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Research Paper

Inter-seasonal and cross-treatment variability in single-crop coefficients for rice evapotranspiration estimation and their validation under drying-wetting cycle conditions

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ABSTRACT

A two-year experiment was conducted to investigate the inter-seasonal and cross-treatment variability in measured rice evapotranspiration (ET_{cMea}), measured single-crop coefficients (K_{cMea}), and treatment-specific calibrated coefficients (K_{cCal}), under different drying-wetting cycles in a subtropical monsoon climate in East China. For each drying-wetting treatment, ET_{cMea} was determined based on data collected in lysimeters, and K_{cMea} was calculated from ET_{cMea}, reference evapotranspiration, and soil moisture deficit coefficient. Following the single-crop coefficient method, K_{cCal} was determined by matching K_{cMea}. In 2012 and 2013, ET_{cMea} varied from 459.5 to 486.7 mm, and 544.5–605.1 mm, respectively. Its inter-seasonal variability was larger than the cross-treatment variability. Stage-wise average K_{cMea} were 1.07–1.17, 1.30–1.51, 1.49–1.54, and 1.17-1.29 in 2012, and 1.06–1.12, 1.31–1.49, 1.43–1.57, and 1.26–1.27 in 2013 during the initial, crop development, mid-season, and late season stages, respectively. Treatment-specific K_{cCal} were calibrated as 1.09–1.20, 1.51–1.60, and 0.74–0.78 in 2012, and 1.05–1.14, 1.47–1.64, and 0.96–1.01 in 2013 for the initial, mid-season, and end-season stages, respectively. The inter-seasonal and cross-treatment variability in K_{cMea} and K_{cCal} was low. Each treatment-specific K_{cCal} set performed similarly when rice ET_c was calculated under different drying-wetting treatments. Cross validation indicated that large daily uncertainty in ET_c estimation occurred when daily ET_{cMea} was high, and uncertainty in seasonal ET_c calculated using different treatment-specific K_{cCal} sets ranged from 45.7 to 60.1 mm (approximate to one irrigation). Calibrating K_{cCal} using more data (season-specific K_{cCal} or mixed treatment K_{cCal}) would improve the accuracy of K_{cCal} in ET_c estimation.

1. Introduction

Crop evapotranspiration (ET_c), which is affected by crop variety, development stage, management practices, weather, and environmental conditions, is important for effective irrigation planning and water resource management (Yu et al., 2000; Martins et al., 2013; Suleiman et al., 2013). The single-crop coefficient method developed by the Food and Agriculture Organization (FAO) is the most updated method for ET_c estimation (Allen et al., 1998; Liu and Luo, 2010; Alberto et al., 2014; Shukla et al., 2014). Guidelines for calculating ET_c of different crops based on reference evapotranspiration (ET_0), soil moisture deficit coefficients (k_s), and single-crop coefficients (K_c) were brought forward by the FAO (Allen et al., 1998). In this method, K_c predominately varies with specific crop characteristics and is affected by cultivation and water management, and k_s expresses the deficit in ET_c due to soil water availability (Allen et al., 1998; Kang et al., 2000; Zhang et al., 2004; Wang et al., 2005; Ferreira et al., 2012; Suleiman et al., 2013; Wei et al., 2015).

Many studies applied the single-crop coefficient method to estimate ET_c, and local calibration of K_c was suggested accordingly by most researchers to improve location specific performance (Kashyap and Panda, 2001; Kuo et al., 2006; Shahrokhnia and Sepaskhah, 2013; Howell et al., 2015; Muniandy et al., 2016). For

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most studies of the locally calibrated K_c (K_{cCal}), calibrated coefficients were determined based on primary data collected for one or several years and validated for other years (Hunsaker et al., 2005; Popova et al., 2006), or determined based on data from one or several treatments and validated for other treatments (Martins et al., 2013). However, adequate information on the variability in K_{cCal} among different varieties, crop seasons, or management practices (e.g., cultivation, irrigation) is still lacking.

At the same time, it is known that measured K_c (K_{cMea}) varies with local climate and field management practices. For rice, K_{cMea} during different growth stages varies greatly among different irrigation regimes and growing seasons. In Philippines, K_{cMea} were reported as 1.04, 1.11, 1.04, and 0.93 for flooded rice, and 0.95, 1.00, 0.97, and 0.88 for aerobic rice during the vegetative, reproductive, ripening, and fallow stages, respectively (Alberto et al., 2011). For rice under aerobic conditions, K_{cMea} were 0.81, 0.89, 1.15, and 1.23 in 2012, and 0.84, 1.01, 1.04, and 0.90 in 2013 during the initial, crop development, mid-season, and late season stages, respectively (Alberto et al., 2014). Different cultivation practices also resulted in different K_{cMea}. The average K_{cMea} were found to be 1.01, 1.02, 1.09, and 1.05 for flooded rice, and 1.00, 0.96, 1.02, and 1.04 for rice under system of rice intensification irrigation regimes during the initial, crop development, reproductive, and late growth stages, respectively (Arif et al., 2015). For rice cultivated on raised beds, K_{cMea} were reported as 0.62, 0.75, 1.16, and 0.67, and 0.61, 0.97, 1.42, and 0.91 for rice in conventional flat lands during the initial, crop development, mid-season, and late season stages, respectively (Choudhury et al., 2013). As a result of varied rice K_{cMea}, K_{cCal} might vary greatly among different irrigation regimes, growing seasons, or cultivation practices. For example, Vu et al. (2005) found that for three different rice varieties in Tokyo, K_{cCal} varied from 1.09 to 1.28 and 1.02–1.46 during the initial and mid-season stages, respectively. Choudhury and Singh (2016) found that K_{cCal} for flooded rice in India at the initial, mid-season, and end-season stages were 1.06, 1.73, and 1.36 in 2001, and 1.20, 1.88, and 1.45 in 2002.

Recently, water-saving irrigation (WSI) techniques for rice were developed and applied as a countermeasure to cope with increasing water scarcity. In WSI rice fields, the soil remains under alternate drying-wetting cycles, which leads to changes in rice ET_c (Xu et al., 2017) and K_c (Alberto et al., 2011; Arif et al., 2015). Irrigation water is applied according to soil moisture thresholds (e.g., controlled irrigation in China, or system of rice intensification in Madagascar) or drying days (e.g., intermittent irrigation in Indonesia, or alternate wetting and drying in Philippines) (Nugroho et al., 1994; Rejesus et al., 2011; Peng et al., 2013; Berkhout et al., 2014). The thresholds of soil moisture or drying days differ with WSI techniques. As a result, the frequency of drying-wetting cycles and the degree of field drying might be quite different among rice fields under different WSI schemes (Mao, 2001), depending on different groundwater levels, or percolation rates. Yet, information on the variability in K_{cCal} under different drying-wetting cycle conditions is still inadequate.

Keeping this in view, we made an attempt to study the ET_c consumption and K_c derivation of non-flooded controlled irrigated (NFI) rice under different drying-wetting cycles using lysimeters in East China. The main objectives of this study included: i) Investigating the inter-seasonal and cross-treatment variability in measured ET_c (ET_{cMea}) and K_{cMea} under different drying-wetting cycles; ii) Calibrating treatment-specific coefficients K_{cCal} ($K_{ciniCal}$, $K_{cmidCal}$, and $K_{cendCal}$ for the initial, mid-season, and end-season stages, respectively) individually for each treatment in both seasons, then investigating the variability in these coefficients, and testing their performance in rice ET_c estimation using cross validation; iii) Comparing the performance of treatment-specific K_{cCal} with season-specific K_{cCal} (calibrated using mixed data from different drying-wetting treatments within a specific season) or mixed treatment K_{cCal} (calibrated using all datasets from both seasons).

2. Materials and methods

2.1. Site and experiment description

To achieve the different drying-wetting cycles in rice fields under NFI practices, three subsurface drainage control regimes (field groundwater level-FL, and two controlled subsurface drainage levels- CL1 and CL2) were imposed in lysimeters with three replications during 2012 and 2013 rice seasons at Kunshan Experiment Station (31° 15′ 50″ N; 120° 57′ 43″ E), East China. The lysimeters (width × length × depth = 2 m × 2.5 m × 1.3 m) were sealed at the bottom and covered with a movable shelter to remove the influence of rainfall. The lysimeters were filled with dark yellow hydromorphic paddy soil, with volumetric saturated soil water contents of 52.0, 50.1, and 47.9% at soil depth ranges of 0–20, 0–30, and 0–40 cm, respectively.

In the NFI rice fields, ponding water depth was maintained between 5 and 25 mm during the first 7–8 days after transplanting. During the following stages, irrigation was applied to saturate the soil when soil moisture approached the lower thresholds (flooding was avoided), except during the periods of fertilizer and pesticide application (flooding water up to 5 cm deep was maintained for less than 5 days).Water depths, soil moistures, irrigation water volume, and subsurface drainage volume were measured to calculate daily ET_{cMea} by using water balance calculation. Detailed information about groundwater control levels, the techniques used to achieve them, NFI practices, field measurement, and the calculation of ET_{cMea} were reported earlier (Xu et al., 2017). In the FL, CL1, and CL2 treatments, there were 13, 11, and 14 drying-wetting cycles in 2012, and 14, 12, and 13 cycles in 2013. Consequently, out of the 97 days (from transplanting to end of milk maturity), there were 52, 49, and 52 non-flooded days in 2012, and 49, 51, and 52 non-flooded days in 2013 (Fig. 1).

A medium maturing high yield rice variety, hybrid Japonica Rice Jia 04–33, grown widely in Southeast China, was used as experimental material. Rice seedlings were transplanted at a density of 1.13 million seedlings per hectare on June 28 and harvested in late October (Oct 28, 2012 and Oct 27, 2013). Fertilizers and pesticides were applied according to local practices. The seasonal average air temperatures were 25.1 and 26.7 °C, with wind speeds of 1.3 and 1.1 m s^{-1}, and relative humidities of 82.1 and 81.1% in 2012 and 2013 rice seasons, respectively.

2.2. Calculation of measured daily crop coefficients

With the FAO-56 single-crop coefficient method, ET_c was calculated using Eq. (1). Daily K_{cMea} was calculated by dividing daily ET_{cMea} by ET_0 and k_s (as shown in Eqs. (2) and (3), respectively) (Mao et al., 1995; Allen et al., 1998).

$$ET_c = k_s \mathrm{K_c} \mathrm{ET_0} \tag{1}$$

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

$$\mathrm{k_s} = \begin{cases} 1 & \theta_r \geq \theta_{rc1} \\ \ln\left(1 + 100\theta_r\right) / \ln 101 & \theta_{rc2} < \theta_r < \theta_{rc1} \\ \alpha \exp[(\theta_r - \theta_{rc2})/\theta_{rc2}] & \theta_r < \theta_{rc}2 \end{cases} \tag{3}$$

where R_n and G are net radiation and soil heat flux density, MJ m^{-2} d^{-1}. T is the mean daily air temperature, °C. u_2 is wind speed at a height of 2 m, m s^{-1}. e_s and e_a are saturation vapor pressure and