig. 6b and c). The over-simulation of Rn by 5–8% during middle seasons mainly occurred at night (e.g., Fig. 6b) and contributed to over-simulated H (Table 5). For the late seasons (Table 5), the under-simulation of Rn by 1–12% resulted in under-simulated H in 2003 and 2005, but in 2004 the over-simulation of H was probably due to the under-simulation of LE by 23% caused by under-simulated soil water content (Fig. 2a). The under-simulated Rn during hours 10:00–14:00 for the late seasons (e.g., Fig. 6c) coincides with crop senescence and a sharp decrease of simulated LAI (Fig. 2b). Error is likely related to the fact that the senesced leaves are not simulated in the model and were not considered in the simulation of Rn.

Across the three wheat seasons (Table 5), better simulation of seasonal Rn and LE were obtained than that of H and G. The over-simulated seasonal H was mainly associated with over-simulated Rn, especially during the early seasons. Better simulations (with low MD values) of the energy balance components occurred in 2003 than in 2004 and 2005, mainly attributed to better simulations of soil water and crop growth (Table 3).

3.5. Model evaluation for energy balance in the maize season

For the early maize seasons, the under-simulation of Rn and the over-simulation of LE resulted in under-simulated H and G

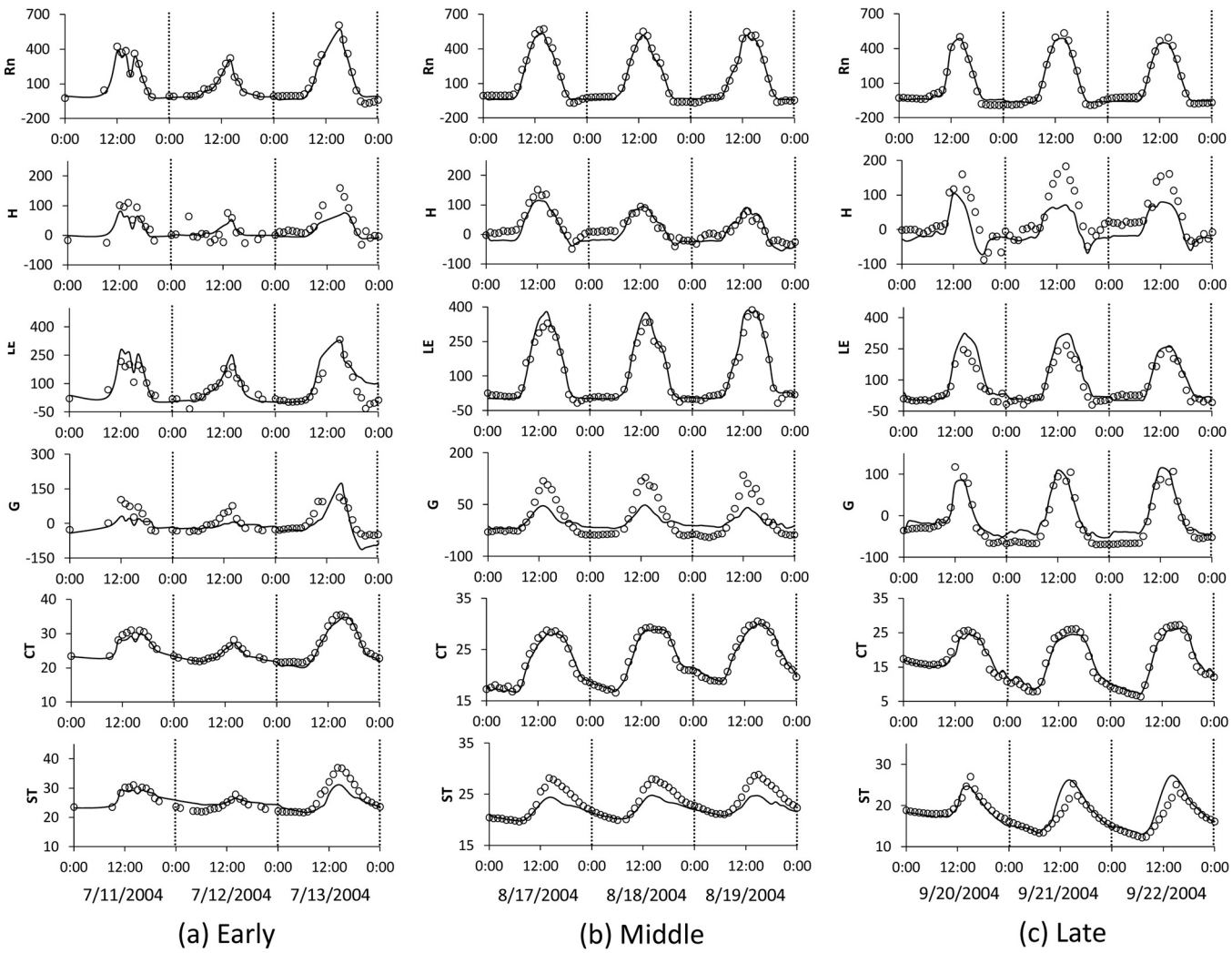

Fig. 7. Observed and simulated diurnal net radiation (Rn, W m^{-2}), sensible heat (H, W m^{-2}), latent heat (LE, W m^{-2}), ground heat flux (G, W m^{-2}), crop canopy temperature (CT, °C) and soil temperature at 5 cm depth (ST, °C) by the hybrid RZ-SHAW during early (a), middle (b) and late (c) maize seasons in 2004.

(Table 5 and Fig. 7a). The over-simulation of LE (mainly soil evaporation during this period as shown in Fig. 3c) was mainly due to over-simulated soil water content (Fig. 2a), which resulted in under-simulated soil surface temperature (especially during hours 10:00–13:00, e.g., Fig. 7a). Compared with the early wheat seasons (Table 5), better simulations of LE and canopy temperature were obtained for the early maize season in 2004 (e.g., Fig. 6a vs. Fig. 7a) and comparable simulations of energy balance were found in 2003 or 2005 (Table 5).

During the middle and late maize seasons with high LAI and plant height, the simulation of Rn and LE was improved comparing to the early season (e.g., Fig. 7a vs. Fig. 7b and c in 2004; Table 5). Better LE simulation was consistent with better ET simulation (Fig. 5). The under-simulation of Rn by 2–12% and the over-simulation of LE by 4–20% (mainly occurred during hours 11:00–15:00 as shown in Fig. 7b and c) resulted in under-simulation of H by 50–97% across the three crop seasons. Similar to the late wheat season, under-simulated H and Rn may be due in part to not considering senesced leaves, however this is not as obvious in the maize simulation (Fig. 2b). Although LE and Rn are simulated relatively well, the magnitudes of these fluxes are much greater than that of H and G; as a result, any small error in simulated LE and Rn can be transferred to a large relative error in simulated H and G. As shown in Fig. 7b and c, the simulated canopy temperature during these days was close to the observed data with slightly under-simulation at noon mainly due to the over-simulated LE (Figs. 2b and 3c).

Across the three maize seasons (Table 5), with the model under-simulated seasonal Rn, H and G and over-simulated seasonal LE for the three crop seasons (related to over-simulated ET as shown in Figs. 4 and 5d, f). The sum of LE and H, however, were similar with less than 5% difference between measured and simulated data (Table 5). Better simulations of seasonal Rn with relative MD values of −6% to −8% and seasonal LE with relative MD values of 8% to 14% were obtained than that of seasonal H and G with relative MD values of −29% to −65%.

Comparing the wheat and maize seasons, Rn and H were over-simulated for the wheat seasons, but under-simulated for the maize seasons. LE was generally better simulated for the wheat seasons than for the maize seasons (Table 5). The simulations of energy components for the middle and late crop seasons, however, were comparable with previous simulation results at similar growth stages at the experimental site (Xiao et al., 2006; Yu et al., 2007) or at other locations (Ma et al., 2012).

Table 5
Comparisons between measured and simulated energy balance components (net radiation, Rn, heat flux, H, lateral heat flux, LE, and ground heat flux, G) at early seasons for wheat (October-March) and for maize (July), middle seasons for wheat (April) and for maize (August), and late seasons for wheat (May) and for maize (September), from 2003 to 2005 (The energy balance components were calculated from the aggregation of 24 h fluxes measurements with unit of MJ m^{-2}; MD is difference between measured and simulated).

Crop season	Measured				Simulated				MD			
	Rn	H	LE	G	Rn	H	LE	G	Rn	H	LE	G
2003 wheat												
Early	182	68	103	11	210	121	77	12	28	53	−26	1
Middle	229	18	190	21	240	36	190	14	11	18	0	−7
Late	397	60	308	29	395	49	306	40	−2	−11	−2	11
Whole	807	147	600	61	845	206	573	66	38	59	−27	5
2003 maize												
Early	380	129	211	40	341	95	240	7	−39	−34	29	−33
Middle	243	48	187	7	225	23	194	9	−18	−25	7	2
Late	180	46	134	1	170	10	159	1	−10	−36	25	0
Whole	802	223	532	48	737	127	593	17	−65	−96	61	−31
2004 wheat												
Early	319	106	224	−12	457	191	354	−89	138	85	130	−77
Middle	250	−14	240	24	271	18	238	14	21	32	−2	−10
Late	416	52	329	35	365	72	253	40	−51	20	−76	5
Whole	984	143	793	47	1093	281	845	−34	109	138	52	−81
2004 maize												
Early	482	115	309	58	449	86	317	47	−33	−29	8	−11
Middle	271	41	216	14	255	18	233	4	−16	−23	17	−10
Late	167	38	143	−14	163	1	171	−9	−4	−37	28	5
Whole	920	194	668	58	866	104	721	41	−54	−90	53	−17
2005 wheat												
Early	233	116	194	−77	300	194	219	−113	67	78	25	−36
Middle	255	−37	265	27	274	−2	265	12	19	35	0	−15
Late	442	−15	421	35	410	28	359	24	−32	43	−62	−11
Whole	929	64	880	−15	985	219	843	−77	56	155	−37	−62
2005 maize												
Early	432	130	222	81	410	94	274	43	−22	−36	52	−38
Middle	278	49	222	7	268	15	245	8	−10	−34	23	1
Late	188	31	151	7	168	8	158	2	−20	−23	7	−5
Whole	898	210	594	95	846	117	677	52	−52	−93	83	−43

4. Summary and conclusions

Based on estimated soil water content and crop growth (LAI, plant height, aboveground biomass and crop yield), the revised hybrid RZ-SHAW model simulated energy balance reasonably well from 2003 to 2005. The daily ET was slightly under-simulated for the wheat seasons and was over-simulated for the maize seasons. Better simulations of soil water content and crop growth generally resulted in better LE and other energy balance simulations. Model performances for simulating energy balance components varied greatly within a crop season, and generally better simulations of Rn, LE and canopy temperature were obtained during the middle crop seasons (April–May for wheat and July–August for maize) than during early crop growth stages (June for maize and October–March for wheat). On a monthly basis, RMSE values ranged from 21.1 to 52.9 W m^{-2} for Rn, from 13.3 to 66.4 W m^{-2} for H, from 16.3 to 87.3 W m^{-2} for LE, and from 11.5 to 81.9 W m^{-2} for G across the three years, respectively.

Although further improvements in simulating ET (LE) and other surface energy balance components were needed for early crop seasons (such as winter time), the above simulation results demonstrated that the revised RZ-SHAW model was applicable for simulating surface energy balance and canopy temperature as well as crop growth and production across different climate and crop seasons in the North China Plain. The hybrid model can be potentially applied to quantify the effect of crop growth on energy balance (such as LE) in the wheat–maize double cropping system under different agronomic management practices in the region.

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