Temporal Upscaling of Rice Evapotranspiration Based on Canopy Resistance in a Water-Saving Irrigated Rice Field

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ABSTRACT

An important element of the hydrologic cycle, the hydrometeorological parameter of evapotranspiration (ET), is critical in the development of effective water resources planning and irrigation scheduling. The ET varies in response to changes in resistance at the canopy surface r_c and soil moisture content θ , especially under water-saving irrigation (WSI) practices. Drawing on data collected by eddy covariance in WSI rice paddies in eastern China in 2015 and 2016, variations in ET were studied by calculating and analyzing hourly canopy resistance r_c^h and daily canopy resistance r_c^d . Discrepancies were noted between true daily ET (ET_{tr}^d) with respect to the estimated daily ET (ET_{rc}^d) at different periods [0700–1600 local time (UTC + 8)]. To estimate ET_{rc}^d in the WSI rice fields, the mean r_c^h value between 0900 and 1000 LT, and between 1000 and 1100 LT performed considerably better than r_c^h for a single time. Seasonal estimated ET (ET_{rc}^s) can be accurately calculated by interpolating r_c^d at different time intervals, thereby achieving a greater correlation and consistency at 2-day intervals. Then a generalized two-segment line of r_c^d variation was used to calculate ET_{rc}^s , achieving good results and showing that in the absence of observational data, ET_{rc}^s could be easily calculated through a simplified pattern of variability. In conclusion, an ET temporal upscaling method for a WSI paddy, based on variation in r_c^h and r_c^d values, was optimized and is recommended for local application. Future work will focus on temporal upscaling of ET by extrapolating remote sensing instantaneous estimates to daily values.

1. Introduction

Showing great temporal variability, evapotranspiration (ET), a key process in the hydrological cycle, serves as an important link between underlying surface and near-surface turbulence dynamics (Kalma and Calder 1994; Kalma et al. 2008; Wang and Dickinson 2012; Jiang et al. 2016). Key to studying a wide range of ecosystems (Valentijn et al. 2006; Cleugh et al. 2007; Katerji and Rana 2006), ET must be accurately determined at different temporal scales to properly assess an ecosystem's energy balance (Liu et al. 2017) or to improve an agroecosystem's water management protocols (Kang et al. 2003;

Mu et al. 2011). Variations in meteorological conditions and crop physiology traits result in a significant temporal variation in ET and energy balance (Farah et al. 2004; Gentine et al. 2007). Finding that ET in wheat (*Triticum aestivum* L.) fields varied significantly across temporal scales, Gentine et al. (2007) noted that canopy coverage and soil moisture content θ were key factors in estimating daily ET (ET^d) from hourly ET (ET^h) data. Guo et al. (2014) suggested that net radiation strongly affected both diurnal variation in ET^h and seasonal variation in ET^d , whereas vapor pressure deficit solely and strongly affected ET^h . In practice, agricultural water management and hydrometeorological studies generally require ET at daily or longer time scales (Farah et al. 2004; Colaizzi et al. 2006; Tang et al. 2015). However, for

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large regions and long-term monitoring, ET measurements are labor-intensive and require a large investment in equipment, making the acquisition of accurate daily regional- or global-scale ET estimates a challenge. Remote sensing, which can cope with the spatial variability of surface characteristics, is an ideal tool for acquiring instantaneous spatial ET data at the regional scale, especially in regions with nonhomogeneous vegetation cover and a complex terrain (Verstraeten et al. 2005; Allen et al. 2007; Chowdary et al. 2009). However, as remote sensing only provides primary instantaneous estimates of ET, methods to extrapolate ET^d from instantaneous remote sensing observations are needed.

Several methods, including the evaporative fraction method, crop coefficient method, canopy resistance method, Katerji–Perrier, advection-aridity method, and daily sine function, can be used to estimate ET^d , based on the assumption that the diurnal course of ET is similar to that of solar irradiance (Shuttleworth 1989; Malek et al. 1992; Zhang and Lemeur 1995; Colaizzi et al. 2006; Allen et al. 2007; Hoedjes et al. 2008; Han et al. 2011; Chen et al. 2013). Shuttleworth (1989) was the first to note that the evaporation fraction, defined as the ratio between latent heat flux and available energy ($R_n - G$, where R_n is the net radiation and G is the ground heat flux), was constant over a certain period of the day in clear weather, and that the evaporation fraction at noon was close to the daily average. An ET conversion method from ET^h to ET^d was established with the evaporation fraction as an intermediate variable (Zhang and Lemeur 1995; Hoedjes et al. 2008). Allen et al. (2007) extrapolated ET^h to ET^d using the crop coefficient as an intermediate variable. With canopy resistance as the intermediate variable, ET^d was estimated based on ET^h by Liu et al. (2012) in Australia. However, these methods have different applicabilities and strengths given their different theoretical foundations and supportive research.

The canopy resistance r_c method, involving the determination of crop-specific r_c according to theories of energy balance and aerodynamics applied at different temporal scales, allows a rational upscaling of ET for various crops. In quantitative analysis, the r_c value reflects the variation in canopy conditions and represents critical controls on heat and vapor flux transfer through the soil–plant–atmosphere continuum (SPAC) system within the canopy (Finnigan et al. 2003). The ET exhibits its specific variations in response to changes in r_c at the canopy surface (Ershadi et al. 2015; Xu et al. 2017). Accordingly, studying variations in r_c can provide insights into changes in crop ET. The variability in underlying surface and climate conditions has largely precluded the development of an apparatus or method

for the direct measurement of r_c at crop surfaces. However, r_c can be inversed from results of latent and sensible heat fluxes, radiation balance, and some other relevant variables using the Penman–Monteith (PM) equation (Oue 2005; Katerji et al. 2011). Most studies which have employed r_c in achieving a temporal upscaling of ET have been reported for upland crops (Rana et al. 1997; Lecina et al. 2003; Yan et al. 2015), and have played an important role in exploring temporal variability in ET. Liu et al. (2012) was the first to try to upscale daytime ET^h [1200–1300 local time (LT; UTC + 8)] to ET^d , with r_c as an intermediate variable, doing so for corn (*Zea mays* L.) and canola (*Brassica napus* L.). Yet, the specific time for ET^h measurement which works the best for daily ET estimation is different across sites due to differences in the underlying surface or microclimatic conditions.

Rice (*Oryza sativa* L.) is the main cereal crop cultivated in China, particularly in the middle and lower reaches of the Yangtze River, which is the largest rice belt in China (Ding et al. 2017). The area planted to rice in this region, and rice extends over roughly 20×10^6 ha, accounting for about 50% of the nation's rice cropping area (Ministry of Water Resources of China 2016). Impact assessments under different future climate scenarios show solar radiation to be gradually decreasing as is the availability of water resources for rice in south China (Tao et al. 2013; Yang et al. 2014). Seriously challenges of food security and global water scarcity are motivating regulators to adopt water-saving irrigation (WSI) practices for rice cultivation (Belder et al. 2004; Kato et al. 2011). Extensive use of WSI is the inevitable choice of agricultural development in China, and it is also an important in fulfilling rules of “water-saving priority” for water resources management in China. Meanwhile, the widespread implementation of WSI results in changes in energy interception, θ , and crop growth, as well as heat and vapor flux transfer within the rice canopy (Gao et al. 2003; Castellvi et al. 2006; Linquist et al. 2015). Yet information regarding the energy balance and aerodynamics, as well as changes in r_c in WSI rice fields, remains unclear. Accordingly, whether a method performs well or not in estimating rice ET should be assessed, as is the selection of the most representative time for r_c^h .

Therefore, the objectives of this study were 1) to explore the diurnal variation (during daytime) of r_c for WSI rice; 2) to estimate daily ET (ET_r^d) from r_c^h as an intermediate variable; 3) to select an appropriate time interval for estimating seasonal ET (ET^s) based on daily canopy resistance r_c^d ; 4) to propose a generalized seasonal process of r_c for the estimation of ET_r^s in rice paddies subjected to WSI practice in east China. The results will

TABLE 1. Irrigation records in WSI rice field in 2015 and 2016.

Growth stages	2015		2016	
	Date	Irrigation amount (mm)	Date	Irrigation amount (mm)
Paddy preparation	23 Jun	118.0	28 Jun	115
Regreening	—	—	6 Jul	35
Tillering	5 Jul	30.4	8 Jul	39.5
	25 Jul	70.2	18 Jul	52.5
	—	—	22 Jul	52
	—	—	28 Jul	41.9
	—	—	9 Aug	45.5
Jointing–booting	9 Aug	48.1	—	—
	3 Sep	38.6	—	—
Heading–flowering	7 Sep	46.3	5 Sep	37
Milk stage	16 Sep	43.2	—	—
Full rice season	—	394.9	—	418.4

facilitate the application of the proposed r_c upscaling procedure in agriculture and hydrometeorology for estimating ET^d at regional scale over WSI rice field from remote sensing data.

2. Materials and methods

a. Site description and field management

Field measurements were conducted during rice seasons in 2015 and 2016 at the Kunshan Irrigation and Drainage Experiment Station (latitude $31^{\circ}15'15''N$, longitude $120^{\circ}57'43''E$), situated in China's Tai Lake region. This area is subject to a subtropical monsoon climate bringing $1097.1 \text{ mm yr}^{-1}$ in precipitation and generating potential evaporation (measured by an E601 evaporation pan) of $1365.9 \text{ mm yr}^{-1}$. The mean daily temperature T_a and relative humidity (RH) were 24.6°C and 81.5% during rice season, respectively. The volumetric saturated soil moisture θ_s , field capacity θ_f , and wilting point θ_w were 0.502 , 0.392 , and $0.179 \text{ m}^3 \text{ m}^{-3}$, respectively. Rice seedlings, at interrow and intrarow spacings of 0.23 and 0.16 m , respectively, were transplanted to the field on 27 June 2015 and 1 July 2016. The rice was irrigated when the soil moisture approached a threshold, according to local WSI practices. These varied according to the crop's phenological stage (Xu et al. 2012). Detailed records of irrigation events are presented in Table 1. Fertilizers and pesticides were applied to the WSI rice field according to the local farming practice.

An open-path eddy covariance (EC) system was installed at the site to measure the water and heat fluxes over flat rice fields with a fetch of about 200 m in all directions. Rice is the unique crop at the station, and is short and of consistent height. The EC system, which was aligned perpendicular to the prevailing southeast

wind direction, was made up of a CSAT3A sonic anemometer (Campbell Scientific Inc., United States) and an EC150 open-path infrared gas analyzer (Campbell Scientific Inc., United States) operating at a frequency of 10 Hz , both installed 2.5 m above the soil surface. To ensure the quality and integrity of meteorological data, an EC system and an automatic meteorological station (WS-STD1, DELTA-T, United Kingdom) were employed to measure net radiation R_n , air temperature T_a , wind speed u , atmospheric pressure P_a , precipitation P , soil heat flux G_s , volumetric θ , and soil temperature T_s (measured at depths of 0.10 , 0.20 , and 0.30 m).

To trigger irrigation, the θ of the 0 – 0.20-m soil layer was measured daily (when soil was not flooded) at 0800 LT , using time domain reflectometry (TDR; Trase system, Soil Moisture Equipment, United States) and buried waveguides. The soil saturation level θ_r (as the ratio of θ and θ_s), water depth Δd , and wetting–drying cycles, as influenced by irrigation and precipitation events in WSI fields in 2015 and 2016, are depicted in Fig. 1. Canopy height h and leaf area index (LAI) were measured for 20 specific plants at 5-day intervals. Daily h and LAI were determined by linear interpolation (Fig. 2).

Rice ET at canopy and field scales were measured independently by weighing microlysimeters (ET_{ML}) and EC system (ET_{EC}). Three weighing microlysimeters were installed in the WSI rice field, and used to measure hourly ET_{ML} (ET_{ML}^h) based on the hourly mass change. The configuration and location of the lysimeters and the method of ET_{ML} measurement were described in greater detail in Liu et al. (2018a). In our previous work, slight differences were found in both amplitude and phase between ET_{ML} and ET_{EC} because of a spatial scale effect (Liu et al. 2018a). A relationship was developed between measured ET_{ML} and ET_{EC} values, such that field scale ET could be calculated from ET

FIG. 1. Variation of soil moisture conditions and corresponding precipitation P and irrigation I under water-saving irrigation during the rice cropping seasons of (a) 2015 and (b) 2016 (θ_r and Δd represent soil saturation level and water depth, respectively).

measured at the canopy scale, and termed ET_{tr} in the present study. In conclusion, measured ET_{EC} values served to compute canopy resistance by the PM equation, and the ET_{tr} calculated from measured ET_{ML} values were used as the true ET, compared with the estimated value, to evaluate the performance of the ET upscaling method.

b. Data analysis and quality control of the EC system

For the data quality control of the EC measurement, raw data (10 Hz) were processed by EdiRe, and necessary corrections (e.g., coordinate rotation via 2D rotation, sonic virtual temperature conversion for sensible heat flux, density fluctuation correction for latent heat

flux, spectral loss correction, and spike detection) were implemented following procedures outlined in the literature (Anthoni et al. 2004; Mauder et al. 2006; Ueyama et al. 2012; Masseroni et al. 2013). Flux data were averaged in 30-min blocks. The prevailing wind in the rice growing season is a southeast trade. The source area was estimated based on procedures and parameters selected based on the results of Kljun et al. (2004), along with atmospheric conditions and wind directions (Aubinet et al. 2012). Fluxes were discarded when the calculated footprint was beyond the edge of the study area of WSI paddy field (Masseroni et al. 2012). When the observations exceeded the mean value by more than threefold the standard deviation, it was labeled a

FIG. 2. Variation of (a) canopy height h and (b) leaf area index (LAI) under water-saving irrigation in rice, for the 2015 and 2016 seasons.

spike (Falge et al. 2001a). Likewise, values measured during or within one hour before or after precipitation events were excluded (Anderson and Wang 2014). Flux data were filtered when the friction velocity u^* was lower than a threshold of 0.1 m s^{-1} (Anthoni et al. 2004). Finally, the missing flux date, accounting for approximately 22% over the whole rice season from 2015 to 2016, were determined by linear interpolation (for lacunae $\leq 3 \text{ h}$) or, for long data gaps, by a mean diurnal average method within a 10-day window (Falge et al. 2001b).

To improve the energy balance for EC measurement in the rice field, surface soil heat flux G_0 was calculated based on G_s —measured by heat flux plates buried at a depth of 0.08 m—by integrating the soil heat storage Q in soil above the soil heat flux plate, calculated on the basis of soil temperature and moisture data (Meyers and Hollinger 2004; Liu et al. 2017). The daily energy balance ratio (EBR), calculated by using the corrected fluxes, averaged 0.93 and 0.85 in the 2015 and 2016 rice seasons, respectively. Any energy gap is entirely related to the underestimation of sensible and latent heat fluxes (Wilson et al. 2002;

Foken 2008; Foken et al. 2011). The energy balance was closed through the evaporative fraction (EF) method (Gebler et al. 2015). The estimated EF values during the 2015 and 2016 rice cultivation seasons are shown in Fig. 3. Then, after the energy balance closure correction, the latent flux (LE) assessed over 30-min intervals and then used to calculate rice ET (Chávez et al. 2009; Gebler et al. 2015).

c. Method for temporal upscaling

1) HOURLY-TO-DAILY UPSCALING

To estimate the ET_{rc}^d based on field measurement at a specific hour, with r_c^h as an intermediate variable, Eq. (1) was used to calculate the daytime hourly r_c^h for 0700–0800, 0800–0900, 0900–1000, 1000–1100, 1100–1200, 1200–1300, 1300–1400, 1400–1500, and 1500–1600 LT (UTC + 8) based on hourly ET_{EC} and meteorological variables. Then, the hourly ET_{EC}^h measurement at each specific hour was extended to a daily scale through the canopy resistance method, using daily meteorological data [Eq. (2)] (Malek et al. 1992; Liu et al. 2011):

FIG. 3. Variation of evaporative fraction (EF) under water-saving irrigation in the 2015 and 2016 rice seasons.

$$r_c^h = \frac{r_a^h \left[\frac{\Delta^h (R_n^h - G_0^h) + \rho^h C_p (e_s^h - e_a^h)}{r_c^h - \lambda^h \text{ET}_{\text{EC}}^h (\Delta^h + \gamma^h)} \right]}{\gamma^h \lambda^h \text{ET}_{\text{EC}}^h}, \quad (1)$$

$$\lambda^d \text{ET}_{r_c}^d = \frac{\frac{\Delta^d (R_n^d - G_0^d) + \rho^d C_p (e_s^d - e_a^d)}{r_a^d}}{\Delta^d + \gamma^d \left(1 + \frac{r_c^h}{r_c^d} \right)}, \quad (2)$$

where d and h as superscripted letters indicate the parameter's daily- and hourly-averaged values, respectively; e_a is the actual vapor pressure (kPa); e_s is the saturation and vapor pressure (kPa), where $e_s - e_a$ is the vapor pressure deficit (VPD); r_a is the aerodynamic resistance of water vapor transfer from the surface to ambient air (m s^{-1}); r_c is the canopy resistance of water vapor transfer from the surface to ambient air (m s^{-1}); C_p is the specific heat capacity of air, $C_p = 1.013 \times 10^{-3} \text{ MJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$; ET_{EC} is the evapotranspiration measured by systems (mm); ET_{ML} is the evapotranspiration measured by microlysimeters (mm); $\text{ET}_{r_c}^d$ is the daily evapotranspiration (mm) estimated by upscaling; G_0 is surface soil heat flux ($\text{MJ m}^{-2} \text{ s}^{-1}$), where $G_0 = G_s + Q$, with G_s being the soil heat flux measured at 0.80 m beneath the soil surface and Q being the change in soil heat storage in the 0–0.80-m surface soil layer; P is the atmospheric pressure (kPa); R_n is net radiation ($\text{MJ m}^{-2} \text{ s}^{-1}$); T_a is the average temperature ($^\circ\text{C}$); γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), $\gamma = 0.00163 P/\lambda$; λ is the latent flux of heat (MJ kg^{-1}), $\lambda = 2.501 - (2.361 \times 10^{-3})T_a$; ρ is the density of dry air (kg m^{-3}); and Δ is the slope of the saturation-to-vapor pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$).

Assuming that samples passing quality control were generally near neutral atmospheric stability, the aerodynamic resistance r_a is calculated at either an hourly r_a^h or daily r_a^d time scale, based on hourly or daily average wind speeds [Eq. (3)] (Alves et al. 1998):

$$r_a = \frac{\ln \frac{z_m - d}{z_{0m}} \ln \frac{z_h - d}{z_{0h}}}{k^2 u} \quad (3)$$

where d is zero-plane displacement height (m), with $d = 0.63h$; h is the rice canopy height (m); k is von Kármán's constant (0.41); u is wind speed at 2.5 m above the soil surface (m s^{-1}); z_h is the height of relative humidity measurements (m); z_m is the height of wind measurements (2.5 m in the EC system); z_{0h} is the roughness length governing transfer of heat and vapor (m), $z_{0h} = 0.1z_{0m}$; and z_{0m} is roughness length governing momentum transfer (m), $z_{0m} = 0.123h$.

2) THE DAILY-TO-SEASONAL UPSCALING

In both 2015 and 2016, Eq. (4) was used to calculate the r_c^d at sparse specific days based on $\text{ET}_{r_c}^d$ measured by EC (ET_{EC}^d) after energy balance correction, along with meteorological variables of rice growth period. For days without ET_{EC}^d measurements, r_c^d was calculated by linear interpolation between two adjacent known values of r_c^d , prior to $\text{ET}_{r_c}^d$ being calculated according to r_c^d and daily meteorological data. Assuming ET_{EC}^d to be measured at intervals of 2, 5, 10, 15, and 20 days, r_c^d values on these days were calculated first, and then for days without ET_{EC}^d measurement r_c^d values were interpolated. In the end, $\text{ET}_{r_c}^d$ values over the full rice growing season were estimated and averaged as seasonal average daily ET (ET_{EC}^s) by Eq. (5) (Malek et al. 1992; Liu et al. 2011):

$$r_c^d = \frac{r_a^d [\Delta^d (R_n^d - G_0^d) + \rho^d C_p (e_s^d - e_a^d)]}{r_a^d - \lambda^d \text{ET}_{\text{EC}}^d (\Delta^d + \gamma^d)} \quad (4)$$

$$\text{ET}_{r_c}^s = \frac{1}{\lambda^s m} \sum_{k=1}^{k=m} \left[\frac{\frac{\Delta_k^d (R_{n_k}^d - G_{0_k}^d) + \rho_k^d C_{p_k} (e_{s_k}^d - e_{a_k}^d)}{r_{a_k}^d}}{\Delta_k^d + \gamma_k^d \left(1 + \frac{r_{c_k}^d}{r_{a_k}^d} \right)} \right], \quad (5)$$

where k represents the day of the season; m is the total number of days in the season; s and h superscripted letters indicate the parameter's seasonal- and daily averaged values, respectively; and ET_{rc}^s is the calculated seasonal average daily value during the rice growing season (mm day^{-1}).

d. Statistical analysis

The ET_{tr} calculated from the measured ET_{ML} values were used as the true ET, to compare with estimated upscaling value. Linear regression slope, coefficient of determination (R^2), root-mean-square error (RMSE), and index of agreement (IOA) were used to assess the performance of the temporal upscaling method, and reveal the agreement between the estimated and true ET:

$$R^2 = \frac{\left[\sum_{i=1}^{i=n} (O_i - \bar{O})(P_i - \bar{P}) \right]^2}{\left[\sum_{i=1}^{i=n} (O_i - \bar{O})^2 \sum_{i=1}^{i=n} (P_i - \bar{P})^2 \right]}, \quad (6)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{i=n} (P_i - O_i)^2}{N}}, \quad (7)$$

$$\text{IOA} = 1 - \frac{\sum_{i=1}^{i=n} (P_i - O_i)^2}{\sum_{i=1}^{i=n} (|P_i - \bar{O}| + |O_i - \bar{O}|)^2}, \quad (8)$$

where n is the number of samples; P_i and O_i are the i th estimated and true values, respectively, where $i = 1, 2, 3, \dots, n$; and $\bar{P}$ and $\bar{O}$ are the mean estimated and true values, respectively.

3. Results and discussion

a. Daily ET (ET_{rc}^d) estimated based on hourly canopy resistance r_c

1) VARIATION IN HOURLY CANOPY RESISTANCE (r_c^h) DURING DAYTIME

Diurnal variation of mean r_c^h in rice season is shown in Fig. 4. In the morning (0700–0800 LT), r_c^h was negative, and then increased gradually to be positive during 0800–0900 LT. Then, r_c^h was almost constant from 0900 to 1200 LT, before a slight decrease between 1200 and 1300 LT. This is owing to increased stomatal conductance at noon when the light is strongest (Alves et al. 1998; Allen et al. 2006). After this, r_c^h tended to increase rapidly, more than 150 s m^{-1} at 1500–1600 LT both in 2015 and 2016. Theoretically, canopy resistance should

FIG. 4. Diurnal variation in average hourly canopy resistance r_c^h during daytime in the 2015 and 2016 rice seasons. Note: 1) The abscissa in the figure at the label 8:00 represents the eigenvalue of the period 0700–0800 LT, and so on. 2) The result of <0 during the period of 0700–0800 LT is an artificial effect of the algorithm, making no physical nor physiological sense. 3) Error bars represent the standard error of the mean.

be high in the morning and evening, due to the lower light intensity and leaf stomatal conductance. However, the r_c^h in the morning was extremely low (even less than zero prior to 0800 LT), and the average r_c^h was 35 s m^{-1} with little variation during morning hours (0900–1200 LT). A result of $r_c < 0$ in current study (circled in red in Fig. 4) is the result of inversion by the PM equation, which is an artificial effect of the algorithm. Specifically, vapor condensation occurred in early morning within the rice field when the air humidity was high, especially before sunrise (generally RH higher than 95%) (Malek et al. 1999; Kabela et al. 2009; Hanisch et al. 2015; Liu et al. 2018b). Meanwhile, the soil hygroscopic water (during the nonflooding period in WSI rice paddy) was easy to produce in which the air humidity was high, and it accumulated prior to sunrise (Verhoef et al. 2006; Zhang et al. 2015). That favored the process of evapotranspiration over a short period after sunrise. As a result, the measured actual ET increased, and the r_c^h inverted from actual hourly ET by the PM equation is extremely low. Similar results were reported by Malek et al. (1992), Allen et al. (2006), and Perez et al. (2006), who found that r_c^h was negative or had no defined value in the early morning. Thus, canopy resistance inverted by the PM equation should be treated seriously and cannot be derived simply when dew formation occurs or when leaves are covered with dew.

It should also be noted that r_c^h tended to increase, with high values in the afternoon. This phenomenon is partially ascribed to the hourly time course of the environmental variables in the afternoon. The values of r_c^h , which were influenced by climatic factors, increased

FIG. 5. The diurnal variation of average hourly (a) available energy ($R_n - G_0$), (b) vapor pressure deficit (VPD), and (c) air temperature T_a during daytime in the 2015 and 2016 rice seasons.

drastically after 1300 LT, showing an opposite variation to $R_n - G_0$ and a similar variation to T_a or VPD (Fig. 5). In fact, canopy resistance is subject to the variation in $R_n - G_0$ (or R_n) in two ways: (i) crop stomatal conductance decreases with a decrease in radiation intensity; and (ii) as the source of energy for evaporation and transportation in the field energy balance, a decrease in $R_n - G_0$ tends to result in low r_c^h in the afternoon. Clearly, canopy resistance also depends highly on VPD (Fig. 5). When the VPD increases, i.e., T_a increases while the air humidity decreases, the air water potential is lower than the leaf water potential, resulting in the increase of water loss by transpiration and the decline in leaf water potential. With the decrease of the leaf–air water potential difference, the transpiration rate is limited and the canopy temperature increases, which causes a relatively high r_c^h in later afternoons. The increase tendency in rice r_c^h in the afternoon agrees well with results on grass, either in semiarid or Mediterranean climates, that showed that hourly canopy resistance increased in the afternoon in an irregular parabolic pattern (Todorovic 1999; Lecina et al. 2003; Allen et al. 2006; Perez et al. 2006). Results on upland crops (soybean or winter wheat) whose canopy resistance increased in the afternoon with

the largest increment occurring during sunset (Bailey and Davies 1981; Hu et al. 2005).

2) ESTIMATING ET_{rc}^d FROM r_c^h AT A SPECIFIC TIME

Daily simulated rice ET (i.e., ET_{rc}^d), was calculated from daily meteorological data and r_c^h at different daytime hours [Eq. (2)]. Performance of ET_{rc}^d calculations against the true ET_{tr}^d in the 2015 and 2016 rice season is shown in Fig. 6. For ET_{EC}^d estimated from r_c^h at specific times from 0700 to 1600 LT, the regression slope between ET_{rc}^d and ET_{tr}^d decreased gradually, with the maximum values of 1.201 and 1.189 at 0700–0800 LT in 2015 and 2016, and minimum values of 0.805 and 0.851 at 1500–1600 LT, respectively. Correspondingly, ET_{rc}^d calculated based on r_c^h at different hours reduced gradually from values greater than the true ET_{tr}^d to values inferior to it, i.e., from 4.801 to 3.118 mm day^{-1} in 2015 ($\text{ET}_{tr}^d = 3.835 \text{ mm day}^{-1}$), and from 4.671 to 3.299 mm day^{-1} in 2016 ($\text{ET}_{tr}^d = 3.816 \text{ mm day}^{-1}$). The error of the estimated ET_{rc}^d was large when it was calculated with r_c^h at sunset or sunrise (Fig. 6). The ET_{rc}^d , estimated with r_c^h from 0900 to 1000 LT or 1000 to 1100 LT, matched well with ET_{tr}^d . The correlations between ET_{rc}^d and ET_{tr}^d were the best in those periods,

FIG. 6. Average diurnal variation in model performance based on statistical indexes (slope, RMSE, R^2 , and IOA) for ET estimation during daytime in the 2015 and 2016 rice seasons.

with high R^2 (>0.90) and IOA (>0.97), and low RMSE ($<0.51 \text{ mm h}^{-1}$).

The reason these two hours provide the best estimation may be related to the neutral stability assumption for the atmospheric boundary layer. In several current studies on r_a model implementation, neutral atmospheric stability conditions have been assumed rather than actual stability conditions (Brunet et al. 1994; Anadranistakis et al. 2000; Patton et al. 2016). Results showed that an acceptable accuracy in ET estimation was achieved when it was estimated at weekly or longer intervals or scale (Anadranistakis et al. 1999). This suggests that the assumption of neutral stability was easily satisfied. However, when ET was estimated on a short time scale (intraday variation), the actual atmospheric stability conditions should be taken into account (Dupont and Patton 2012; Liu et al. 2015), although some studies have shown that it is feasible to neglect the correction of atmospheric stability in calculating crop ET (Van Zyl and De Jager 1987; Zhou et al. 1994).

The frequency of atmospheric stability (neutral stability, stable and unstable situations) are generally associated with diurnal variation. Stable conditions mainly occur at night, while unstable conditions may dominate around noon. From night to daytime, the atmospheric stability varies from stable to unstable, and the occurrence of neutral stability conditions are observed to be dominant in the morning (0900–1100 LT) and afternoon (1400–1600 LT). During other periods, the boundary layer is often either unstable or stable, which violates the neutral stability assumption, and consequently the equation of r_a is invalid. In addition, considering the tendency in r_c^h variation is smallest from 0900 to 1100 LT, it is preferred for temporally upscaling rice ET from hourly to daily.

3) IMPROVING THE PERFORMANCE IN $\text{ET}_{r_c}^d$ ESTIMATION

According to the results in Fig. 6 and Table 2, the $\text{ET}_{r_c}^d$ estimated based on r_c^h during 0900–1000 LT or 1000–1100 LT matched ET_{tr}^d well, compared with other specific hours. Furthermore, the average value of r_c^h during 0900–1000 LT and 1000–1100 LT performed much better in $\text{ET}_{r_c}^d$ estimation than the r_c^h from a single hour (either 0900–1000 LT or 1000–1100 LT) in a WSI rice field (shown in Fig. 6 and Table 2). For the 2015 dataset, the estimated $\text{ET}_{r_c}^d$ was $3.789 \text{ mm day}^{-1}$; the RMSE was $0.422 \text{ mm day}^{-1}$, and the R^2 and IOA were 0.934 and 0.983, respectively, based on r_c^h averaged across the period of 0900–1100 LT. For the 2016 dataset, the calculated value was also in acceptable agreement with the true value: $R^2 = 0.945$, RMSE = $0.431 \text{ mm day}^{-1}$, and IOA = 0.988. Therefore, one can improve the predictive performance of rice $\text{ET}_{r_c}^d$ estimation in WSI fields by averaging the r_c^h across the periods of 0900–1000 LT and 1000–1100 LT.

b. Seasonal ET ($\text{ET}_{r_c}^s$) estimated based on daily canopy resistance (r_c^d)

1) SEASONAL VARIATION OF RICE r_c^d

Seasonal variation of daily rice r_c^d inversed by ET_{EC}^d in 2015 and 2016 is shown in Fig. 7. During the first 100 days after transplantation, the value of r_c^d fluctuated in a narrow range around the average value over this period (41.8 and 39.3 s m^{-1} in 2015 and 2016, respectively), which was much lower than the value of 70 s m^{-1} of a reference crop surface (Allen et al. 1989; Todorovic 1999). In the maturity period at the end of the rice season (100+ days after transplanting), r_c^d increased linearly with time up to a value above 200 s m^{-1} when soil

TABLE 2. Performance of the ET estimation by the canopy resistance method for a WSI rice field.

Year	Time (UTC + 8)	Slope	R^2	RMSE (mm d ⁻¹)	IOA	r_c^h (s m ⁻¹)	ET _{tr} ^d (mm day ⁻¹)	ET _{rc} ^d (mm day ⁻¹)
2015	0700–0800	1.201	0.438	1.688	0.796	–24.6	3.835	4.801
	0800–0900	1.040	0.762	0.756	0.943	28.5		4.118
	0900–1000	1.003	0.921	0.477	0.981	33.4		3.889
	1000–1100	0.959	0.904	0.498	0.977	36.4		3.699
	1100–1200	0.943	0.848	0.689	0.957	39.9		3.660
	1200–1300	0.926	0.867	0.624	0.966	30.3		3.624
	1300–1400	0.910	0.852	0.683	0.961	62.2		3.551
	1400–1500	0.886	0.863	0.634	0.967	101.0		3.430
	1500–1600	0.805	0.774	0.772	0.936	168.6		3.118
	0900–1100	0.975	0.934	0.422	0.983	34.8		3.789
2016	0700–0800	1.189	0.683	1.449	0.897	–33.8	3.816	4.671
	0800–0900	1.074	0.804	0.686	0.974	23.8		4.134
	0900–1000	1.013	0.923	0.487	0.985	37.8		3.918
	1000–1100	0.974	0.906	0.508	0.981	38.4		3.726
	1100–1200	0.950	0.849	0.781	0.960	45.0		3.657
	1200–1300	0.934	0.862	0.752	0.943	26.1		3.740
	1300–1400	0.890	0.873	0.639	0.968	61.2		3.529
	1400–1500	0.901	0.667	1.094	0.918	99.3		3.578
	1500–1600	0.851	0.784	0.937	0.932	158.3		3.299
	0900–1100	0.993	0.945	0.431	0.988	38.1		3.822

moisture declined, and the rice canopy showed gradual senescence.

Notably, the variation of r_c^d in a WSI rice field was different from that of grass under optimal water conditions, as well as that of upland crops. For grass, r_c^d varied in a parabolic pattern, with r_c^d at the beginning and end of the year being much higher than r_c^d in June to July (minimum of 45 s m⁻¹) (Todorovic 1999). For upland crops, lower θ and lower canopy coverage in early growth stages resulted in low evaporation and crop transpiration; consequently, the value of r_c^d was relatively large (Irmak et al. 2013; Bastidas-Obando et al. 2017). However, in the WSI rice field, evaporation from the interplant (soil or water) surface was high in the early stage (regreening and early tillering stages) when the temperature and radiation were higher. The r_c^d , inversed by PM (characterized as a single-source “big leaf” model by which the sources of heat and water vapor from rice field were considered to occur at a single level within the canopy), was generally smaller than that of upland crops. In middle phenological stages, when rice growth was vigorous and crop ET was high, r_c^d was minimal. Since the θ is much greater in a WSI rice field than in upland fields, the rice r_c^d was smaller than that of upland crops and grass (Lecina et al. 2003; Jiang et al. 2016; Bastidas-Obando et al. 2017). In the rice crop’s mature period, the leaves’ ability to transpire weakens; meanwhile, R_n decreases and θ is relatively low, resulting in a low ET. Accordingly, the calculated r_c^d increased. The increasing tendency in the rice crop’s r_c^d at the mature stage was in close agreement with r_c^d values for upland crops (Lecina et al. 2003; Bastidas-Obando et al. 2017).

In 2015 and 2016, on days when the field was flooded or the soil at saturation, the average r_c^d values were 32.2 and 33.1 s m⁻¹, respectively. These values were inferior to the seasonal average value for r_c^d (52.3 and 50.4 s m⁻¹ in 2015 and 2016, respectively) and much lower than the average r_c^d for days without flooding water (62.3 and 58.3 s m⁻¹ in 2015 and 2016, respectively). On days without flooding water in the WSI rice field, r_c^d increased with a decrease in θ from θ_s to θ_f or an even lower moisture level (Fig. 7). Similar results, where r_c^d was generally low on days with sufficient soil moisture were noted in different ecosystems: e.g., agricultural crops, pastures, forest, and bare soil (McNaughton and Jarvis 1991; Zhang and Lemeur 1995).

2) ESTIMATING ET_{rc}^s BY INTERPOLATING r_c^d AT DIFFERENT INTERVALS

Based on the ET_{EC}^d measured by EC at intervals of 2, 5, 10, 15, and 20 days, seasonal rice evapotranspiration ET_{rc}^s was estimated at these different time intervals. The calculated values were underestimated to a certain extent (approximately 0.3 mm day⁻¹) compared with ET_{tr}^s (Table 3). The regression slopes between the estimated and true values ranged between 0.892 and 0.922. Generally, the correlations were acceptable both in 2015 and 2016, with the R^2 greater than 0.90 and 0.93, RMSE less than 0.47 and 0.49 mm day⁻¹, and IOA up to 0.97 and 0.98, respectively.

Theoretically, the longer the interval, the more likely it is to misrepresent the r_c^d of the whole season. The correlation and consistency between the estimated and true values were higher at 2-day intervals. The accuracy

FIG. 7. Daily rice canopy resistance r_c^d calculated inversely based on EC measured ET_{EC}^d in (a) 2015 and (b) 2016, corresponding to variation in soil moisture conditions θ .

of estimation was slightly reduced for intervals of 5, 10, 15, and 20 days, but the difference in performance among different intervals was not clear and the simulation results were also good, because the seasonal variability pattern of

r_c^d was simple and consistent. Specifically, the $\text{ET}_{r_c}^s$ estimated with a 20-day interval was almost the same as the result with 5-day interval, and was closer to ET_{tr}^s than $\text{ET}_{r_c}^s$ estimated with 10- or 15-day intervals with 2015 dataset.

TABLE 3. Statistics for the performance of the upscaling method over the full growth period of the rice crop.

Year	Time interval (days)	Slope	R^2	RMSE (mm day^{-1})	IOA	r_c^d ($\text{m}^{-1} \text{s}$)	ET_{tr}^s (mm day^{-1})	$\text{ET}_{r_c}^s$ (mm day^{-1})
2015	2	0.905	0.934	0.415	0.981	60.5	3.835	3.496
	5	0.901	0.916	0.441	0.975	54.8		3.508
	10	0.901	0.911	0.470	0.975	57.5		3.496
	15	0.892	0.909	0.465	0.973	61.6		3.468
	20	0.919	0.913	0.463	0.976	44.7		3.578
	$r_c^d = \text{trend line}$	0.913	0.910	0.438	0.974	52.3		3.570
	$r_c^d = 52.3 \text{ s m}^{-1}$	0.886	0.907	0.463	0.972	52.3		3.502
2016	2	0.913	0.938	0.462	0.983	55.3	3.816	3.531
	5	0.922	0.935	0.476	0.981	46.4		3.574
	10	0.911	0.936	0.467	0.982	58.8		3.514
	15	0.918	0.934	0.474	0.980	57.1		3.535
	20	0.904	0.932	0.485	0.979	58.9		3.505
	$r_c^d = \text{trend line}$	0.915	0.934	0.468	0.980	50.4		3.547
	$r_c^d = 50.4 \text{ s m}^{-1}$	0.891	0.927	0.486	0.977	50.4		3.514

FIG. 8. Regression analysis of the simulated daily ET (ET_{tr}^d) calculated based on the generalized r_c^d line and true ET (ET_{tr}^d) in the rice seasons of (a) 2015 and (b) 2016.

Moreover, a fixed r_c^d value, the seasonal average r_c^d of 52.3 and 50.4 $s\,m^{-1}$ in 2015 and 2016, respectively, was used to estimate the ET_{tr}^s , and the variation of r_c^d was generalized as a two-segment line (red dotted line in Fig. 7) and was compared with the results from the canopy resistance method shown in Table 3. The ET_{tr}^s , computed from the fixed r_c^d value with regression slopes of 0.886 and 0.891 in 2015 and 2016, respectively, was smaller than values estimated by the varied r_c^d and the true values, although the correlation was also very good. The ET_{tr}^s computed based on the generalized r_c^d were more accurate and consistent, compared with some interpolation results. The ET_{tr}^s values of 3.570 and 3.547 $mm\,day^{-1}$ in 2015 and 2016, respectively, showed RMSE values of 0.438 and 0.468 $mm\,day^{-1}$, R^2 of 0.910 and 0.934, and IOA of 0.974 and 0.980. In general, ET_{tr}^s in WSI rice field can be accurately estimated by the upscaling method, which is recommended over linear interpolation for longer intervals, since its accuracy is not significantly reduced and the data inputs can be effectively reduced. Additionally, the ET_{tr}^s simulation based on the generalized r_c^d was also an effective and easy method when there was a lack of measured data.

3) THE GENERALIZED r_c^d LINE FOR ET ESTIMATION

The overall variability pattern of r_c^d was simplified as a two-segment line during the WSI rice season (Fig. 7). The two-segment line can be described as 1) constant for the first 100 days after transplanting and 2) a linear increase during the maturity stages after 100 days from transplanting. According to the local calibrated results for 2015 and 2016, the two-segment line can be expressed in Eq. (9), where d represents the number of days after transplanting. This was used to calculate the ET_{tr}^s in the

WSI paddy and was compared with the ET_{tr}^s values in the same years, as shown in Fig. 8. For the 2015 dataset, the four accuracy indicators, slope, R^2 , RMSE, and IOA had values of 0.915, 0.910, 0.441 $mm\,h^{-1}$, and 0.974, while in 2016 these values were 0.912, 0.933, 0.470 $mm\,h^{-1}$, and 0.980, respectively. The overall result was even better than the estimation through the r_c upscaling method by linear interpolation over longer intervals (10-, 15-, or 20-day intervals), which indicated that the ET of WSI paddy can be calculated accurately through the simplified variability pattern of r_c^d in the absence of observed data:

$$r_c^d = \begin{cases} 40.6, & d \leq 100, \\ 5d - 459.45, & 100 < d \leq 120. \end{cases} \quad (9)$$

The linear equation [Eq. (9)] for estimating rice r_c^d of is much simpler than the empirical model used for other types of vegetation (Kelliher et al. 1995; Alves and Pereira 2000; Liu et al. 2012; Yan et al. 2015). It is simple and performs well in calculating rice ET in the east China, but the constant r_c in the first 100 days of rice growth is very hard to assess since the vegetation's canopy resistance varies with prevailing climatic conditions (Ortega-Farias et al. 2010; Zhao et al. 2015). Furthermore, if this simple equation, which is believed to be a local result, performs acceptably or not in other locations remains unknown. To plan rational irrigation, more work needs to be carried out at other sites to find generic methods of r_c^d estimation with fewer measurements.

4. Conclusions

With canopy resistance r_c as an intermediate variable, rice ET was upscaled temporally either from hourly to

daily or from daily to seasonal, based on diurnal variation of hourly r_c (r_c^h) and seasonal variation of daily r_c (r_c^d). The daily ET ($ET_{r_c}^d$) estimated with r_c^h during the hours of 0900–1000 LT or 1000–1100 LT showed close agreement with the true value (ET_{tr}^d). Moreover, in an WSI rice field, the average r_c^h value over the periods of 0900–1000 LT and 1000–1100 LT combined performed much better in $ET_{r_c}^d$ estimation than the r_c^h from a single hour. For daily-to-seasonal upscaling, the $ET_{r_c}^s$ calculated by interpolating r_c^d at different time intervals underestimated rice ET to a certain extent compared with (ET_{tr}^s), with a 2-day interval offering the best performance. A generalized two-segment line can be used for depicting the seasonal variation of r_c^d and estimating $ET_{r_c}^s$. In conclusion, canopy resistance (r_c) is a test competent in estimating rice ET by upscaling hourly ET to daily ET or upscaling daily ET to seasonal ET. Hourly r_c measured during the hours of 0900–1000 LT and 1000–1100 LT is suitable for estimating daily ET based on instantaneous estimates of ET by remote sensing. In case of sparse data availability, seasonal ET of rice can be estimated by linear interpolation the r_c^d , or by calculating r_c^d with a simple two-segment linear equation. Future validation will be conducted to estimate rice ET with more field measurements in a greater variety of stations, or with remote sensing data.

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