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Actual evapotranspiration and crop coefficients for tropical lowland rice (*Oryza sativa* L.) in eastern India

Sumanta Chatterjee[1,2] · Paul C. Stoy[3,4] · Manish Debnath[1] · Amaresh Kumar Nayak[1] · Chinmaya Kumar Swain[1] · Rahul Tripathi[1] · Dibyendu Chatterjee[1] · Smruthi Sagarika Mahapatra[1,5] · Ammara Talib[4] · Himanshu Pathak[6]

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Abstract

Accurate measurements of actual evapotranspiration (ET_a) and crop coefficients (K_c) are essential to know crop water requirements and to improve irrigation scheduling. The eddy covariance (EC) technique is increasingly being used to do so. Precise information on K_c for lowland rice is essential for local- and regional-scale irrigation planning but it is lacking for tropical humid climates such as those found in eastern India. We used the EC technique to measure ET_a and K_c—the ratio of ET_a to reference potential evapotranspiration (ET_0)—of tropical lowland rice in eastern India over 2 years. ET_0 was estimated by four different approaches—the Food and Agriculture Organization-Penman–Monteith (FAO-PM) method, the Hargreaves and Samani (HS) method, the Mahringer (MG) method, and pan evaporation (E_{pan}) measurements. Measurements were taken when rice was grown in the dry season (January–May) and wet season (July–November) and in between growing seasons when the field was kept fallow. The magnitude of average ET_a during dry seasons (2.86 and 3.32 mm d^{-1} in 2015 and 2016, respectively) was higher than that of the wet seasons (2.3 and 2.2 mm d^{-1}) in both the study years. Of the four methods tested for ET_0 estimation, the FAO-PM method best-represented ET_0 in this region of India. The energy balance was found to be more closed in the dry seasons (75–84%) and dry fallow periods (73–81%) as compared to the wet season (42–48%) and wet fallow (33–69%) periods of both years of study, suggesting that lateral heat transport was an important term in the energy balance. The estimated K_c values for lowland rice in dry seasons by the FAO-PM method at the four crop growth stages, namely, initial, crop development, reproductive, and late-season, were 0.23, 0.42, 0.64, and 0.90, respectively, in 2015 and 0.32, 0.52, 0.76, and 0.88, respectively, in 2016. The FAO-PM, HS, and MG methods produced reliable estimates of K_c values in the dry seasons, whereas E_{pan} performed better in wet seasons. The actual K_c values derived for tropical lowland rice in eastern India are different from those suggested by the FAO implying revision of K_c values for regional-scale irrigation scheduling.

Keyword Eddy covariance · Lowland rice · Crop evapotranspiration · Crop coefficient · Energy balance closure

Highlights

- Actual evapotranspiration (ET_a) and crop coefficients (K_c) for tropical lowland rice in Eastern India were calculated using eddy covariance approach.
- The magnitude of ET_a during dry seasons were higher than the wet seasons in both the study years.
- The FAO-PM, Hargreaves-Samani and Mahringer methods produced reliable estimates of K_c values in dry seasons.
- The K_c values derived in this study are different from those suggested by the FAO for rice.

✉ Amaresh Kumar Nayak
aknayak20@yahoo.com

Extended author information available on the last page of the article

1 Introduction

Rice, a major global staple food crop, occupies about 44 million ha (Mha) of cropped land in India meeting food requirements for about 65% of the population of India (Mohanty and Yamano 2017; Chatterjee et al. 2020a). In India, rice is cultivated in uplands and lowlands under both rainfed and irrigated water inputs which consume about 42% of the available water supply. It has been projected that 20–60 Mha of irrigated rice in Asia may suffer from water scarcity by 2025 (Bouman 2007; Elliott et al. 2014). Worldwide, irrigation utilizes between 90–94% of global water consumption and it has the maximum share (96–98%) in South Asia in part due to large-scale rice cultivation (Siebert et al. 2015). In India, the withdrawal of groundwater for agricultural purposes has increased by 70% since the 1970s (Zeigler and Mohanty 2010). Available irrigation water must be managed precisely so that it meets crop water requirements while avoiding water misuse and maximizing water use efficiency (Chatterjee 2014; Chatterjee et al. 2016, 2017, 2018) to improve rice yield and quality (Liu et al. 2019). Understanding energy and water balances in rice fields including the actual evapotranspiration (ET_a) is a prerequisite for irrigation scheduling and crop-environmental modeling (Hossen et al. 2012; Chatterjee et al. 2020b; Debnath et al. 2021).

Evapotranspiration (ET) is a central term in the global water and energy cycles (Jung, 2010) and its precise quantification is critical in understanding the role of the land surface in the climate system. Multiple methods can be used to measure ET (e.g., Stoy et al. 2019), and the eddy covariance (EC) micrometeorological method has been increasingly employed since the turn of the last century (Suyker and Verma 2008; Li et al. 2008; Ding et al. 2010; Liu et al. 2011; Alberto et al. 2014; Timm et al. 2014). High-frequency fluctuations in wind speed, air temperature, and water vapor are used to measure water vapor and heat fluxes from the surface to the atmosphere using the EC approach (Dyer 1961; Shuttleworth 2007). The EC technique is typically used to measure ET over half-hourly periods (Baldocchi 2003) at scales of 0.1 to 1 km (Rana and Katerji 2000) depending on sensor placement and the characteristics of turbulence but is prone to uncertainties including those due to lack of energy balance closure (Stoy et al. 2013; Foken 2008). Despite these uncertainties, EC measurements of ET tend to converge on expected values from watershed-scale studies (Jung et al. 2010), which lends support to the concept that ET measurements have little bias and can be used for ecosystem-scale studies of the water balance.

The notion of the crop coefficient (K_c)—the ratio of ET_a to reference potential evapotranspiration (ET_0)—is often used for irrigation planning. Lysimeters have been historically used to determine K_c (Allen et al. 1994) but some recent studies have used EC for this purpose (Li et al. 2008; Alberto et al. 2011, 2014; Timm et al. 2014) often in conjunction with the FAO Penman–Monteith approach for estimating ET_0 (Allen et al. 1994). The FAO approach requires multiple meteorological data inputs which may be a limitation in remote areas or developing countries. Therefore, there is a need to test alternative approaches for ET_0 estimation for water resource management across different cropping systems.

Of the rice cropping systems of India, the flooded lowland rice ecosystem is different from upland cropping systems because of the presence of a continuous water stratum above the soil surface which affects the components of surface energy balance including ET (Tsai et al. 2007; Maruyama and Kuwagata, 2010; Alberto et al. 2011; Hatala et al. 2012; Hossen et al. 2012; Chatterjee et al. 2019b, c; Swain et al. 2018; Chatterjee et al. 2020b) for which soil moisture play an important role (Chatterjee et al. 2019a, 2020c, 2021a). However, only a few studies (e.g., Mohan and Arumugam, 1994; Alberto et al. 2014) have estimated K_c and measured ET_a using EC in lowland rice systems across growing and fallow seasons to understand the role of rice agriculture in water resource management. The objectives of our study were (1) to investigate the variation in daily and seasonal ET_a of lowland rice in the tropical humid region of eastern India through EC system (2) to compare the standard FAO Penman–Monteith method with other ET_0 methods that require fewer meteorological data inputs, and (3) to estimate K_c of lowland rice in different growing seasons. The hypothesis that will be tested in this study are as follows: (1) the actual ET of lowland rice vary with seasons and stages of rice production and (2) the K_c values derived from the EC system for the tropical lowland rice in eastern India are different from other regions and FAO recommended values.

2 Materials and methods

2.1 Site description and crop establishment

This study was conducted at the Indian Council of Agricultural Research-National Rice Research Institute (ICAR-NRRI), Cuttack, Odisha, India (20° 26′ 60″ N latitude, 85° 56′ 10.9″ E longitude) (Fig. 1). The climate of this region is tropical humid, with hot and wet summers (March to June) and brief and mild winters (December to February). The mean annual, mean maximum, and mean minimum air temperature values recorded in this region were 30.2 °C, 38.5 °C, and 20 °C in 2015 and 30.5 °C, 38.3 °C, and 20.8 °C in 2016, respectively. The total annual rainfall for 2015 and 2016 was 1312 mm and 1316 mm, respectively (Fig. 2). The soil was an Aeric Endoaquept with sandy clay loam texture (26% clay, 22% silt, and 53% sand), bulk density 1.41–1.43 Mg m^{-3}, pH (1:2.5 soil:water ratio) 6.21–6.32, electrical conductivity 0.42–0.45 dS m^{-1}, total carbon 11.2–11.4 g kg^{-1}, and total nitrogen 0.8–0.9 g kg^{-1} (Chatterjee et al. 2020a).

Observations were made for two consecutive years (2015 and 2016) in lowland rice. Years were categorized into the dry season (Julian days 1–123), dry fallow (Julian days 124–187), wet season (Julian days 188–316), and wet fallow (Julian days 317–365). Twenty-one-day-old seedlings of rice cultivar viz. Naveen (CR 749–20-2, IET 14,461) and Swarna Sub-1 (MTU7029, IR05F102) were transplanted with a spacing of 20 cm × 15 cm during January in the dry season and during July in the wet season. The crop was harvested in May during the dry season and in November during the wet season. Rice growth was divided into four growth stages following Pradhan et al. (2012): (i) the initial growth

Fig. 1 Study area showing the locations of eddy covariance system (light blue triangle) and weather station (yellow triangle) in lowland rice in eastern India (image courtesy – https://gadm.org/, and Google Earth, Maxar Technologies, July 30, 2020)

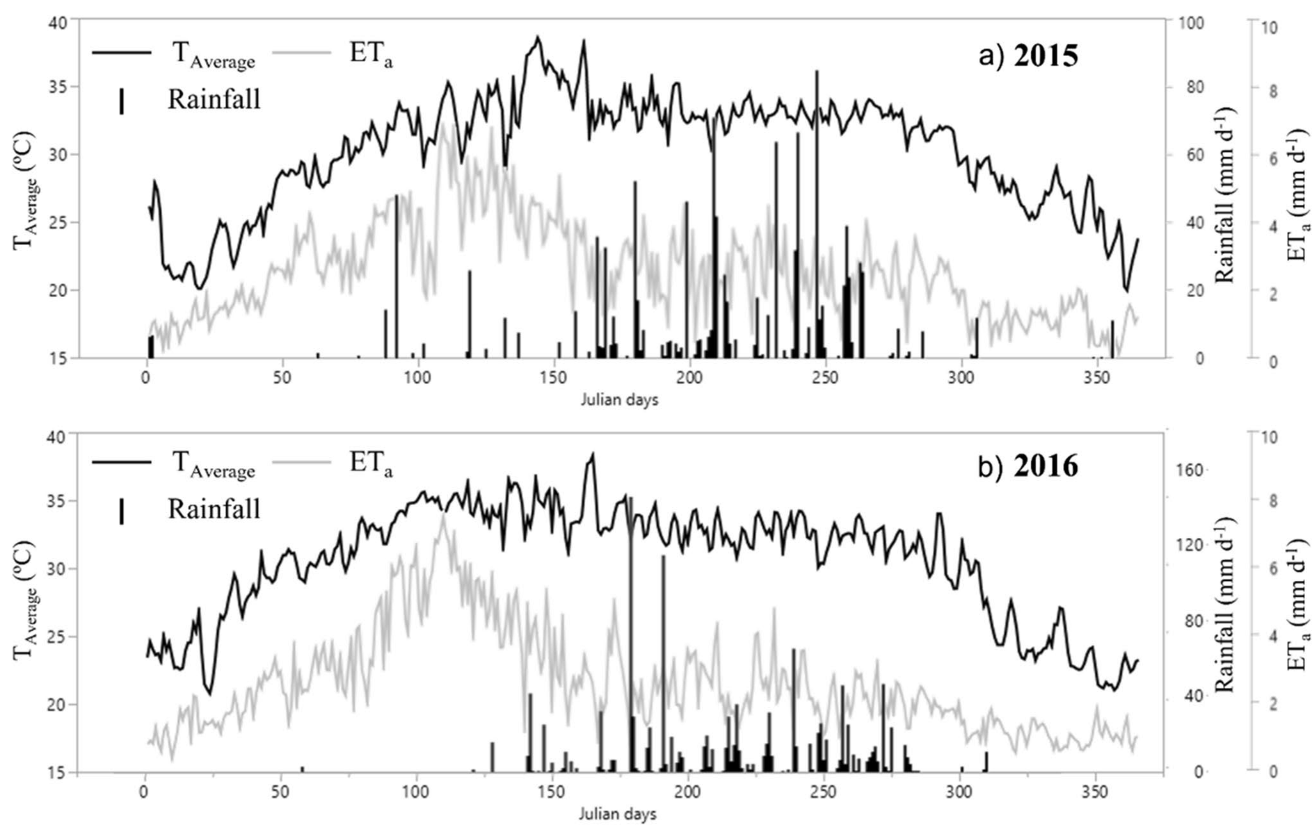


Fig. 2 Daily average air temperature ($T_{Average}$), rainfall, and actual evapotranspiration (ET_a) in a lowland rice in eastern India in 2015 (**a**) and 2016 (**b**)

stage which extending from planting to 10% ground cover; (ii) the crop development stage extending from 10 to 80% ground cover; (iii) the mid-season stage extending from 80% ground cover to beginning of maturity, and (iv) the late-season stage extending from the beginning of maturity to harvest. The field was flooded with 8 cm of standing water during both dry and wet season treatments. Flood irrigation continued throughout the seasons until 2 weeks before harvest to provide a non-limiting environment for optimal crop growth. A dose of 100 kg N ha^{-1} was applied in three split applications at basal, maximum tillering, and panicle initiation stages. Compost was applied at the rate of 5 Mg ha^{-1} (composition: C: 240–245 g kg^{-1}, N: 11.2–11.6 g kg^{-1}, P: 3.9–4.1 g kg^{-}1, and K: 6.1 g kg^{-1}) once in a year at the time of field preparation of the wet season (during June).

2.2 Measurements of fluxes, microclimate, weather, and plant parameters

The micrometeorological tower with eddy covariance system was established in the center of the 2.25 ha lowland rice field (Fig. 1) and measured sensible heat flux (H), surface latent heat flux (LE), net radiation (Rn), soil heat flux (G), air temperature from which a daily average was taken ($T_{Average}$), and wind speed and direction. All the aerial sensors were mounted above the canopy at 1.5 m height from the ground surface (Davey and Pielke, 2005; Kamoutsis et al., 2013; Chatterjee et al. 2020c, 2021b). The EC system consisted of three-dimensional wind speed and sonic temperature measurements from a fast response three-axis sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) coupled to an open-path infrared gas analyzer (LI-7500, LICOR Inc., Lincoln, NE, USA) and measured at 10 Hz on a data logger (CR3000, Campbell Scientific). Relative humidity and air temperature were measured with temperature-humidity sensors (HMP45C, Campbell Scientific) on a half-hourly basis. The four-component radiation sensor (CNR4, KIPP and ZONEN, Delft, the Netherlands) was used for recording Rn and incoming global radiation (Rg). Soil temperature was measured at 5 and 15 cm using soil temperature probes (107 B, Campbell Scientific). Leaf area index (LAI) was measured by LAI-2200C Plant Canopy Analyzer (LICOR Inc., Lincoln, NE, USA) over the crop growing period in both the seasons at each growth stage. Daily weather data were collected from the agrometeorological weather station (class II type, India Meteorological Department) which was located about 240-m away from the EC system (Fig. 1).

2.3 *Measurement of actual evapotranspiration (ET_a) by eddy covariance*

Turbulent fluxes of H and LE were calculated using:

$$H = \rho_a C_p \overline{T' \, W'} \quad (1)$$

$$LE = \lambda \rho_a \overline{q' w'} \quad (2)$$

where ρ_a (kg m^{-3}) is the density of air, $C_p = 1004$ J kg^{-1} K^{-1} is the specific heat of air at constant pressure, and λ (J kg^{-1}) is the latent heat of vaporization of water which was calculated as a function of air temperature (Aubinet et al. 1999). LE and H are the latent and sensible heat flux (W m^{-2}), $q'w'$ is the covariance between the deviation of vertical wind speed from its mean (w′, m s^{-1}) and deviations of the water vapor mixing ratio from its mean (q′, kg kg^{-1}), and $T'w'$ is the covariance between w′ and deviation from mean sonic temperature (T′, K).

The latent heat flux (LE) measured by the EC system was converted to depth per time units to calculate ET_a from the field (Ding et al. 2010).

$$ET_a = \frac{3600 \times LE}{\lambda \times \rho_w} \quad (3)$$

where ET_a (mm h^{-1}) is calculated using the measured LE (W m^{-2}), λ is the latent heat of vaporization (MJ kg^{-1}) which is equal to $2.501–0.00236 \times T_s$ where T_s is the sonic temperature measured by sonic anemometer of the EC system, (°C), ρ_w is the density of water (10^3 kg m^3), and 3600 converts from hour to second. Finally, the ET_a values were converted to mm d^{-1}.

2.4 Data processing, quality control, and gap filling

The EC raw flux data were processed, and quality controlled by the procedure according to Mauder and Foken (2011) using the EddyPro software v7.0.6 (LICOR Inc., USA). We estimated the time lag compensation by maximizing the correlation between scalar concentrations and vertical wind speed (Goulden et al. 1996). Empirical transfer functions were used for the correction of frequency response losses (Aubinet et al. 1999). Coordinate rotations were applied to the wind orthogonal components prior to flux calculations (Kaimal and Finnigan, 1994). The Webb-Pearman-Leuning (Webb et al. 1980) density correction was also applied to flux data. The anomalous spikes in flux data because of incongruous meteorological conditions were discarded by quality checks for spike detection (Vickers and Mahrt, 1997), and the friction velocity (U*) filter for insufficient nighttime turbulence was applied (Reichstein et al. 2005; Papale et al. 2006). Missing EC data due to unsuitable weather conditions, power outages, or removal during quality checks were gap-filled (Alberto et al. 2013, 2014) using the look-up table approach (Falge et al. 2001).

2.5 *Measurement of reference evapotranspiration (ET_0)*

Daily weather parameters obtained from the ICAR-NRRI institute weather station were used to compute grass reference evapotranspiration (ET_0) using (a) FAO Penman–Monteith (FAO-PM) (Allen et al. 1998), (b) Hargreaves and Samani (1985) (HS), (c) Mahringer (1970) (MG), and (d) US Class A Pan Evaporimeter methods. We tested multiple methods for computing ET_0 to find an approach that is robust with minimal inputs to be able to apply to sites that lack full energy balance measurements.

2.6 Reference evapotranspiration: FAO-PM method

Evapotranspiration depends upon the interaction of weather, plant, and soil conditions. ET_0 can be used for describing the influence of weather alone. To calculate ET_0 on a daily basis (mm d^{-1}), the FAO: Penman–Monteith was used (Allen et al. 1998):

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T_{Average}+273} U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \tag{4}$$

where Rn is the net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), $T_{Average}$ is the daily mean air temperature at 2 m (°C), U_2 is the wind speed at 2 m (m s^{-1}), e_s is the saturation vapor pressure at 2 m (kPa), e_a is the actual vapor pressure at 2 m (kPa), ($e_s - e_a$) is the vapor pressure deficit (VPD, kPa), Δ is the slope of vapor pressure curve (kPa ◦C^{-1}), and γ is the psychrometric constant (kPa ◦C^{-1}).

2.7 *ET_0 estimation using a temperature-based approach: the Hargreaves and Samani (HS) method*

Hargreaves and Samani's (1985) method considers only air temperature as a representative of the available energy for evapotranspiration and excludes the influence of wind speed and solar radiation:

$$ET_0 = 0.0023 \times \left(T_{max} - T_{min}\right)^{0.5} \times \left(T_{mean} + 17.8\right) \times Ra \tag{5}$$

where T_{max}, T_{min}, and T_{mean} are the daily maximum, minimum, and mean air temperatures (°C), respectively, and Ra denotes the extraterrestrial radiation (MJ m^{-2} d^{-1}), and the coefficient of 0.408 is used to convert from MJ m^{-2} d^{-1} to mm d^{-1}.

2.8 *ET_0 using a mass transfer-based approach: the Mahringer (MG) method*

The Mahringer (1970) method for ET_0 estimation is based on Dalton's gas law, which combines humidity and wind speed as parameters and shares similar features to the Dalton (1802), Rohwer (1931), and Penman (1948) approaches. In this study we adopted the equation proposed by Mahringer (1970):

$$ET_0 = 0.15072\sqrt{3.6U_2}\left(e_s - e_a\right) \tag{6}$$

which requires measurements of wind speed, relative humidity, and temperature (to calculate e_s) and is thereby more complicated than the HS method but avoids the need to calculate or estimate Rn and G per the FAO-PM approach.

2.9 Pan evaporation measurements

The daily pan evaporation (mm) was measured by a US Class A pan evaporimeter which is located at the weather station of ICAR-NRRI, Cuttack (20° 26′ 60″ N, 85° 56′ 10.9″ E, elevation ~ 23 m) and it is maintained by India Meteorological Department. The diameter of the US Class A pan is 121 cm and depth of 25.4 cm and the bottom of the pan was raised 5 cm above the ground surface on an open-frame wooden platform.

The ET_0 is calculated from the following formula:

$$ET_0 = K_{pan} \times E_{pan} \tag{7}$$

where $ET_{0,}$ K_{pan}, and E_{pan} denote the reference crop evapotranspiration, the pan coefficient, and pan evaporation, respectively. We used 0.71 for the K_{pan} value following Allen et al. (1998).

2.10 *Determination of crop coefficients (K_c)*

K_c was estimated following (Allen et al. 1998):

$$K_c = \frac{ET_a}{ET_0} \tag{8}$$

where ET_a is the actual evapotranspiration measured by the EC system and ET_0 is the reference evapotranspiration.

2.11 Energy imbalance calculation

The slope of the turbulent heat flux (LE + H) and available heat flux (Rn – G) computed using ordinary least squares was used to measure the eddy covariance energy balance closure (Wohlfahrt and Widmoser, 2013; Chatterjee et al. 2019b). Magnitudes of the energy balance parameters have been represented in Table 1.

Table 1 The mean value of micrometeorological and half-hourly eddy covariance data during the dry season, dry fallow period, wet season, and wet fallow periods for the 2015 and 2016 study years

Meteorological drivers	2015				2016			
	DS	DF	WS	WF	DS	DF	WS	WF
LE (W m^{-2})	80.5	99.6	64.9	30.3	93.2	92.5	63.2	31
Rn (W m^{-2})	137.4	155.4	130.9	91.2	132.6	147.6	118.6	104.9
H (W m^{-2})	6.8	16.8	9.5	19	1.2	29.4	12.8	25.5
G (W m^{-2})	−8.9	−7.6	−8.2	−8.8	−9.2	−8.3	−8.9	−10
$T_{Average}$ (°C)	28	34.3	32.2	25.6	30	34.2	31.9	23.7
VPD (kPa)	0.2	0.2	0.2	0.4	0.4	0.4	0.2	0.5

Note: *LE* latent heat flux, *Rn* net radiation, *H* sensible heat flux, *G* ground heat flux at 15 cm depth, $T_{Average}$ average air temperature, *VPD* vapor pressure deficit, *DS* dry season, *DF* dry fallow, *WS* wet season, *WF* wet fallow

2.12 Statistical analysis

The coefficient of determination (R^2), adjusted R^2 value, intercept, the slope of regression equations between E_0 determined by the FAO-PM approach, and other models were computed using least squares (Draper and Smith 1998). Multiple regression analyses, the mean bias error (MBE), root mean square error (RMSE), agreement index (AI) (Willmott et al. 1985), standard error, percentage error (Jamieson et al. 1991), t-statistic value, and p-value were also computed. Equations for MBE, RMSE, and AI are given in Eqs. 9, 10, and 11 as follows:

$$MBE = \sum_{i=1}^{n} \frac{P_i - O_i}{n} \tag{9}$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(P_i - O_i\right)^2}{n}} \tag{10}$$

$$AI = 1 - \frac{\sum_{i=1}^{n} \left(P_i - O_i\right)^2}{\sum_{i=1}^{n} \left|P_i - \bar{O}\right| + \left|O_i - \bar{O}\right|^2} \tag{11}$$

where P_i and O_i are the model predicted values and observed values, respectively, and $\bar{O}$ is the mean of the observed values. These popular statistical matrices were previously used by many researchers (e.g., Stannard, 1993; Yang et al. 2015; Chatterjee et al. 2021a) for inter-model comparison and performance assessment.

3 Results

3.1 Daily, seasonal, and stage-wise variation of actual evapotranspiration in lowland rice

The daily variation of rice ET_a including other meteorological variables (e.g., rainfall, temperature) for 2015–2016 is shown in Fig. 2. Figure 3 illustrates the daily variation in ET_a with respect to E_{pan}, whereas Fig. 4 depicts the stage-wise and seasonal variation of ET_a in 2015 and 2016. The ET_a of rice varied from 0.25 to 6.88 mm d^{-1} and 0.47 to 6.63 mm d^{-1} during the dry seasons of 2015 and 2016, respectively; however, it varied from 1.29 to 6.75 mm d^{-1} during the dry fallow period in 2015 and 2016, respectively (Fig. 3). The maximum ET_a values of 7.60 and 6.87 mm d^{-1} were recorded on the 110th and 109th Julian day of the dry season in 2015 and 2016, respectively (Fig. 3). ET_a increased as LAI increased during the dry season in both years but no such trend was observed during the wet season of both years (Table 2). The ET_a values for the wet season varied from 0.43 to 4.48 mm d^{-1} and 0.89 to 4.79 mm d^{-1} during 2015 and 2016 and it ranged from 0.06 to 2.06 mm d^{-1} and 0.59 to 1.93 mm d^{-1} for the wet fallow period during 2015 and 2016, respectively. The ET_a increased as the crop growth stages progressed during the dry seasons and decreased in both the fallow periods (Fig. 4). The mean ET_a during the dry season, 2.86 and 3.32 mm, was greater than that of the wet season, 2.31 and 2.24 mm, during 2015 and 2016, respectively. The seasonal ET_a values were 352 and 408 mm during the dry seasons, and 297 and 290 mm during the wet seasons for 2015 and 2016, respectively.

The Pearson correlation and multiple linear regression (MLR) analysis between ET_a and other energy balance components during the dry seasons in both years are shown in Tables 3 and 4. Rice ET_a significantly correlated with Rn (r = 0.89), H (r = −0.79), G (r = 0.76), and $T_{Average}$ (r = 0.85) in the 2015. Significant correlation among rice ET_a and other meteorological parameters were also observed during 2016: Rn (r = 0.84), H (r = −0.84), G (r = 0.66), $T_{Average}$ (r = 0.85), and VPD (r = −0.32). When fitted an MLR algorithm, the model performed well for estimating ET_a from energy balance parameters for lowland rice with a model R^2 of 0.91 and 0.85, and RMSE of 0.45 and 0.73, for the years 2015 and 2016, respectively (Table 4).

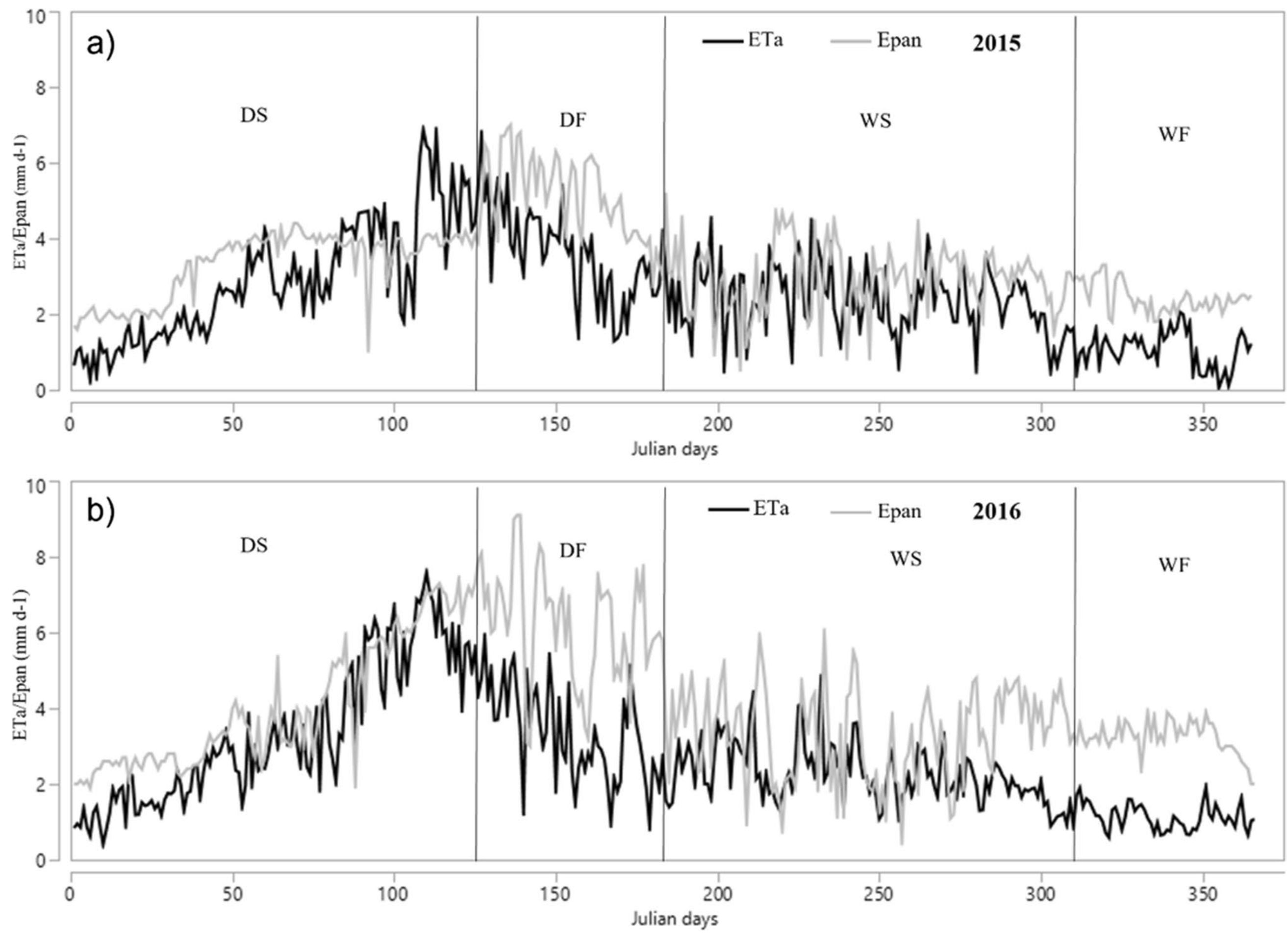
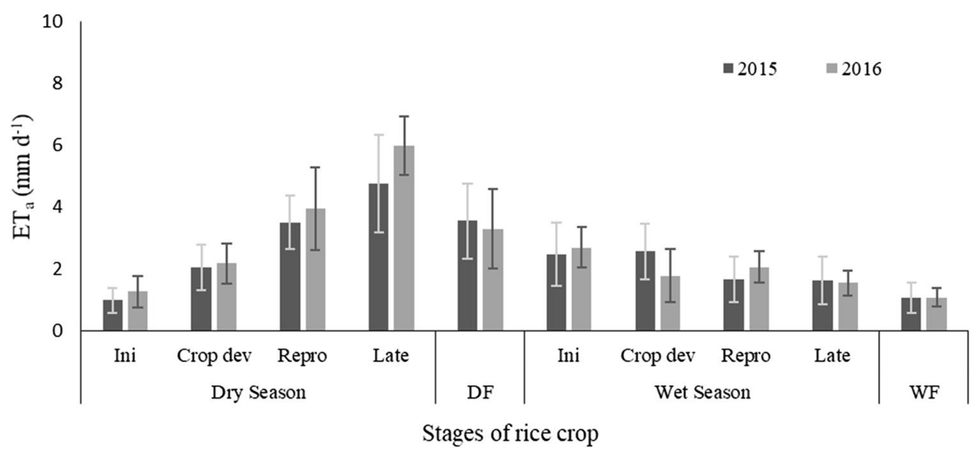


Fig. 3 Daily variation of actual evapotranspiration (ET_a) and pan evaporation (E_{pan}) in 2015 (**a**) and 2016 (**b**). DS = dry season; WS = wet season; DF = dry fallow; WF = wet fallow

Fig. 4 Mean seasonal and stage-wise variation of actual evapotranspiration (ET_a) in a lowland irrigated rice in eastern India during 2015 (black bars) and 2016 (gray bars). Note: DF, dry fallow; WF, wet fallow; Ini, initial stage; Crop dev, crop development stage; Repro, reproductive stage; Late, late-season stage



3.2 *Comparison of reference evapotranspiration (ET_0) with FAO-PM method*

Rice ET_a is controlled by different biophysical factors including vegetation structure and density, growth phase, stomatal conductance, and meteorological conditions. To understand the differences in rice ET_a during its growing seasons, its relations with the atmospheric conditions through ET_0 (Table 5) and the biophysical factors through the K_c (Table 7) were analyzed. Statistics of different

Table 2 Mean actual evapotranspiration measured using eddy covariance and leaf area index measured using a LAI-2200C Plant Canopy Analyzer across crop growth stages and seasons during 2015 and 2016

Seasons	Stages	No. of days	ET_a (mm d^{-1})		LAI (m^2 m^{-2})	
			2015	2016	2015	2016
Dry season	Initial	22	1.01	1.28	2.01	2.25
	Crop development	36	2.07	2.19	4.85	4.53
	Reproductive	43	3.52	3.95	5.03	4.95
	Late season	22	4.75	5.99	2.21	2.37
	Seasonal mean	123	2.86	3.32	-	-
Seasonal total		123	352.2	408.5	-	-
Wet season	Initial	21	2.48	2.71	3.14	2.89
	Crop development	37	2.57	1.80	4.02	3.75
	Reproductive	45	1.67	2.08	5.23	4.69
	Late season	24	1.64	1.56	2.11	2.92
	Seasonal mean	127	2.31	2.24	-	-
Seasonal total		127	296.7	289.6	-	-

Note: ET_a actual evapotranspiration, *LAI* leaf area index

Table 3 Pearson correlation coefficient (r) of actual evapotranspiration (ET_a) with different meteorological parameters for lowland rice in eastern India during the 2015 and 2016 dry seasons. For abbreviations and units, refer to Table 1

Year		ET_a	Rn	H	G	$T_{Average}$	VPD
2015	ET_a	1					
	Rn	0.89^{***}	1				
	H	-0.79^{***}	-0.57^{***}	1			
	G	0.76^{***}	0.79^{***}	-0.55^{***}	1		
	$T_{Average}$	0.85^{***}	0.79^{***}	-0.72^{***}	0.87^{***}	1	
	VPD	-0.17	-0.14	0.26^{**}	-0.21^{*}	-0.20^{*}	1
		ET_a	Rn	H	G	$T_{Average}$	VPD
2016	ET_a	1					
	Rn	0.84^{***}	1				
	H	-0.84^{***}	-0.69^{***}	1			
	G	0.66^{***}	0.65^{***}	-0.51^{***}	1		
	$T_{Average}$	0.85^{***}	0.81^{***}	-0.78^{***}	0.79^{***}	1	
	VPD	-0.32^{***}	-0.23^{*}	0.26^{**}	-0.15	-0.26^{**}	1

$^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

Table 4 Multiple linear regression analysis between actual evapotranspiration against other energy balance parameters for lowland rice in eastern India during the 2015 and 2016 dry seasons. For abbreviations and units, refer to Table 1

Year	Actual ET		Rn	H	G	$T_{Average}$	VPD	RMSE	Model R^2
2015	ET_a (mm d^{-1})	Sig. Prob	*	*	*ns*	*	*ns*	0.45	0.91
		Partial R^2	0.78	0.90	0.91	0.91	0.91		
2016	ET_a (mm d^{-1})	Sig. Prob	*	*	*ns*	*	*ns*	0.73	0.85
		Partial R^2	0.84	0.80	0.85	0.72	0.85		

*The values are significant at $p<0.05$; *Sig. Prob.* significant probability, *RMSE* root mean square error, R^2 coefficient of determination, *ns* not significant

methods of ET_0 estimation in comparison with the FAO Penman–Monteith method during both seasons and both years are shown in Table 6. The relationship between FAO-PM and E_{pan} derived ET_0 in a lowland irrigated rice in eastern India during 2015 and 2016 is depicted in Fig. 5.

During the 2015 dry season, the maximum ET_0 (630 mm) was estimated by FAO-PM and the minimum

Table 5 Stage-wise and seasonal mean reference evapotranspiration (ET_0, mm d^{-1}) estimated using the FAO Penman–Monteith (FAO-PM), Hargreaves and Samani (HS), Mahringer (MG) and Pan evaporation (E_{pan}) during 2015 and 2016

Seasons	Crop growth stages	ET_0 2015				ET_0 2016			
		FAO-PM	HS	MG	E_{pan}	FAO-PM	HS	MG	E_{pan}
Dry season	Initial	4.45	3.95	2.53	1.38	3.97	4.47	2.33	1.68
	Crop development	4.97	4.63	3.31	2.24	4.22	4.61	3.34	2.12
	Reproductive	5.51	4.86	4.39	2.73	5.22	5.00	5.20	3.10
	Late season	5.29	4.71	4.75	2.76	6.83	5.55	9.92	4.75
	Seasonal mean	5.12	4.61	4.05	2.35	5.00	4.89	5.00	2.86
Seasonal total		630	566	498	289	614	601	614	351
Wet season	Initial	2.10	3.76	2.36	1.85	2.04	3.49	1.82	2.66
	Crop development	2.71	3.64	2.49	2.15	2.57	3.04	1.64	2.31
	Reproductive	3.53	3.53	2.19	2.16	3.10	3.21	1.38	2.07
	Late season	4.33	4.01	2.10	2.01	4.71	4.04	2.45	2.72
	Seasonal mean	3.19	3.69	2.29	2.08	3.04	3.36	1.73	2.36
Seasonal total		414	469	290	264	392	427	220	300
Dry fallow (DF)		301	294	331	227	292	259	291	275
Wet fallow (WF)		175	209	99	87	264	241	122	119

was estimated using the E_{pan} approach (289 mm) in 2015. During the 2016 dry season, the maximum ET_0 of 614 mm was estimated by the FAO-PM and MG methods and the minimum with the E_{pan} method (351 mm) (Table 5). During the 2015 wet season, the maximum ET_0 (469 mm) was estimated by the HS method and the minimum with the

Table 6 Statistics of different methods of reference evapotranspiration (ET_0) in comparison to FAO Penman–Monteith method. For abbreviations, see Table 5

Methods	HS		MG		E_{pan}	
	2015	2016	2015	2016	2015	2016
Dry season						
MBE	0.52	0.10	1.07	0.00	2.77	2.14
RMSE	1.30	1.20	1.86	2.09	3.08	2.49
Agreement index	0.70	0.78	0.70	0.76	0.40	0.54
R^2	0.31	0.44	0.38	0.51	0.11	0.38
Adjusted R^2	0.31	0.44	0.38	0.50	0.11	0.37
Standard error	0.85	0.81	1.51	2.05	0.59	0.93
Percentage error	28.2	24.53	45.93	41.80	131.06	87.06
Intercept	2.55	2.64	− 0.20	− 1.45	1.60	0.61
t-statistic	8.93*	10.96*	− 0.40	-2.38*	8.07*	2.21*
p-value	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Slope	0.40	0.45	− 0.20	− 1.45	1.60	0.61
Wet season						
MBE	− 0.47	− 0.30	0.94	1.34	1.15	0.70
RMSE	1.88	1.91	2.15	2.15	2.09	1.90
Agreement index	0.89	0.74	0.76	0.83	0.75	0.83
R^2	0.08	0.10	0.02	0.25	0.09	0.17
Adjusted R^2	0.07	0.10	0.02	0.25	0.08	0.16
Standard error	0.98	0.97	0.98	0.74	0.57	0.76
Percentage error	55.95	56.84	93.89	124.28	100.48	80.51
Intercept	3.19	2.85	2.02	1.06	1.77	1.83
t-statistic	18.17*	17.72*	11.52*	8.62*	17.40*	14.52*
p-value	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Slope	0.16	0.17	0.08	0.22	0.10	0.18

*The values are significant at $p < 0.05$; *MBE* mean bias error, *RMSE* root mean square error, R^2 coefficient of determination

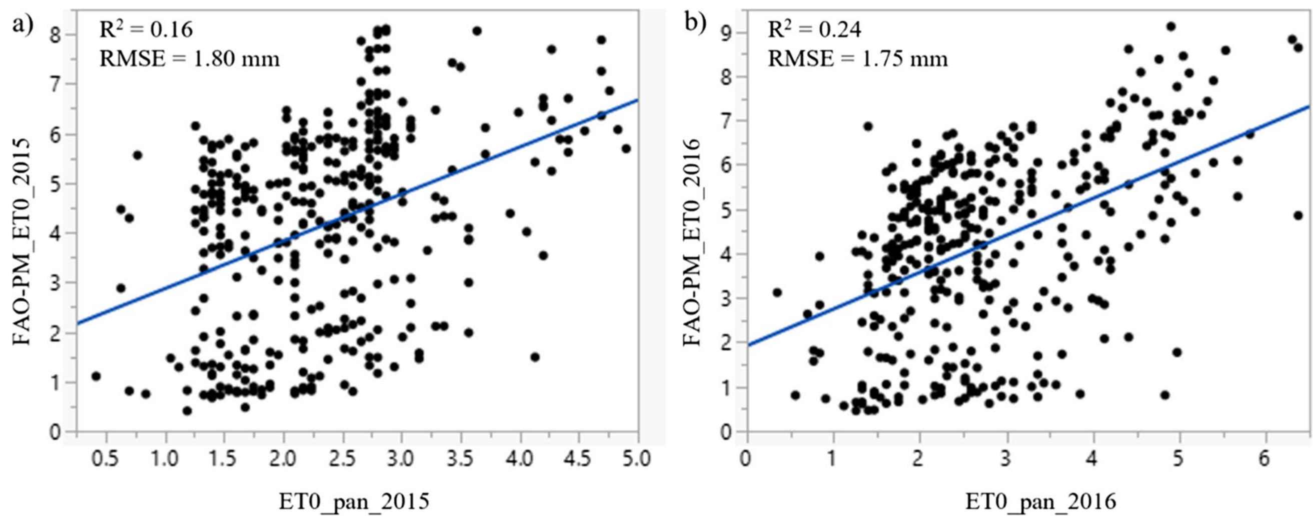


Fig. 5 Relationship between FAO-PM and E_{pan} derived reference evapotranspiration in a lowland irrigated rice in eastern India during 2015 (**a**) and 2016 (**b**). Note: FAO-PM ET0 denotes FAO Penman–Monteith method derived reference ET; ET0_pan denotes pan evaporimeter derived reference ET

E_{pan} method (264 mm), and during the 2016 wet season, a maximum ET_0 of 427 mm was estimated by the HS method and minimum with the MG method (220 mm) (Table 5). During the 2015 dry fallow, the maximum ET_0 (331 mm) was estimated by the MG method and the minimum with the E_{pan} method (227 mm), and during the 2016 dry fallow, a maximum ET_0 of 292 mm was estimated by the FAO-PM method and minimum with the HS method (259 mm). During the 2015 wet fallow, the maximum ET_0 (209 mm) was estimated by the HS method and the minimum was estimated using the E_{pan} method (87 mm) in 2015. During the 2016 wet fallow, the maximum ET_0 of 264 mm was estimated by the FAO-PM and minimum with the E_{pan} method (119 mm) (Table 5).

The RMSE value between ET_0 estimated using the FAO-PM method and the HS, MG, and E_{pan} methods were 1.30, 1.86, and 3.08 mm and 1.20, 2.09, and 2.49 mm for the DS of 2015 and 2016, respectively (Table 6). The relationship between FAO-PM and E_{pan} method has been depicted in Fig. 5. It is worth mentioning that in the dry seasons only the HS model had the percentage error < 30%, whereas, E_{pan} had the highest percentage error in comparison to the FAO-PM, indicating its poor performance in estimating the ET_0 in this region. The order of performance in the dry season: HS > MG > E_{pan}. It was also observed that all the three methods performed very poorly in the wet seasons as compared to the FAO-PM method as indicated by high RMSE and percentage error values and low R^2; however, the percentage error was least with the HS method as compared to other methods during the wet seasons (Table 6).

3.3 Seasonal variation of crop coefficients

The stage-wise mean K_c values for lowland rice in eastern India are shown in Table 7. It can be shown that depending on the choice of ET_0 estimation the magnitude of K_c values slightly varied across the two seasons and at different crop growth stages between 2015 and 2016. For example, during the dry season, K_c values for the initial, crop development, and reproductive and late-season stages were 0.23, 0.42, 0.64, 0.90 and 0.32, 0.52, 0.76, and 0.88 for 2015 and 2016, respectively, based on the FAO-PM method. However, the MG method produced K_c of 0.40, 0.63, 0.80, and 1.00 for the 2015 dry season and 0.55, 0.66, 0.76, and 0.60 for the 2016 dry season in those four stages (i.e., initial to late-season). The percent change in K_c values in 2016 as compared to 2015 is also shown in Table 7. It was observed that during the dry season of 2016 the maximum increased in K_c values was associated with the FAO-PM method followed by the MG, HS, and E_{pan} method as compared to the dry season of 2015. The wet season results were not discussed further as we could not find any significant trend in the K_c values during the wet seasons of 2015 and 2016.

3.4 Eddy covariance energy balance closure

The mean values of energy balance components (e.g., LE, Rn, H, and G) were recorded by the EC system in the lowland rice field during both the seasons (dry and wet seasons) and fallow periods (dry and wet fallows) are presented in Table 1. The available energy (Rn – G) was larger than the turbulent fluxes of sensible and latent heat (H + LE) throughout both years of the study. The linear regression equations

Table 7 Stage-wise mean crop coefficient (K_c) values for lowland rice estimated using different reference evapotranspiration (ET_0) calculation methods. For abbreviations, refer to Table 5. Numbers in brackets indicate percent change of K_c values in 2016 as compared to 2015. Positive sign denotes increase and negative sign indicates decrease in K_c values

Seasons	Crop growth stages	2015				2016			
		FAO-PM	HS	MG	E_{pan}	FAO-PM	HS	MG	E_{pan}
Dry season	Initial	0.23	0.25	0.40	0.73	0.32 (+39.13)	0.29 (+16)	0.55 (+37.5)	0.76 (+4.10)
	Crop development	0.42	0.45	0.63	0.92	0.52 (+23.80)	0.48 (+6.67)	0.66 (+4.76)	1.03 (+11.95)
	Reproductive	0.64	0.72	0.80	1.29	0.76 (+18.75)	0.79 (+9.72)	0.76 (−5)	1.27 (−1.55)
	Late season	0.90	1.01	1.00	1.72	0.88 (−2.22)	1.08 (+6.93)	0.60 (−40)	1.26 (−26.74)
Wet season	Initial	1.18	0.66	1.05	1.34	1.33 (+12.71)	0.78 (+18.18)	1.49 (+41.90)	1.02 (−23.88)
	Crop development	0.95	0.71	1.03	1.20	0.70 (−26.31)	0.59 (−16.90)	1.10 (+6.79)	0.78 (−35)
	Reproductive	0.47	0.47	0.76	0.77	0.67 (+42.55)	0.65 (+38.29)	1.51 (+98.68)	1.00 (+29.87)
	Late season	0.38	0.41	0.78	0.82	0.33 (−13.15)	0.39 (−4.87)	0.64 (−17.94)	0.57 (−30.48)

Table 8 Energy balance closure of lowland rice in eastern India using ordinary least squares

Seasons	2015		2016	
	Equations	R^2 (%)	Equations	R^2 (%)
Dry season	y = 0.84x − 20.90	84*	y = 0.93x − 21.14	75*
Dry fallow	y = 0.76x + 4.23	81*	y = 0.73x + 19.11	73*
Wet season	y = 0.46x + 17.55	48*	y = 0.37x + 34.36	42*
Wet fallow	y = 0.67x − 6.00	69*	y = 0.42x + 14.97	33*
Annual	y = 0.73x − 8.13	72*	y = 0.72x + 1.41	62*

*The values are significant at $p < 0.01$; y and x denote turbulent energy fluxes (H + LE) and available energy fluxes (Rn – G), respectively; R^2 coefficient of determination

by the ordinary least square method indicated a greater value of slope in the dry season (0.84 and 0.92), and the dry fallow period (0.76 and 0.73), while it showed a comparatively lesser value in the case of the wet season (0.46 and 0.37), and the fallow period (0.67 and 0.42) in 2015 and 2016, respectively (Table 8). From Table 8, it can be shown that the R^2 values that were computed among available energy fluxes and turbulent fluxes in lowland rice were significantly higher in the dry seasons ($R^2 = 84$ and 75%) and dry fallow period ($R^2 = 81$ and 73%) of 2015 and 2016, respectively. However, the R^2 values were considerably lower in wet seasons ($R^2 = 48$ and 42%) and wet fallow ($R^2 = 69$ and 33%) of 2015 and 2016, respectively. In other words, the energy balance was more closed in the dry season and dry fallow period as compared to the wet season and wet fallow period of both years of study. The year-round energy balance closure in the lowland rice was 73 and 72%, while the R^2 values were 72 and 62% for 2015 and 2016, respectively. It is also worth noting that the R^2 values were statistically significant ($p < 0.01$) in both years of study.

4 Discussion

4.1 Seasonal variation of actual evapotranspiration and controlling factors

ET_a was higher during the crop growing seasons and the mean ET_a during the dry season was greater than the wet season in both years of study which may be attributed to greater available energy via incoming shortwave radiation during the dry seasons (Timm et al. 2014). A seasonal ET_a of 587 mm for rice in a semi-arid climate in Karnal, India (29° 43′ N, 76° 58′ E), was reported by Tyagi et al. (2000). Bhardwaj (1983) used a weighing lysimeter in a rice field in Dehra Dun, India (30° 20′ 41.6″ N, 78° 00′ 52.6″ E) which is under a sub-humid climatic condition and reported a seasonal ET_a of about 500 mm. This ET_a value is 24 and 18% higher than that of the values measured using the EC system in this study at Cuttack, India, during the dry seasons of 2015 and 2016, respectively. A mean growing season ET of 4.36 and 4.13 mm d^{-1} during the two different growing seasons for dry-seeded rice were reported by Alberto et al. (2014) using the EC system in the Philippines (14° 8′ 49.72″ N, 121° 15′ 58.10″ E), which is comparable to the ET_a values obtained in our study (2.86 and 3.32 mm d^{-1} during dry seasons of 2015 and 2016, respectively).

In Asia, the characteristic daily ET_a rates of rice range from 4 to 7 mm d^{-1} (Tuong 2000; De Datta 1981). A maximum ET_a of 6.5–7.2 mm d^{-1} at 6 to 9 weeks after transplanting was recorded in northern India under sub-humid and semi-arid conditions (Bhardwaj 1983; Sandhu et al. 1982; Tyagi et al. 2000). The ET_a values were much lower in the wet season (Chatterjee et al. 2017) because of the reduced atmospheric demand for water vapor during this season and lower Rn (5–12%).

The average ET_a in the dry season was more than that of the wet season in both study years due to lower Rn (Tyagi et al. 2000). Pearson correlation analysis confirmed that ET_a

has a significant positive and strong linear relationship with air temperature ($T_{Average}$) and net radiation (Rn) during both study years (Table 3). These observations are consistent with the notion that ET_a from irrigated rice crops is energy-limited but also controlled by crop development; ET_a decreased during the fallow periods due to the absence of transpiration from the rice crop (Chatterjee et al. 2019c; Timm et al. 2014). The ET_a increased with an increase in LAI in the dry seasons; however, there was no significant increasing trend observed during the wet seasons. This might be attributed to the average meteorological condition during the wet seasons in this region of India, which are characterized by a high amount of cloud cover, reduced net radiation, and photosynthetically active radiation which in turn caused in damping of diurnal variation of temperature and vapor pressure deficit (Peterson et al. 1995; Brutsaert and Parlange, 1998). These factors might have attributed to the reduction in ET_a; however, these factors have a secondary role in decreasing LAI which is a plant biophysical trait and more controlled by plant physiology and phenology (Levis and Bonan, 2004; Zhang et al. 2012).

It is also worth noting that in many instances the ET_a was greater than Epan values at different stages of rice growth (Tables 2 and 5); however, it is worth noting that the seasonal mean value of ET_a did not exceed the E_{pan} value in both the season of 2015–2016. This research also sheds some light on the general aspects of actual (measured by EC system) and potential ET (in terms of reference ET or E_{pan}). The amount of heat energy for evaporation and supply of moisture at the surface are usually the limiting factors for ET_a. Previous studies are suggesting that the ET rate from plants (i.e., ET_a) can exceed the evaporation pans (E_{pan}) for short periods of time (e.g., at different stages of plant growth) in which there is considerable advected heat and decrease in the diurnal temperature range (Tanner and Pelton, 1960; McIlroy and Angus, 1964; Eagleman, 1967; Peterson et al. 1995; Zhang et al. 2007). More water is lost from plants with increased warm air advection as the lower leaves are supplied with advective energy for use in the ET process (Eagleman, 1967). In this study, the rice field was flooded most of the time suggesting that the soil moisture was not a limiting factor for ET_a (Chatterjee et al. 2020c). The decrease in E_{pan} may also be attributed to a phenomenon called "Pan Evaporation Paradox," which suggests the complementary relationship between actual ET (ET_a) and potential ET (Chattopadhyay and Hulme, 1997; Lawrimore and Peterson, 2000; Hobbins et al., 2004; van Heerwaarden et al. 2010). Further research is needed to study the role of advection energy in ET rate from plants and open surfaces (e.g., pan, lakes).

Moreover, the ET_a was measured using the EC system which relies on some assumptions (e.g., stationarity, mass conservation) and thus contain uncertainty in the data in terms of system errors, correction techniques (e.g., density correction, terrain corrections), and data processing techniques (Baldocchi et al. 2000; Twine et al. 2000; Hollinger and Richardson, 2005; Mauder et al. 2013; Massman and Lee, 2002); however, this is beyond the scope of this paper to study the uncertainties in EC measurements. Further research should be carried out to validate EC with lysimeter data.

4.2 *Comparison of reference evapotranspiration (ET_0)*

Overall good agreement was observed between the FAO-PM and the other three methods during dry seasons of both years of study as compared to the wet seasons. Therefore, while working with water resource management for lowland rice when water is limiting in the dry season, a simpler approach may be adapted which generates defensible K_c values (Tyagi et al. 2000). These findings are perhaps surprising given that simpler methods to calculate ET_0 seek to simplify the representation of diabatic controls over ET_a, which can be reconciled in part by the strong relationship between Rn and inputs to the HS and MG models (Eqs. 5 and 6) during the dry season of both study years (Table 3). A better agreement was observed among the FAO-PM, HS, and MG methods during the 2016 dry season than the 2015 dry season (Table 6) which is likely due in part to the lack of relationship between Rn and VPD during the 2015 dry season (Table 3). From Table 6, it can be shown that for wet seasons the margin of errors was more as compared to dry seasons which is supported by the higher percentage error values and lower R^2 values in wet seasons than that of dry seasons for both years of study. This might be due to the complex relationship between energy balance parameters (e.g., Rn, H, G, and LE) and other meteorological factors (e.g., $T_{Average}$ and VPD) which controls ET_0 in the wet seasons. We didn't find any significant correlation between rice ET_a and energy balance parameters and other meteorological variables during the wet seasons of both years of study in the lowland rice field.

We also observed that the E_{pan} data are still underestimated in this region. This may be due to the following reasons: (a) the ET_0 from the pan was calculated using a uniform pan constant ($K_p = 0.71$ following Allen et al. 1998) which needs to be validated for this lowland rice ecology, (b) the E_{pan} data mimics the evaporation from a free water body (e.g., lake) which sometimes underestimate the role of vegetation in similar moisture condition (e.g., flooded rice), (c) the E_{pan} data may contain some human error in data recording which may cause errors in calculation. We assume that the E_{pan} data contain some uncertainties and error terms due to these reasons which should be used with caution. Some researchers also suggested that the global trend of pan evaporation has been decreasing in contrast to the evaporation from the land surface which is called the "evaporation paradox" (Brutsaert and Parlange, 1998). Bouchet (1963) reported that E_{pan} and actual evaporation diverges from each other when the land dries. Similarly in this study, we observed a more decreasing trend in E_{pan} during the dry seasons and an overall poor relationship between FAO-PM and E_{pan} data (Fig. 5). These observations are further corroborated by Lawrimore and Peterson (2000), Golubev et al. (2001), Hobbins et al. (2004), and Kahler and Brutsaert (2006).

On the other hand, the other methods of calculating ET_0 which used meteorological data (e.g., net radiation, temperature, humidity, wind speed, vapor pressure deficit) in calculation agree well with the FAO-PM method (Table 6); hence, these methods could coherently characterize the representative ET_0 for this lowland rice region in eastern India. This dataset could be further validated with lysimeter data in future research; however, in absence of lysimeter, ET_0 rates are generally estimated from empirical predictive equations that require meteorological data which are widely available.

4.3 Seasonal variation of crop coefficients

The K_c values obtained from the MG and E_{pan} method during the 2015 dry season and K_c values obtained from the FAO-PM, MG, and E_{pan} methods during the 2016 dry season (Table 7) differed from most K_c values reported in the literature (Brouwer and Heibloem 1986; Tyagi et al. 2000; Alberto et al. 2014). Tyagi et al. (2000) reported K_c values of 1.15, 1.23, 1.14, and 1.02 for growth stages—initial, crop development, reproductive, and late-season of rice using FAO-PM approach in northern India. Brouwer and Heibloem (1986) and Alberto et al. (2014) also reported a similar trend in K_c of rice. Crop coefficient values for lowland flooded rice grown in tropical climatic regions are not available by the FAO. The K_c values for rice as reported by FAO (Allen et al. 1998) are 1.05, 1.20, and 0.90–0.60 for initial, crop development, and harvest stage, respectively. Results for K_c (Table 7) shown in our 2-year study period were slightly different than the K_c values reported by the FAO for rice (Allen et al. 1998), Alberto et al. (2011), and Timm et al. (2014), but the performance of the four methods also varied with years (Table 7). This may be due to the variation of ET_a in a different year with varying meteorological factors especially Rn and VPD. In this lowland rice field, the magnitude of K_c values was generally underestimated as compared to the findings of other researchers with respect to rice. This might be due to the lack of energy balance closure in the lowland rice (Table 8). Only 84 and 75% of the energy balance was found to be closed during the dry seasons of 2015 and 2016, respectively (Table 8). In addition, it is observed that the variations of K_c for dry seasons for 2015 and 2016 differed substantially. We found that the actual ET varied in the 2 years (i.e., 2015 and 2016) which is also evident from the average latent heat flux (LE) data in the dry seasons (Table 1) which shows that 2016 had a higher average LE value as compared to 2015. For that reason, the actual ET in 2016 was higher which significantly increased the K_c value in the 2016 dry season (as $Kc = ET_a/ET_0$). This can also be supported from the vapor pressure deficit (VPD) data in Table 1 which shows that 2016 had higher VPD which resulted in higher actual ET in that year as compared to 2015. Energy imbalances in lowland rice might have attributed significantly to the variation in actual ET in this region (Liu et al. 2017; Chatterjee et al. 2020a). In addition, the eddy covariance data have some uncertainties and error terms that may have contributed to the measurements of LE. The nature of the relationship between lowland rice ET_a and meteorological drivers is also not studied extensively for this tropical humid climatic region of India (Chatterjee et al. 2020c). Furthermore, eddy covariance systems have many error terms that are associated with measurements of flux and density, wind advection, and gaps in data which are important to keep in mind when interpreting results.

4.4 The energy imbalance in lowland rice

In most of the eddy covariance networks (Aubinet et al. 1999; Wilson et al. 2002; Leuning et al. 2012), a closure of the energy balance of approximately 75–87% was achieved (Wilson et al. 2002; Barr et al. 2006; Franssen et al. 2010; Stoy et al. 2013). Much of the energy imbalance during the growing seasons occurred during the 1–3 days after the rainfall events as freshwater stored and diverted available energy (Chatterjee et al. 2019b) suggesting that the advection of heat transported in liquid water was a major source of the imbalance. Continuous standing water in the rice field also influenced the partitioning and capture of available energy (Chatterjee et al. 2020a). A slope of 0.73–0.84 was achieved during the dry season and dry fallow period showing better energy balance closure during those periods compared to the wet season and wet fallow period (0.33–0.69). In our 2-year study period, the slope varied from 0.72–0.73, a similar coefficient reported for a rice paddy by Hossen et al. (2012). Hatala et al. (2012) reported a slope of 0.65 for hourly energy balance closure in agricultural peatlands. Discrepancies in energy balance closure may happen due to underestimation in surface energy fluxes measurements (Aubinet et al. 1999; Kanda et al. 2004) and partitioning of unaccounted energy stored in the canopy, standing water, soil, and usage in plant physiological processes such as photosynthesis (Tsai et al. 2007; Timm et al. 2014; Liu et al. 2017). For these reasons, the energy balance closure measured only using the EC method and excluding these minor terms should not be expected to reach 100%.

5 Conclusions

Actual evapotranspiration and crop coefficients were calculated using eddy covariance data from a tropical lowland rice field. A significant positive and stronger correlation of ET_a with $T_{Average}$ and Rn was observed in the dry season of both years of study. Overall good agreement was observed between the FAO-PM and three alternate ET_0 methods during dry seasons as compared to the wet season of both years of study, in part because these approaches use temperature and solar radiation as inputs. As a consequence, the MG and HS methods might be useful during the dry seasons of the lowland rice area of eastern India as these methods produced estimates of ET_0 that are comparable to the FAO-PM approach. In the dry seasons, the FAO-PM method followed by HS and MG method produced estimates of K_c which are in close agreement with the FAO method (Allen et al. 1998) for the reproductive and late-season stages of lowland rice ($K_c = 0.9–0.6$). The E_{pan} method estimated K_c more realistically as compared to other methods during the wet seasons but requires additional measurement infrastructure and further research and should be used with caution. K_c values derived for tropical lowland rice in eastern India for this study are different from those suggested by the FAO which indicates that K_c values may need to be revised for regional-scale irrigation scheduling. From this study, we recommend K_c values for the dry seasons which were obtained from the MG method in 2016 which are 0.55, 0.66. 0.76, and 0.60 for the initial, crop development, reproductive, and late-season stages respectively. For the wet seasons, the K_c values of 1.02.0.78, 1.00, and 0.57 could be used for initial, crop development, reproductive, and the late-season stages, respectively, which were obtained from the E_{pan} method; however, E_{pan} data should be used with caution in this region. Therefore, these K_c and ET_a values may prove to be useful for better projecting precise crop water requirements and irrigation management of tropical lowland rice in eastern India. The methodology could also be implemented in similar edaphoclimatic and data-scarce regions in the world where lysimeters are not available and rice is the major cultivated crop.

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Author contribution SC prepared the first draft. SC, MD, and PCS helped in the data analysis and interpretation. SC, PCS, MD, and AKN contributed to the conceptualization of the work. PCS, CKS, SSM, AT, RT, and HP contributed to the formatting, editing, and revision processes. HP, SC, DC, and AKN assisted in the logistics and data curation. AKN helped in the correspondence process.

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Data availability The data for this research work are available from the corresponding author upon reasonable request.

Code availability The codes for this research work are available from the corresponding author upon reasonable request.

Declarations

Ethics approval This work complied with all the necessary ethical approval processes and consents from all the co-authors before the beginning of the research work.

Consent to participate Consents from all the co-authors were obtained for participating in this study at the beginning of the research work.

Consent for publication Consents from all the co-authors were obtained for publishing this work in the *Theoretical and Applied Climatology* journal before correspondence.

Competing interests The authors declare no competing interests.

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Authors and Affiliations

Sumanta Chatterjee[1,2] · Paul C. Stoy[3,4] · Manish Debnath[1] · Amaresh Kumar Nayak[1] · Chinmaya Kumar Swain[1] · Rahul Tripathi[1] · Dibyendu Chatterjee[1] · Smruthi Sagarika Mahapatra[1,5] · Ammara Talib[4] · Himanshu Pathak[6]

[1] Division of Crop Production, ICAR-National Rice Research Institute, Cuttack 753006, India

[2] Department of Soil Science, University of Wisconsin-Madison, Madison, WI 53706, USA

[3] Department of Biological Systems Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA

[4] Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, WI 53706, USA

[5] Agricultural Microbiology Department, Indira Gandhi Krishi Viswavidyalaya, Raipur, Chhattisgarh 492001, India

[6] ICAR-National Institute of Abiotic Stress Management, Maharashtra 413115, India