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ARTICLE

Parameterization of canopy resistance for modeling the energy partitioning of a paddy rice field

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Abstract Models for predicting hourly canopy resistance (r_c) and latent heat flux (LET) based on the Penman–Monteith (PM) and bulk transfer methods are presented. The micrometeorological data and LET were observed during paddy rice-growing seasons in 2010 in Japan. One approach to model r_c was using an aerodynamic resistance (r_a) and climatic resistance (r^*), while another one was based on a relationship with solar radiation (SR). Nonlinear relationships between r_c and r^*, and between r_c and SR were found for different growing stages of the rice crop. The constructed r_c models were integrated to the PM and bulk transfer methods and compared with measured LET using a Bowen ratio–energy balance method. The root mean square errors (RMSEs) were 155.2 and 170.5 W m^{-2} for the bulk transfer method with r_c estimated using r^* and with a function of SR, respectively, while the RMSEs were 87.4 and 85.7 W m^{-2} for the PM method with r_c estimated using r^* and SR, respectively. The r_c integrated PM equation provided better performance than the bulk transfer equation. The results also revealed that neglecting the effect of r_a on r_c did not yield a significant difference in predicting LET.

Keywords Climate resistance · Bulk transfer method · Canopy resistance · Penman–Monteith model · Meteorological data · Bowen ratio–energy balance method · Latent heat flux

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Introduction

Latent heat flux (LET) as a main component of the energy balance of agricultural systems, which can be expressed as evapotranspiration, plays an important role in atmospheric environment near the ground surface. More than 90% of water used in agriculture is lost by evapotranspiration (Rana and Katerji 2008; Luo et al. 2012; Yang et al. 2016). Accurate determination of evapotranspiration is very important for appropriate management of water resources and irrigation scheduling (He et al. 2009; Rana et al. 2011; Lagos et al. 2013; Li et al. 2014; Yan et al. 2015a). The Penman–Monteith (PM) and the bulk transfer methods are most frequently used and recommended formulas (Jensen et al. 1990; Rana and Katerji 1998; Ortega-Farias et al. 2004; Rana and Katerji 2008; Yan et al. 2008) for estimating LET. However, the application of the PM and bulk transfer models is constrained by accurate parameterization of canopy resistance (r_c), which is a key variable and influenced by climatological and agronomical variables such as canopy structure (Katerji et al. 2011; Yan et al. 2012b, 2015b). As r_c is difficult to model physically and mathematically, it has been proven that using empirical expressions is a practical option (Katerji et al. 2011).

Katerji and Perrier (1983) presented a linear model in which r_c depends on climatic variables and aerodynamic

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resistance (r_a), and many researchers have recommended it for practical use although the model needs calibration (Rana et al. 1997; Alves and Pereira 2000; Steduto et al. 2003; Katerji et al. 2011; Yan et al. 2015b). He et al. (2009) proposed a simple nonlinear relationship between r_c and climatic resistance in an irrigated wheat field in a semiarid region in northwest China. Farahani et al. (2007) pointed out, in most cases, the resistance parameters which were estimated by empirical formulas, posed great uncertainties in estimating LET. Todorovic (1999) developed a mechanistic model, where r_c is also a function of climatic variables and r_a, but the model does not need calibration. However, some researchers (Pauwels and Samson 2006) pointed out that the model was not able to estimate r_c in their study area. The model proposed by Jarvis (1976) suggested that environmental factors such as solar radiation (SR) and vapor pressure deficit (VPD) are the main influencing factors, and the model does not include the influence of r_a on r_c although it was pointed out that r_a is part of r_c. Oue (2005) analyzed the influences of SR, VPD and plant height on r_c by defining a parameter named critical resistance and assessed the influences of climatic factors on r_c. Most of these studies were conducted in a specific growth phase of the crop, while there is little information available on modeling r_c and LET over the entire crop cycle and on the assessment of the accuracy and applicability of the PM and the bulk transfer methods for prediction of LET by integrating different r_c models. Also, the argument about whether neglecting the influence of r_a on r_c leads to low accuracy of LET estimation or not is still not clear. Based on the above references, the estimation of r_c, in this study, was analyzed using a daily energy balance method, r_c estimations as functions of SR and climatic resistance and integrating these r_c values into the PM and the bulk transfer models for different growth stages of a rice crop. The r_c sub-models were based on (1) climatic resistance, with the effect of r_a considered, (2) solar radiation, with the effect of r_a neglected. We compare the difference of LET estimated by the PM and the bulk transfer models combined with two kinds of r_c sub-models to find whether the influence of r_a on r_c is significant or not; finally, we explored the best approach for the estimation of r_c based on global empirical parameters.

Materials and methods

Field observation

The experiment was conducted in a paddy field located at the Ehime University Senior High School, Matsuyama, Japan (33°50′N, 132°47′E) in 2010. The size of the observation field is 57 m by 68 m and is surrounded by other rice and vegetable fields. *Oryza sativa* L. cv. Akita-Komachi, which is one of the main cultivars of rice in Japan, was used for the experiment. The rice plants were transplanted into the field on May 28, 2010, with 25-cm spacing between the rows and 20-cm spacing within a row (a planting density of 20 hills per square meter) and harvested on August 27, 2010. Irrigation was applied to keep the rice crop flooded by a layer water except some days in tillering stage of the rice plants. The elements of radiation balance, i.e., $(1 - alb)$SR and $L_d - L_u$, were measured with a CNR-2 (Kipp & Zonen, the Netherlands) at 2.5 m, and thus, the net radiation ($R_n = (1 - alb)\text{SR} + L_d - L_u$) was calculated. Here, SR is the global solar radiation, alb is the albedo of the paddy field, L_d is the downward longwave radiation from the atmosphere, and L_u is the upward longwave radiation from the paddy field. In addition, the global solar radiation was measured at 2 m height with a second sensor (Decagon, USA,model LI-200SL). L_d was also measured with a PRI-01 (Prede, Japan) at 2 m height, and L_u was estimated using these measurements ($L_u = L_d - (L_d - L_u)$). Soil heat flux was measured at 2 cm depth with a soil heat plate HFT3 (Campbell, USA). Water temperature beneath the canopy was measured with three thermocouple sensors by setting the sensors at three different depths within the water layer (just under the water surface, 2–3 cm above the soil surface and just on the soil surface), the measurement of water temperature just under the water surface was seen as water surface temperature (T_g), and the average water temperature at the three depths was seen as water body temperature (T_w) and used for the calculation of heat storage within the water body. Vertical profiles (0.5, 1.0 and 2.0 m) of air temperature (T_a) and relative humidity above the canopy were measured with solid-state temperature and relative humidity sensors HMP-45A (Vaisala, Finland). The lowest sensor was moved up to about 10 cm above plant height with the growth of the rice plants. The accuracy of the sensors was validated by putting all the sensors at same height before the field observation. Wind speed was measured with three three-cup anemometers 014A (MetOne, USA) at the same height as T_a. All the data were sampled every 10 s, averaged every 10 min and recorded by a data logger CR23X (Campbell, USA). In this study, the direction of the prevailing winds during growing season was westerly, and the maximum fetch-to-height ratio of the top sensor was around 100:1, so, we did not consider the influence of fetch due to the similar coverage and irrigation intensity for 200 m of upwind of the observation field. The observed meteorological data during rice-growing season are shown in Fig. 1. Leaf area was measured by sampling 3 rice plants every 7 or 10 days (Yan and Oue 2011). The upper side area of each leaf was measured, and average leaf area for 1 plant was calculated. The leaf area index (LAI) was calculated with plant density and leaf area for 1 plant. Plant height was measured with 10 fixed rice plants

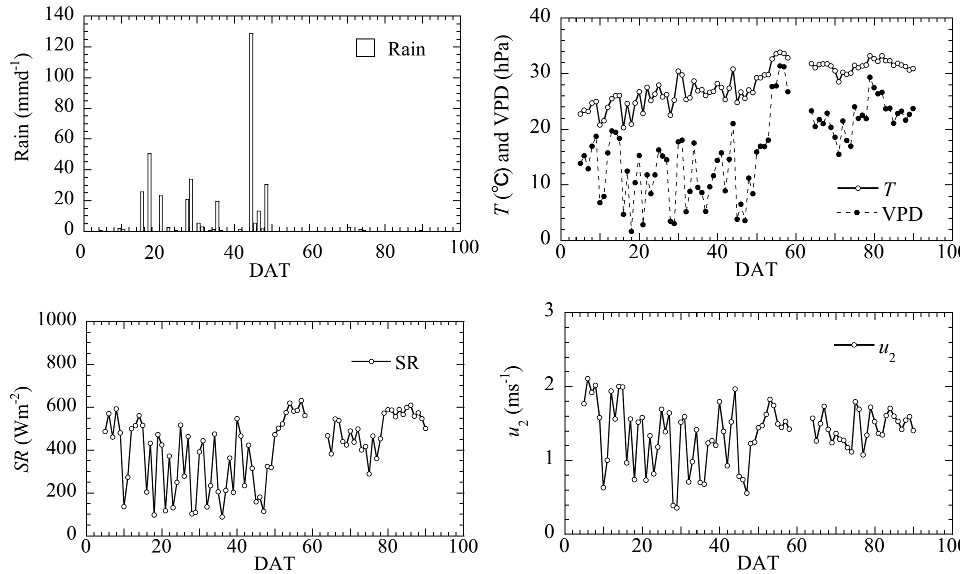


Fig. 1 Variations of meteorological data during rice-growing season; rainfall, air temperature (T), vapor pressure deficit (VPD), solar radiation (SR) and wind speed (u_2), DAT is days after transplanting

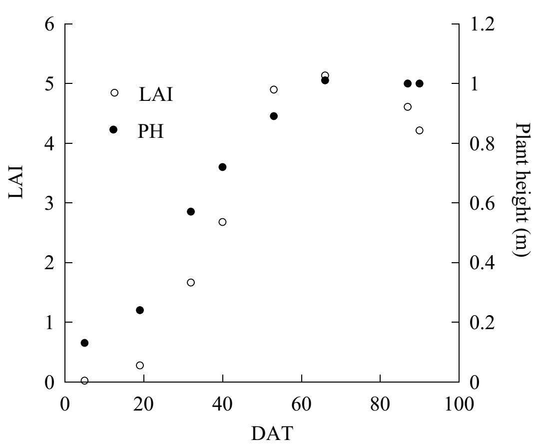


Fig. 2 Variations of leaf area index (LAI) and plant height (PH)

at same time with leaf area measurement. Figure 2 shows the variations of plant height and LAI. The maximum values of plant height and LAI were 1.0 m and 5.1, the LAI increased after transplanting and decreased after heading, and the heading day of rice plants was July 25, 2010, 57 days after transplanting (DAT).

The hourly evapotranspiration (ET_c) during rice-growing season was estimated using the Bowen ratio–energy balance method. The Bowen ratio and the energy balance equation are the basis for the method of determining ET_c using micro-meteorological and soil heat flow measurements (Wight et al. 1993). The pan evaporation above the rice plant was measured using a round brown pan (20 cm diameter × 25 cm deep) which was set on a piece of wood plate surface at a height of 1.5 m. The water depth within the pan was always kept higher than 2 cm. In this study, the pan evaporation was measured as the method to benchmark ET_c. The water depth in the paddy field was measured twice a day (at 8:00 and 18:00) with a ruler by hand by selecting different places in the field.

Methods

Bowen ratio–energy (BREB) balance method, bulk transfer equation and Penman–Monteith model

The energy budget in the paddy field is written as

$$R_n = \mathrm{LET} + H + G + \Delta W \tag{1}$$

where R_n is the net radiation (W m^{-2}), LET is latent heat flux (W m^{-2}), H is total sensible heat flux (W m^{-2}), G is soil heat flux, and ΔW is the change of energy storage in the water body (W m^{-2}). The Bowen ratio (β) is the ratio of sensible heat flux to latent heat flux (H/LET) and can be estimated from the temperature and vapor pressure gradients, $\beta = \gamma\Delta T/\Delta e$, ΔT is the air temperature gradient which was determined by the measurement of air temperature at different height as descripted in field observation section, Δe is the vapor pressure gradient, and γ is the psychrometric constant. LET was obtained based on the heat balance at the canopy surface expressed by the rearranged energy balance equation as LET = $(R_n - G - \Delta W)/(1+\beta)$ (Wight et al. 1993).

H and LET can be also written as

$$H = \frac{c_p \rho_a (T_s - T_a)}{r_a} \tag{2}$$

$$\mathrm{LET} = \frac{c_p \rho_a [e_*(T_s) - e_a]}{\gamma (r_a + r_c)} \tag{3}$$

based on the bulk transfer equation, where c_p is the specific heat of air (J kg °C^{-1}), ρ_a is the density of air (kg m^{-3}), r_a is the aerodynamic resistance (s m^{-1}), r_c is the canopy resistance (s m^{-1}), T_s is the surface temperature of the paddy field (°C), i.e., the total surface temperature of the rice canopy and water surface, it can be calculated by Stefan–Boltzman Law (Yan et al. 2012a) using the measurement of upward and downward longwave radiation (L_u and L_d), $e^*(T_s)$ is the saturated vapor pressure at T_s and e_a is air vapor pressure (Pa), and γ is the psychrometric constant (Pa °C^{-1}).

The heat storage ΔW is expressed as

$$\Delta W = c_w \rho_w d_w \frac{dT_w}{dt} \tag{4}$$

where c_w is the specific heat of water ($c_w = 4.18$ J kg^{-1} K^{-1}), d_w is the depth of the water layer (m) beneath the rice canopy, the average value of d_w measured at 8:00 and 18:00 was applied for calculation, ρ_w is the density of water (kg m^{-3}), and T_w is the water temperature (°C) at time t.

LET also can be expressed as (Allen et al. 1998):

$$\text{LET} = \frac{\Delta\left(R_n - G\right) + \frac{\rho_a c_p (e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \tag{5}$$

based on the PM model. The PM model represents the essential physics and biology of the evaporative process from a vegetative surface, where LET is the latent heat flux density (W m^{-2}), R_n and G are, respectively, the net radiation and soil heat flux (W m^{-2}), Δ is the saturation vapor pressure slope (Pa °C^{-1}), ρ_a is the mean air density at constant pressure (kg m^{-3}), c_p is the specific heat of moist air (J kg °C^{-1}), e_s and e_a are, respectively, the saturation and actual vapor pressure of the air (Pa), γ is the psychrometric constant (Pa °C^{-1}), r_a is the aerodynamic resistance (s m^{-1}), and r_c is the canopy resistance (s m^{-1}).

Different methods for estimating resistances

Aerodynamic resistance r_a To apply the bulk transfer equation and the PM model, the big challenge is to model two resistances (r_a and r_c). The r_a is commonly defined by the following equation:

$$r_a = \frac{1}{uk^2}\left[\ln\left(\frac{z_{\text{ref}} - d + z_H}{z_H}\right) + \psi_H\right] \cdot \left[\ln\left(\frac{z_{\text{ref}} - d + z_m}{z_m}\right) + \psi_m\right] \tag{6}$$

where k is von Karman's constant (= 0.41), z_{ref} is the reference height of measurements (for both temperature and wind speed) [m], u is the mean wind speed [m s^{-1}] at height z_{ref}, d is the zero plane displacement [m], z_H is the surface roughness for the heat flux [m], assumed to be equal to roughness length for water vapor, taken to be $0.1z_m$, z_m is the surface roughness for momentum flux [m], and ψ_H and ψ_m are the atmospheric stability correction factor for the heat flux and momentum flux, respectively, and are functions of $(z_{\text{ref}} - d)/L$ (see Brutsaert 1982) where L is the Monin–Obukhov length (m). The parameters d and z_m are defined as 0.63 and 0.13 of the canopy height, respectively (Monteith 1973).

The r_a estimated from Eq. (2) based on the measurements of meteorological conditions and H can be written as

$$r_a = \frac{c_p \rho_a \left(T_s - T_a\right)}{H} \tag{7}$$

Computation and parameterization of canopy resistance r_c The success of the bulk transfer and the PM models for estimating LET may depend on the accurate modeling of r_c (Yan et al. 2015b). An approach to estimate r_c through relationships obtained between r_c, computed by the PM or bulk transfer equation, and climatic variables. The r_c computed from the bulk transfer equation (Eq. 3) and PM model (Eq. 5) based on the measurements of meteorological conditions and LET can be written as

$$r_c = \frac{c_p \rho_a \left[e_*\left(T_s\right) - e_a\right]}{\gamma \text{LET}} - r_a \tag{8}$$

and

$$r_c = \left[\frac{\Delta\left(R_n - G\right) + \frac{\rho_a c_p (e_s - e_a)}{r_a}}{\text{LET}} - \Delta\right]\frac{r_a}{\gamma} - r_a, \tag{9}$$

respectively.

One approach for estimating r_c, suggested by Katerji and Perrier (1983), was establishing a relationship between two ratios r_c/r_a and r^*/r_a. The parameter r^* was first introduced by Monteith (1965) and mainly depends on climatic variables and is referred to as climatic resistance (Perez et al. 2006). The derivation of the Katerji and Perrier method is shown below (Yan et al. 2015b). First, Eq. (5) can be written in the form as:

$$LET = \frac{\Delta\left(R_n - G\right)\left[1 + \frac{\rho_a c_p (e_s - e_a)}{\Delta(R_n - G)} \cdot \frac{1}{r_a}\right]}{(\Delta + \gamma) + \gamma\frac{r_c}{r_a}} \tag{10}$$

and can be arranged as

$$LET = \frac{\Delta}{\Delta + \gamma}\left(R_n - G\right)\frac{1 + \frac{\rho_a c_p (e_s - e_a)}{\Delta(R_n - G)} \cdot \frac{1}{r_a}}{1 + \frac{\gamma}{\Delta + \gamma} \cdot \frac{r_c}{r_a}} \tag{11}$$

By defining a climatic resistance given as

$$r^* = \frac{\Delta + \gamma}{\gamma} \frac{\rho_a c_p (e_s - e_a)}{\Delta (R_n - G)} \quad (12)$$

So, Eq. (10) can be rewritten as

$$\mathrm{LET} = \frac{\Delta}{\Delta + \gamma}(R_n - G)\frac{1 + \frac{\gamma}{\Delta+\gamma} \cdot \frac{r^*}{r_a}}{1 + \frac{\gamma}{\Delta+\gamma} \cdot \frac{r_c}{r_a}} \quad (13)$$

Katerji and Perrier (1983) presented a linear link between r^*/r_a and r_c/r_a. In this study, we found a nonlinear functional relationship between r^*/r_a and r_c/r_a which has a higher correlation coefficient than the linear relationship shown in Yan et al. (2015b):

$$\frac{r_c}{r_a} = a \times \frac{r^*}{r_a} + b \times \sqrt{\frac{r^*}{r_a}} + c \quad (14)$$

where a, b and c were empirically calibrated. By submitting Eq. (14) into Eq. (13), the PM model contains only standard climatological variables.

Another approach which was presented by Jarvis (1976) was a hyperbolic function for modeling r_c with solar radiation and vapor pressured deficit (VPD) as

$$r_c = \frac{a_1}{SR} + b_1 \quad (15)$$

where a_1 and b_1 are experimental constants; a_1 represents the activity of bulk stomatal aperture in response to solar radiation (SR) and is dependent on VPD. This approach has been questioned because same variables considered in Jarvis model are already considered when computing r_c by the PM or the bulk transfer equations. Also, this procedure only includes the physiological component of r_c, but not consider the aerodynamic component (Alves and Pereira 2000). In the present study, we found a power function which can provide a higher correlation coefficient than a hyperbolic function.

The accuracy and applicability of r_c estimated by r^* (Katerji and Perrier 1983) and by SR (Jarvis 1976) were assessed by integrating two r_c sub-models into the PM and the bulk transfer models in the present study area and compared the predicted LET with measured using the Bowen ratio energy balance method.

Statistical analysis

For validating the accuracy of the constructed model, statistical indices, root mean square error (RMSE), systematic root mean square error ($\mathrm{MSE_s}$), unsystematic root mean square error ($\mathrm{MSE_u}$) and index of agreement (d) were calculated as (Yan et al. 2015b)

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_{i=1}^{n}(P_i - M_i)^2\right]^{1/2} \quad (16)$$

$$\mathrm{MSE_s} = \left[\frac{1}{n}\sum_{i=1}^{n}(\hat{P}_i - M_i)^2\right]^{1/2} \quad (17)$$

$$\mathrm{MSE_u} = \left[\frac{1}{n}\sum_{i=1}^{n}(\hat{P}_i - P_i)^2\right]^{1/2} \quad (18)$$

$$d = 1 - \left[\frac{n \cdot \mathrm{RMS}^2}{\sum_{i=1}^{n}\left((\left|P_i - \overline{M}\right| + \left|M_i - \overline{M}\right|)^2\right)}\right] \quad (19)$$

where P_i and M_i are predicted and measured hourly LET, i is the sample number, i = 1, 2….n, and M is the average measured hourly LET. The $\mathrm{MSE_s}$ estimates the model's linear (or systematic) error; hence, the better the regression between predictions and observations, the smaller the systematic error. The unsystematic difference is a measure of how much of the discrepancy between estimates and observations is due to random processes or influences outside the legitimate range of the model. A good model will provide low values of the RMSE, explaining most of the variation in the observations. The systematic error should approach zero, and the unsystematic error should approach RMSE. The index of agreement is a measure of the match between the departure of each prediction from the observed mean and the departure of each observation from the observed mean (Yan et al. 2015b).

Results and discussion

Diurnal variations of energy budget of the paddy rice field

Fourteen typical days were randomly selected to analyze the energy budget in different growing stages: initial or tillering stage, June 5, 6, 11, 12 and 24; developed or reproductive growth phase, July 20, 24 and 25; middle or booting and heading stage, August 15, 16 and 17; late or ripen and harvest stage, August 23, 24 and 25 of rice plant. The energy budget in the paddy rice field was characterized by the major partitioning to latent heat flux as shown in Fig. 3. Net radiation (R_n) ranged from − 72.2 to 806.2 W m^{-2} from 6:00 to 20:00, and maximum R_n ranged from 743.9 to 806.2 W m^{-2}. LET which is the main

Fig. 3 Variations of energy partitioning for different growing stage of paddy rice

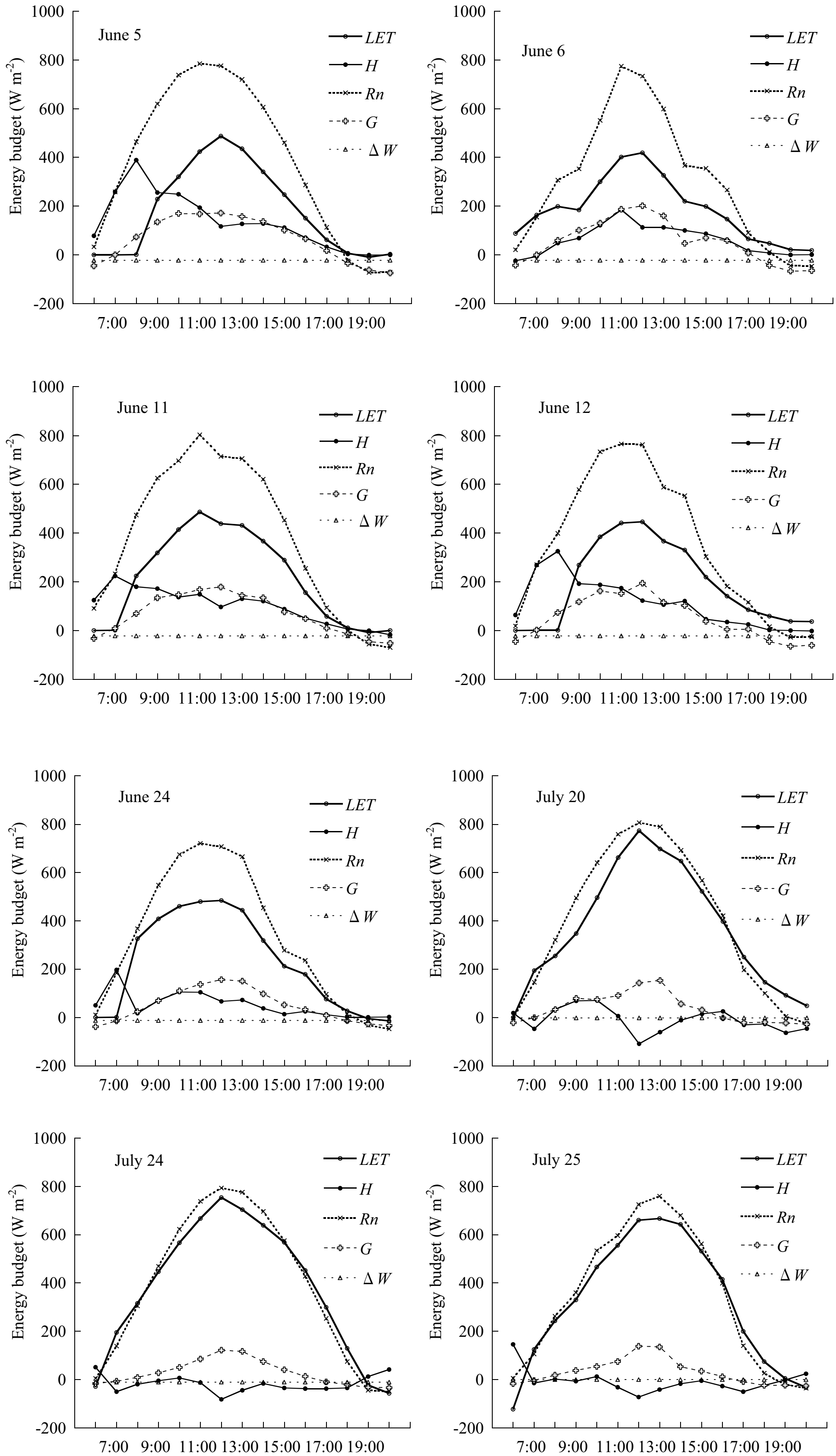
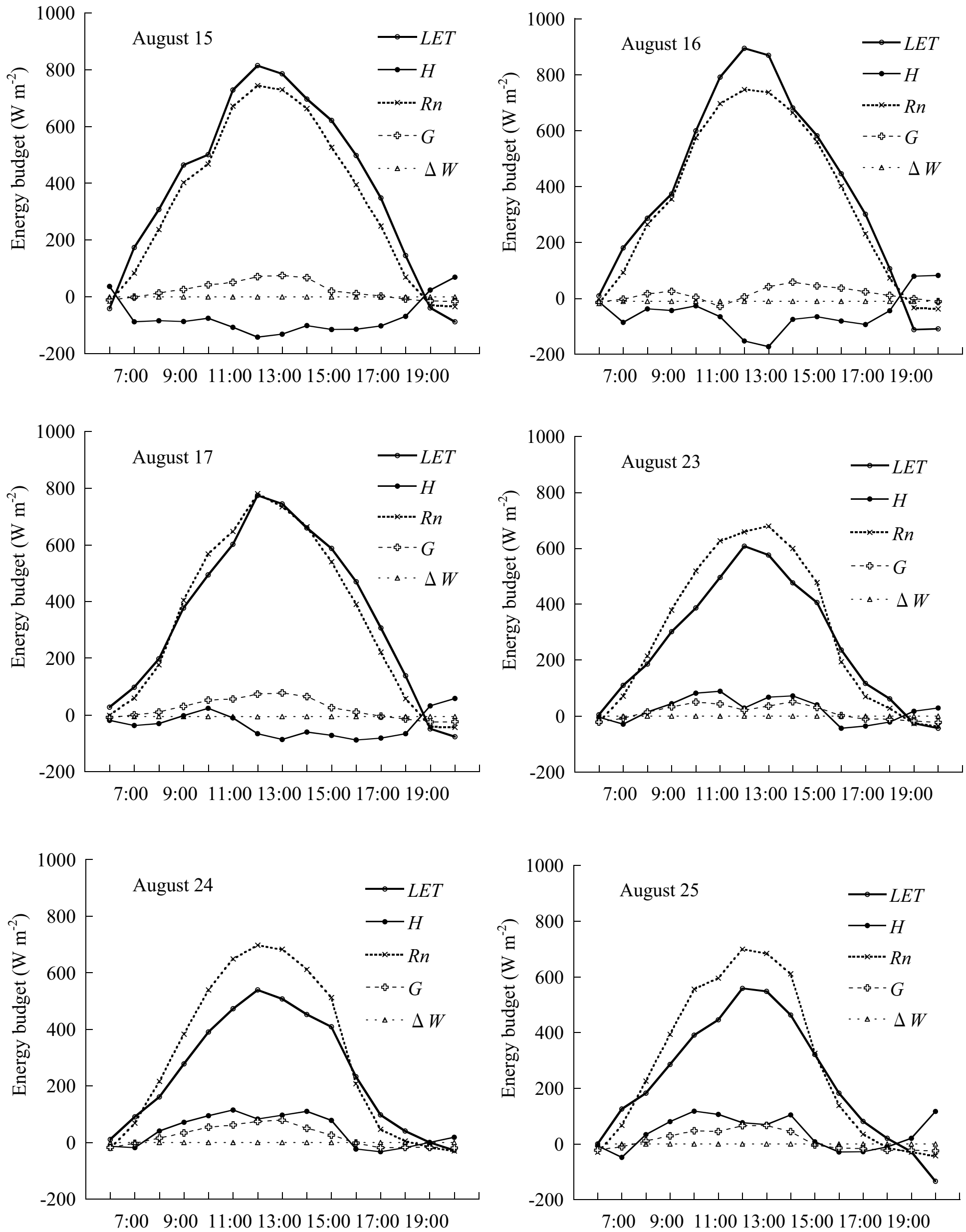


Fig. 3 (continued)



component of R_n varied from − 134.2 to 893.9 W m^{-2}, and the average ratio of LET to R_n was 58, 95, 110 and 83% for initial, developed, middle and late growing stages, respectively. Sensible heat flux was positive value and higher in the morning than in the afternoon in the initial growing stage of rice plant. The daytime maximum, minimum and average values were 388.5, − 24.1 and 90.9 W m^{-2}, respectively, and the ratio of H to R_n ranged from 16 to 35% in this stage. H tended to negative value in the developed and middle growing stages, and the daytime averaged value was − 11.9 and − 53.3 W m^{-2} for each stage. In the late season, H increased to positive values and the average value was 34.6 W m^{-2}. The average soil heat fluxes (G) were 56.2, 31.4, 18.9 and 14.5 W m^{-2} for initial, developed, middle and late growing stage of rice plant, respectively; the average ratio of G to R_n was 16, 9, 5 and 5% for each growing stage. The term ΔW was estimated from the temporal variation of water temperature and the water depth in paddy field, and the value of ΔW is very low and near to zero when the water depth was near to 0.

Computation of canopy and aerodynamic resistance

The comparison of canopy resistance r_c which was calculated from the bulk transfer equation (Eq. 8, $r_{c\ bulk}$) and the PM method (Eq. 9, $r_{c\ PM}$) is shown in Fig. 4. Both methods assume that exchanges of sensible and latent heat between the canopy and the atmosphere occur at a hypothetical plane,

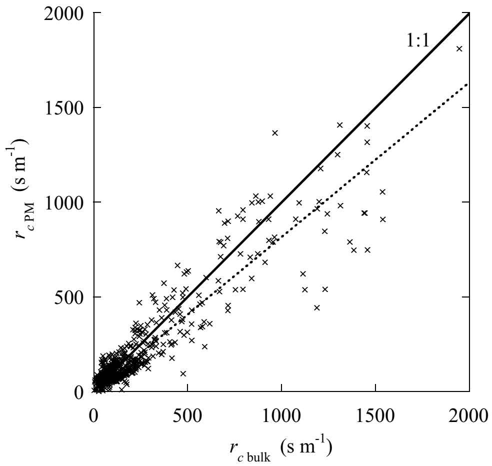


Fig. 4 Comparison of canopy resistance calculated by the Penman–Monteith ($r_{c\ PM}$) and bulk transfer equation ($r_{c\ bulk}$)

i.e., a single layer, located within the canopy. As shown in Fig. 4, the values of r_c estimated by each method are similar and highly correlated. The PM method provides a more practical approach because the canopy surface temperature is not needed. We analyzed the daytime variation of r_c estimated by the PM method below.

Yan et al. (2015b) presented the hourly variations of r_a and r_c in buckwheat and maize fields. In order to compare the difference of r_a and r_c among different fields, we show the hourly variations of r_a and r_c in paddy field which are obtained from Eqs. (6) and (9) in Fig. 5. We chose four typical clear days during the rice-growing period for analysis. Among these days, the maximum values of SR ranged from 888.3 to 951.1 W m^{-2}, and VPD ranged from 8.78 to 36.62 hPa. The values of r_a estimated by the classical logarithmic profile equations were higher in the morning, then decreased and tended to remain relatively constant from 10:00 to 19:00. Similar daily variation of r_a for grass and wheat was presented by Perez et al. (2006) and He et al. (2009), respectively. The values of r_a were higher in paddy rice field than in maize and buckwheat fields presented by Yan et al. (2015b) due to the higher wind speed in maize field in Inner Mongolia of China and in buckwheat-growing season.

Similar to the result presented by Yan et al. (2015b) for buckwheat and maize, the value of r_c in rice field is small and tends to remain relatively constant on average from 9:00

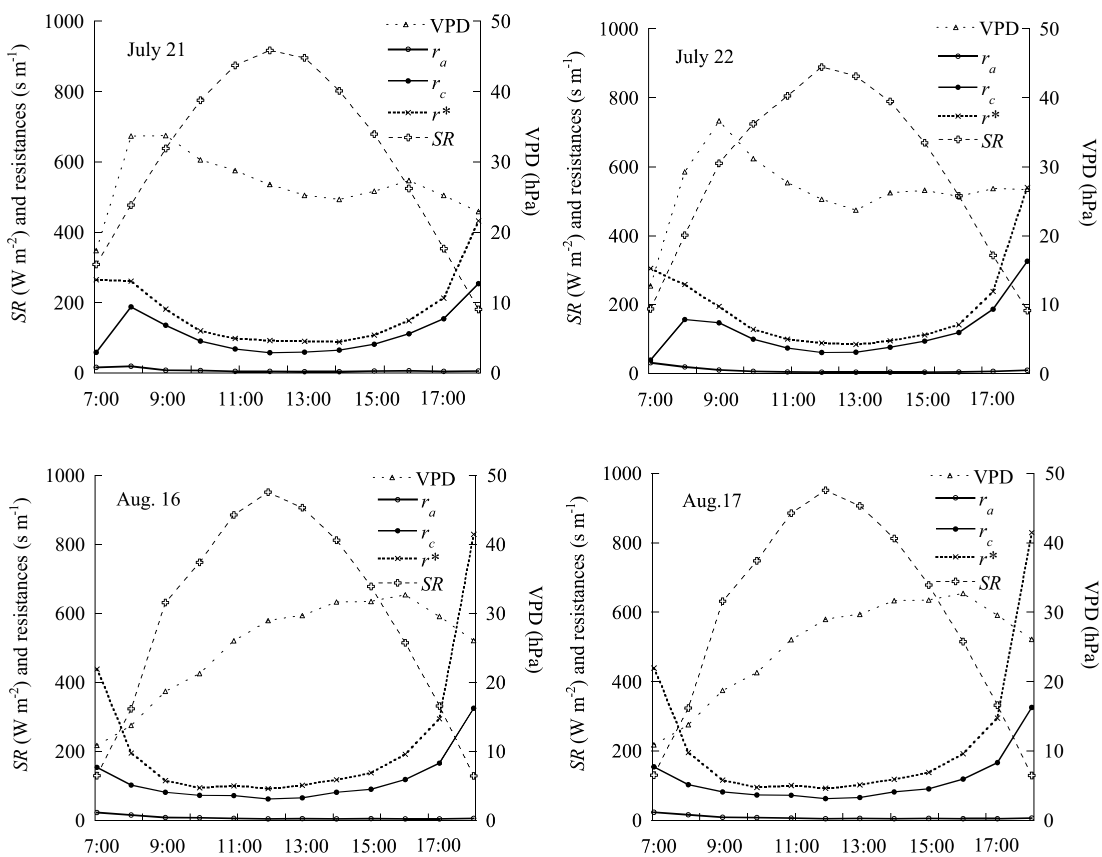


Fig. 5 Variations of aerodynamic resistance (r_a), canopy resistance (r_c), climatic resistance (r^*), SR and VPD at paddy rice field in four typical days (July 21–22, August 16–17)

to 14:00. Then, r_c tends to increase gradually in the afternoon. High VPD and r^* in the morning in July 21 and 22 might be the reason of higher r_c values in these days. In present study, we got same result that r_a was lower than r_c for all days. It has been mentioned but not validated in Yan et al. (2015b) that r_c has an indirect aerodynamic component although it is commonly assumed that it mainly represents a stomatal response (Alves et al. 1998). Alves and Pereira (2000) analyzed the relationship between r_c and r_a for net radiation larger than 500 W m^{-2} and VPD in the range of 1.5–2.0 kPa and found that r_c increases with the decrease in r_a, meaning that r_c increases with the increase in wind speed; namely high wind speed can lead to the closure of stomata. In this study, applying two methods for r_c, considering and without considering the influence of r_a on r_c, is to testify whether there is significant difference in modeling r_c between two methods.

Parameterization of canopy resistance with different approaches (r* and SR)

The diurnal variation of experimental values of $r_{c\,bulk}/r_a$ and $r_{c\,PM}/r_a$ versus r^*/r_a is shown in Fig. 6. $r_{c\,bulk}$ and $r_{c\,PM}$ represent r_c calculated by the bulk transfer and PM methods, respectively. Following Yan et al. (2015b), we analyzed the correlations between $r_{c\,bulk}/r_a$ and $(r^*/r_a)^{0.5}$, and between $r_{c\,PM}/r_a$ and $(r^*/r_a)^{0.5}$ by dividing the whole growing stage of rice into two categories: LAI < 1.5 and LAI ≥ 1.5. As shown in Eqs. (20)–(23), nonlinear relationships were obtained between r_c/r_a and $(r^*/r_a)^{0.5}$ for rice crop.

$$\frac{r_{cbulk}}{r_a} = 2.15 \times \frac{r^*}{r_a} - 7.85 \times \sqrt{\frac{r^*}{r_a}} + 13.6 \quad R = 0.91 \text{ for } LAI < 1.5 \tag{20}$$

$$\frac{r_{cbulk}}{r_a} = 0.16 \times \frac{r^*}{r_a} + 2.14 \times \sqrt{\frac{r^*}{r_a}} - 1.03 \quad R = 0.86 \text{ for } LAI \geq 1.5 \tag{21}$$

$$\frac{r_{cPM}}{r_a} = 0.81 \times \frac{r^*}{r_a} - 0.69 \times \sqrt{\frac{r^*}{r_a}} + 2.48 \quad R = 0.98 \text{ for } LAI < 1.5 \tag{22}$$

$$\frac{r_{cPM}}{r_a} = 0.11 \times \frac{r^*}{r_a} + 4.21 \times \sqrt{\frac{r^*}{r_a}} - 7.11 \quad R = 0.92 \text{ for } LAI \geq 1.5 \tag{23}$$

Although the similar relationships between r_c/r_a and $(r^*/r_a)^{0.5}$ were obtained for rice and buckwheat (Yan et al. 2015b), the coefficients a, b and c in Eq. (14) obtained in present study were completely different from the values in other studies (He et al. 2009: wheat field, 0.88, 0.82 and − 1.95; Yan et al. 2015b: buckwheat field, 0.73, 1.25 and − 0.28, and maize field, 3.09, 2.41 and 0.62). Farahani et al. (2007) and He et al. (2009) pointed out that the coefficients in Eqs. (20)–(23) change with hydrological and meteorological conditions, such as soil moisture, which is the main dominant factor for predicting LET (Yan et al. 2015b). Katerji and Perrier (1983) and Katerji and Rana (2006) presented linear relationship of r_c/r_a and r^*/r_a to calculate LET for alfalfa, sunflower, grain sorghum, grass and soybean. Alves and Pereira (2000) also presented a linear relationship of r_c/r_a and r^*/r_a to calculate LET for lettuce. Katerji and Rana (2006, 2008) used linear relationships between r_c/r_a and r^*/r_a observed on soybean, sweet sorghum and vineyard showed better correlation coefficients with values of 0.69, 0.92 and 0.78, respectively. Katerji et al. (2011) showed a linear relationship between r_c/r_a and r^*/r_a on grass with R equal to 0.77 which is lower than the results obtained in the present study with R higher than 0.86. Li et al. (2015) applied linear relationships of r_c/r_a and r^*/r_a to calculate

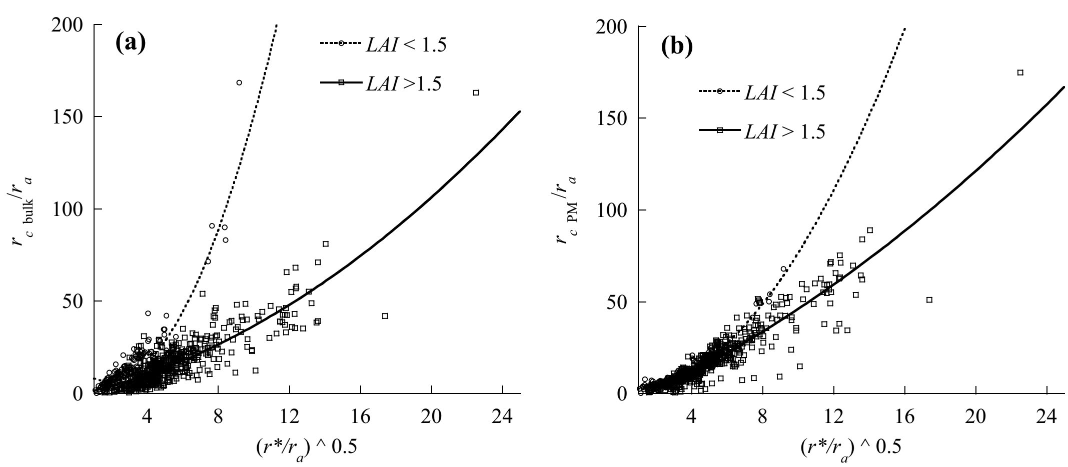


Fig. 6 Diurnal variation of experimental values of **a** $r_{c\,bulk}/r_a$ versus r^*/r_a, and **b** $r_{c\,PM}/r_a$ versus r^*/r_a on an hourly basis at paddy rice field, $r_{c\,bulk}$ and $r_{c\,PM}$ represent canopy resistance r_c calculated by the bulk transfer and Penman–Monteith methods, respectively

LET for maize and vineyard. Perez et al. (2006) presented two different linear relationships between r_c/r_a and r^*/r_a and between r_c/r_a and $(r^*/r_a)^{0.5}$ to calculate LET for grass. Although different types of relationships between r_c/r_a and r^*/r_a were obtained for different crops based on Katerji and Perrier (1983), according to Li et al. (2015) and Perez et al. (2006), the best performance and useful method for predicting LET is using the PM method by incorporating the r_c sub-model constructed by the relationship of r_c/r_a and r^*/r_a.

Another way of predicting r_c with SR and VPD, presented by Jarvis (1976), was also applied for comparison in this study. As shown in Fig. 7, we found high correlations between $r_{c\ bulk}$, $r_{c\ PM}$ and SR, but low correlations with VPD, so, we predicted $r_{c\ bulk}$ and $r_{c\ PM}$ with SR by dividing LAI into two categories (LAI < 1.5 and LAI ≥ 1.5) as

$$r_{cbulk} = 3.63 \times 10^4 \times \frac{1}{SR^{0.8336}} \quad R = 0.76\, for\, LAI < 1.5 \tag{24}$$

$$r_{cbulk} = 1.07 \times 10^4 \times \frac{1}{SR^{0.8101}} \quad R = 0.75\, for\, LAI \geq 1.5 \tag{25}$$

$$r_{cPM} = 3.58 \times 10^4 \times \frac{1}{SR^{0.8766}} \quad R = 0.89\, for\, LAI < 1.5 \tag{26}$$

$$r_{cPM} = 0.72 \times 10^4 \times \frac{1}{SR^{0.7111}} \quad R = 0.72\, for\, LAI \geq 1.5 \tag{27}$$

The variations of $r_{c\ bulk}$ and $r_{c\ PM}$ versus SR for different LAI periods are shown in Fig. 7. We found that both r_c calculated by the bulk transfer and PM methods had good correlations with SR.

Calculation of hourly LET by the bulk transfer and PM equations with r_c from different approaches

The LET of a rice field could be predicted with the bulk transfer and PM models by incorporating the two kinds of r_c sub-models (r_c estimated by r^* and r_c estimated by SR). Theoretically speaking, the constructed models should be validated using different data from the calibration of the models; however, due to the limitation of the study period, we applied data from the same season for the model validation in this study, and more validation of the constructed model will be done in the next step. The comparisons between measured and modeled LET by the bulk transfer and the PM methods with r_c from different approaches for rice are shown in Figs. 8 and 9. The bulk transfer method resulted in higher absolute errors at noon with both r_c sub-models (r_c estimated by r^* and r_c estimated by SR). The reason might be that r^* which was used to predict r_c was derived from the PM equation originally. In contrast, data in Fig. 9 showed good agreement between measured LET and modeled LET by the PM equation with both r_c estimated by r^* and SR. However, the agreement was improved by estimating r_c using r^* than by estimating r_c using SR. The reasons might not only be that r_c estimated by r^* has the advantage of taking into account the set of climatic variables affecting r_c (R_n, VPD), but also be r_c estimated by r^* takes into account the influence of r_a on r_c. The average absolute errors between measured LET and modeled LET by the PM equation with r_c estimated by r^* and SR were 55.9 and 63.6 W m^{-2}, respectively, while the errors between measured LET and modeled LET by the bulk transfer method with r_c estimated by r^* and SR were 118 W m^{-2} and 116 W m^{-2}, respectively. The relative errors between measured LET and modeled LET by the PM method with r_c estimated by r^* and SR were 20 and 22%,

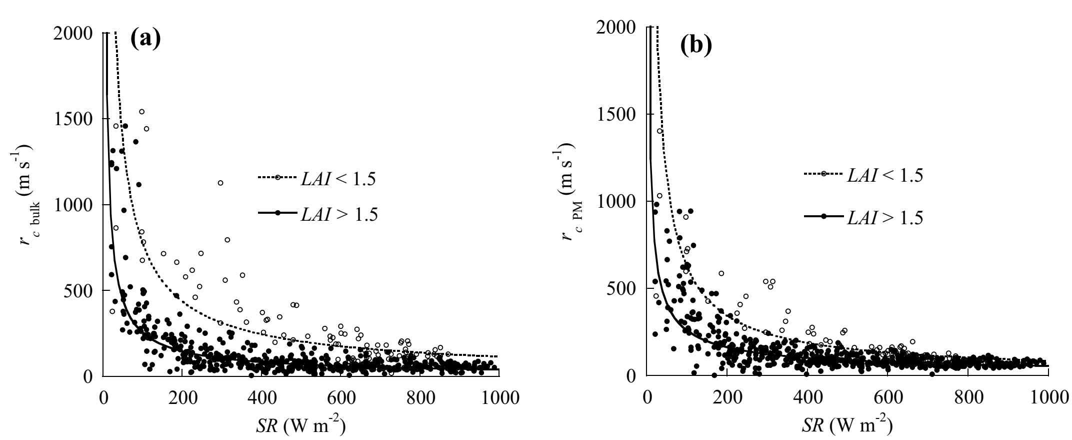


Fig. 7 Correlations of **a** $r_{c\ bulk}$ and SR **b** $r_{c\ PM}$ and SR in different rice-growing stages

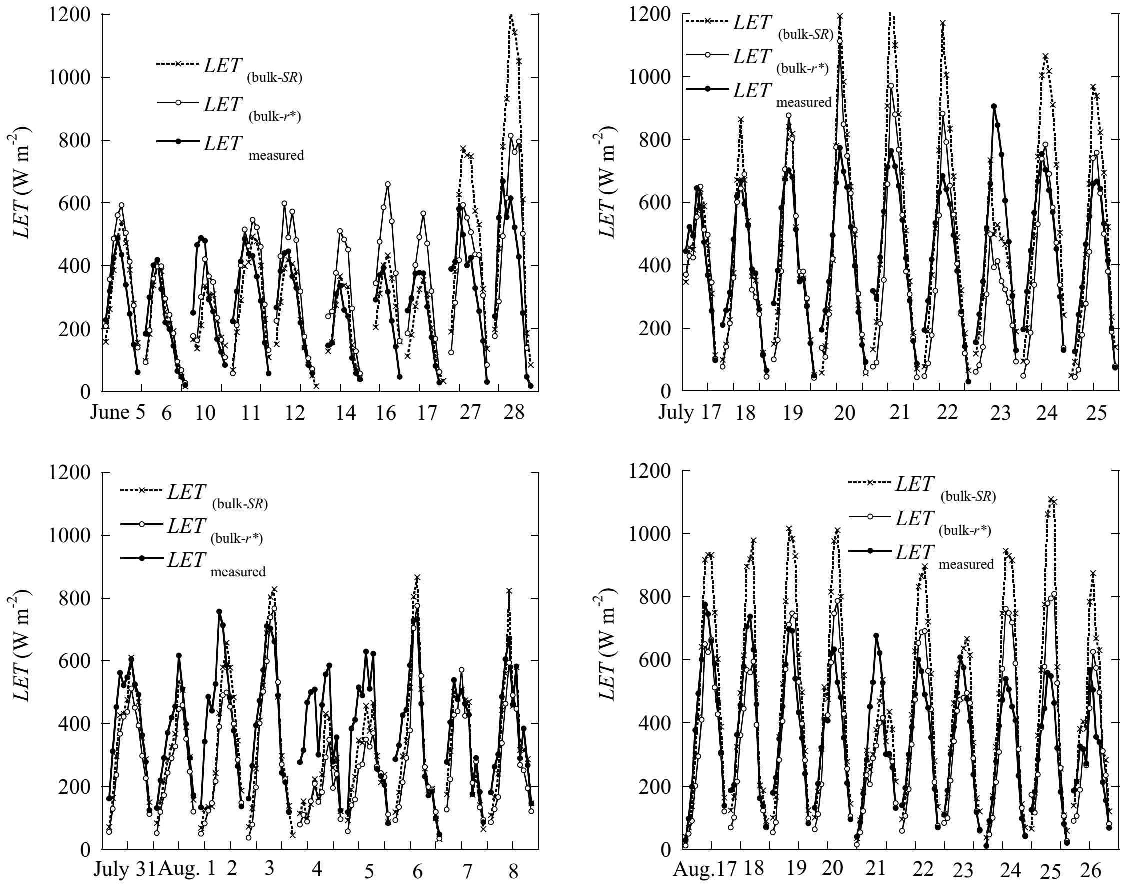


Fig. 8 Hourly variations of measured and modeled LET for paddy rice field; LET $_{(\text{bulk-SR})}$ represents LET calculated from the bulk transfer equation with canopy resistance modeled by SR, while LET $_{(\text{bulk-}r^*)}$ represents LET calculated from the bulk transfer equation with canopy resistance modeled by r^*, and LET $_{\text{measured}}$ represents LET measured by Bowen ratio–energy balance method

respectively, while the relative errors were 37 and 35% for the bulk transfer equation with r_c estimated by r^* and SR.

Figure 10b shows that there were high correlations between measured LET and predicted LET by the PM method with r_c estimated by r^* and SR. The coefficients of determination (R^2) were 0.92 and 0.89 for r_c estimated by r^* and SR, respectively. Figure 10a shows relatively low correlations between measured LET and predicted LET by the bulk transfer equation with r_c estimated by r^* and SR, and the coefficients of determination (R^2) were 0.55 and 0.62 for r_c estimated by r^* and SR, respectively. The other statistical parameters, such as systematic mean square errors (MSE_s), unsystematic mean square errors (MSE_u) and index of agreement (d), are shown in Table 1. The results showed that both methods could predict LET with relatively high accuracy, but the PM method provided better agreements with measured values, while the constraint of the application of the bulk transfer equation is that canopy surface temperature, which is needed in the equation, is difficult to accurately measure. The statistical analysis showed that there were no significant differences between measured and predicted LET for both the PM and bulk transfer equations with r_c estimated by r^* and SR. Although questioned by other researchers, this method was applicable in present paddy rice field study, even though the model did not consider the influence of an aerodynamic component on r_c. However, the resulting coefficients for Eqs. (20)–(27) in the present study still need validation based on data in different climates.

Applicability of methods

As indicated in the above results, the PM model performed better compared with the bulk transfer method using r_c estimated either by r^* or by SR. Other researchers (Rana et al. 1994; Katerji et al. 2011; Yan et al. 2012b) also presented that the PM model performed best if r_c could be predicted accurately. Li et al. (2015) pointed out that many r_c models may not be suitable for predicting LET over the entire growth stage in arid regions. In our study, we developed r_c models by dividing the rice-growing season into two stages based on our experimental data aggregated

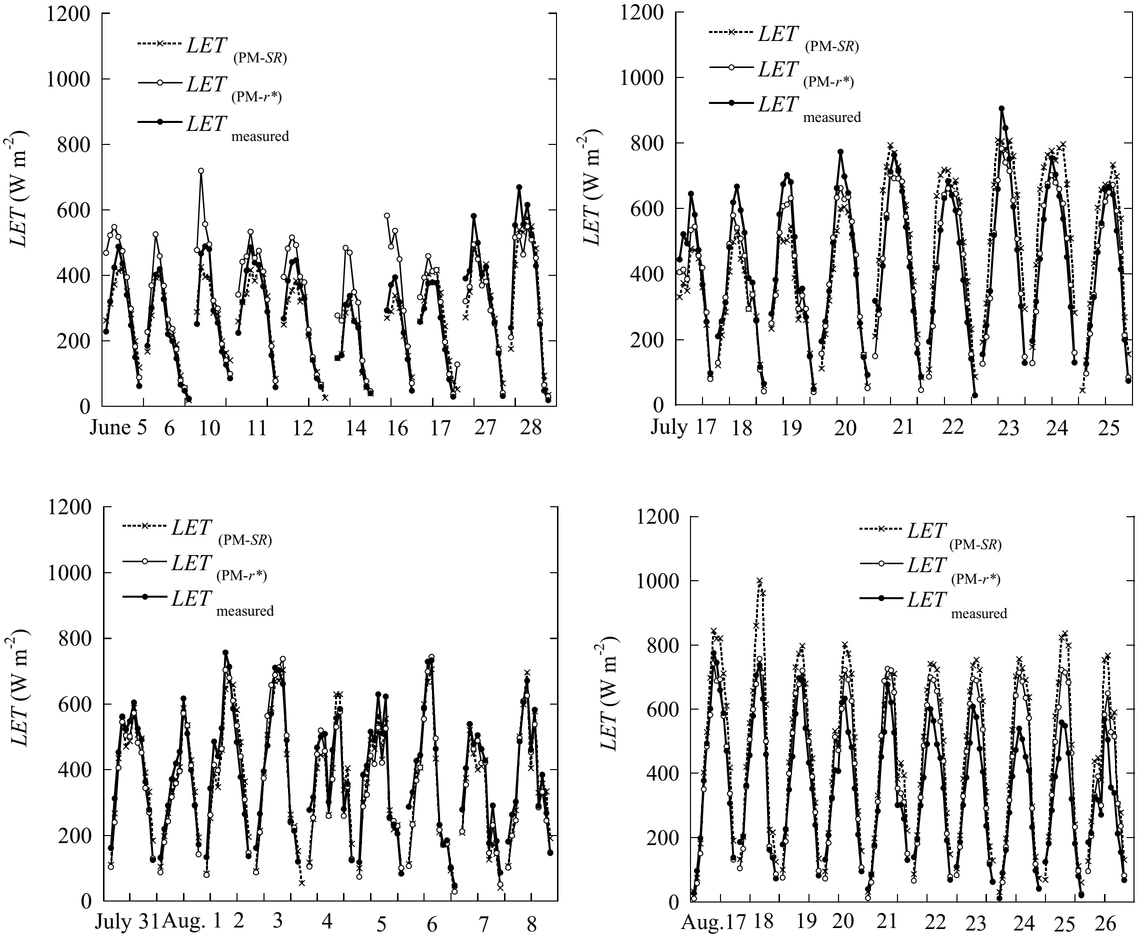


Fig. 9 Hourly variations of measured and modeled LET for paddy rice field; $LET_{(PM\text{-}SR)}$ represents LET calculated from the Penman–Monteith equation with canopy resistance modeled by SR, while $LET_{(PM\text{-}r^*)}$ represents LET calculated from the Penman–Monteith equation with canopy resistance modeled by r^*, and $LET_{measured}$ represents LET measured by Bowen ratio–energy balance method

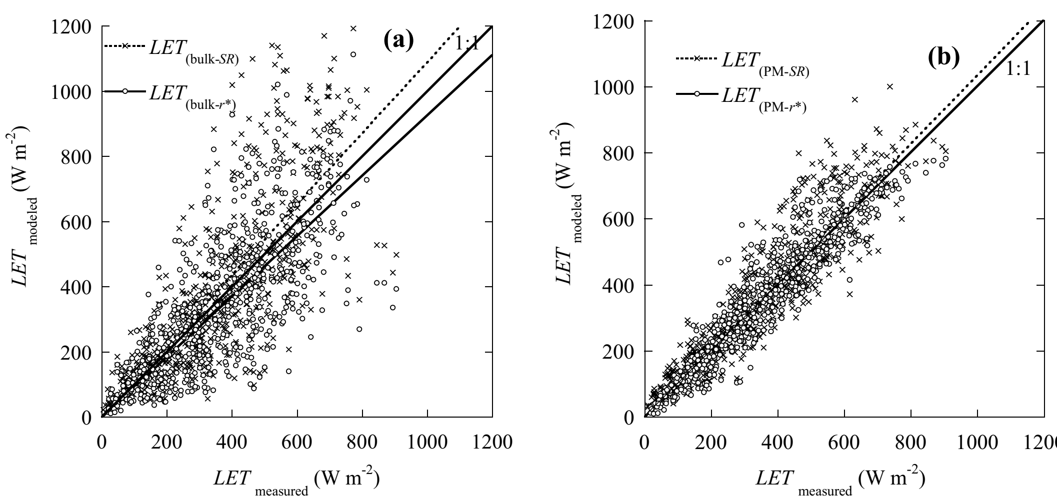


Fig. 10 Comparisons of **a** measured LET and modeled LET by the bulk transfer equation with canopy resistance from SR and r^* of rice paddy field, **b** measured LET and modeled LET by the Penman–Monteith equation with canopy resistance from SR and r^* of rice paddy field

Table 1 Error analysis statistics of the comparison between measured LET and predicted LET by the bulk transfer and the PM methods with r_c estimated by r^* and SR sub-models for rice

		P	M	a	R^2	RMSE	MSE_s	MSE_u	d
Bulk transfer method	r_c estimated by r^*	339.9	355.2	1.09	0.55	155.2	29.4	151.7	0.85
	r_c estimated by SR	386.3	355.2	1.04	0.62	170.5	36.3	166.5	0.85
PM method	r_c estimated by r^*	367.7	355.2	1.00	0.92	87.4	0.40	87.4	0.95
	r_c estimated by SR	371.5	355.2	0.93	0.89	85.7	16.1	84.5	0.95

* P and M are mean predicted and measured LET (W m^{-2}), respectively; a is slope of least square regression line; R^2 is coefficients of determination, RMSE is root mean square error; MSE_s is systematic mean square error; MSE_u is unsystematic mean square error; d is index of agreement; b, R^2 and d are dimensionless

to an hourly scale. The results indicated that LET could be predicted by the PM model by combining the r_c sub-models with the RMSE and the index of agreement equal to 87.4 W m^{-2} and 0.95, respectively. On the other hand, Katerji et al. (2011) presented that neglection of the effect of r_a on r_c would yield big differences in the prediction of LET. However, we only found slight difference in predicting LET when we predicted r_c by SR without considering the effect of r_a, e.g., the RMSE is equal to 87.4 and 85.7 W m^{-2} by the PM model with r_c estimated by r^* (the effect of r_a was considered) and as a function of SR (the effect of r_a wasn't considered), respectively, the index of agreement is equal to 0.95 for both case. Difference in results from other researchers may be due to the differences in climate, semiarid as compared with our humid climate or plant status, i.e., conditions of water stress as compared with present study where the paddy rice field consistently had a high water content.

Traditionally speaking, the bulk transfer method should result in accurate LET if accurate surface temperature measurements are made (Yan et al. 2012b); however, the results obtained in this study were different with either r_c estimated by r^* or as a function of SR; we confirmed that the surface temperature which was used in the bulk transfer equation was measured properly and accurately in this study. It could be deduced that r_c estimated by r^* or by SR might not be suitable to be integrated into the bulk transfer equation for prediction of LET. One disadvantage of using the bulk transfer method is that the surface temperature, the main parameter of the model, was difficult to measure in practice.

Finally, the simple empirical r_c sub-models, constructed in this study, were limited to the calibrations based on climatic, vegetative and soil conditions for a specific site. However, it would be a simple, relatively accurate and easily applied way for predicting LET for the entire growth season of rice plant compared to the mechanistic method which does not need specific calibration, such as Todorovic r_c model (Todorovic 1999). Shi et al. (2008) concluded that the Todorovic r_c model overestimated LET by about 30%. Katerji et al. (2011) presented that the Todorovic r_c model underestimated LET and the observed slope between measured and calculated values of LET for the grass canopy was 0.79, while the result obtained in this study is ranged from 0.93 to 1.09. Pauwels and Samson (2006) indicated that the Todorovic r_c model was not able to estimate r_c in the conditions of their study.

Conclusion

In this study, the PM and the bulk transfer methods were applied to predict the LET in a paddy rice field by combining two different r_c sub-models. The r_c computed by the PM and the bulk transfer equation were compared and found there was good agreement between two methods. The r_c was parameterized by a climatic resistance r^* with polynomial relationships and also parameterized with power functions of SR for different growing stages of paddy rice plant. The r_c sub-models were integrated into the PM and the bulk transfer model for predicting hourly LET, and the accuracy was compared with measured LET by Bowen ratio–energy balance method. It can be concluded that: (1) The PM model provided better estimates of measured *LET* than the bulk transfer method with constructed r_c sub-models, (2) neglecting the effect of aerodynamic resistance on r_c did not make significant difference in prediction of *LET* although r_a was considered as part of r_c theoretically, and (3) simple empirical r_c sub-model combined with the PM model would be an easy, alternative and priority way for predicting the LET in the similar climatic areas (semi-humid and maximum SR near to 1000 W m^{-2}), although more assessments need to be done for the application of the models for other plants and areas.

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Authors' contributions Haofang Yan, first author, contributed to conception and design, acquisition of data, analysis and interpretation of data, drafting the manuscript and revising it critically for important intellectual content, final approval of the version to be published. Chuan Zhang contributed to conception and design, acquisition of data, participated sufficiently in the work and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Oue Hiroki contributed to conception and design, acquisition of data and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest

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