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# Application of an energy balance method for estimating evapotranspiration in cropping systems

Saseendran S. Anapalli[a,*], Timothy R. Green[b], Krishna N. Reddy[a], Prasanna H. Gowda[c], Ruixiu Sui[a], Daniel K. Fisher[a], Jerry Moorhead[d], Gary Marek[d]

[a] USDA-ARS, Crop Production Systems Research Unit, Stoneville, MS, 38776, United States
[b] USDA-ARS, Water Management and Systems Research Unit, Fort Collins, CO, 80525, United States
[c] USDA-ARS, Forage and Livestock Production Research Unit, El Reno, OK, 73036, United States
[d] USDA-ARS, CPRL,2300 Experiment Station Road, Bushland, TX, 79012, United States

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ABSTRACT

Accurate quantification of evapotranspiration (ET, consumptive water use) from planting through harvest is critical for managing limited water resources for crop irrigation. Our objective was to develop and apply a land-crop surface residual energy balance (EB) method for quantifying ET and to estimate ET of corn (*Zea mays* L.) for the first time in the climate of the lower Mississippi (MS) Delta region. Actual ET ($ET_e$) was estimated as the residual term of the energy balance equation from measurements of net solar irradiance ($R_n$) and computed sensible heat ($H$) and ground heat ($G_o$) fluxes. The $H$ flux was computed from measurements of the air and crop canopy temperature differential and modeling the aerodynamic resistance ($r_a$) to heat and water transport in the turbulent atmospheric boundary layer above the canopy. The $G_o$ flux was estimated by measuring heat flux at 8 cm depth and accounting for heat storage in the soil layer above it. The developed EB procedure was tested using simultaneous measurements of EB data and lysimetric ET in a cotton (*Gossypium hirsutum* L.) field at Bushland, Texas, USA in 2008. The lysimeter measured ET compared well with the computed $ET_e$ under cotton (RMSE of daily ET = 1.2 mm, and seasonal ET within 1% error). Further, we quantified irrigated corn ET using EB in a silt loam soil at Stoneville in 2016. The computed seasonal values of $ET_e$ were greater than shortgrass reference ET ($ET_o$) by 27 mm and less than alfalfa reference crop ET ($ET_r$) by 80 mm. The instrumentation used in the EB method can be moved, and the estimated ET was comparable with lysimeter measured ET. As such, this method provides a cost-effective, viable alternative for quantifying ET, which should be broadly tested in other locations and cropping systems.

## 1. Introduction

The eddy-covariance (EC), and energy balance (EB) methods provide two scientifically sound methods for indirect but potentially accurate measurements of water fluxes from cropping systems (Baldochi, 2003; Gowda et al., 2014; Parent and Anctil, 2012; Shurpali et al., 2013; Uddin et al., 2013). Because of the availability of fast response sensors and data loggers for automated measurement and storage of water and eddy transport data in the plant canopy boundary layer, the EC technique is gaining a reputation as the preferred method for quantifying ET (Amiro, 2009). Even after several physical and instrument corrections are applied to the flux data, it has a widely acknowledged energy balance closure error between energy inputs and outputs, introducing an amount of doubt in the reliability of the measured ET under limited irrigation water management (Amiro, 2009; Allen et al., 2011; Baldochi, 2003; Foken et al., 2006; Liu et al., 2017; Tallec et al., 2013). While the search for energy balance closure in the EC technique continues, the EB approach, in which all the components of energy exchange in the system other than latent heat energy are measured and accounted for in the frictional sub-layer immediately above the plant canopy, provides an alternative approach for fast measurement and quantification of crop ET in field crops in medium size experiments (Amiro, 2009; Tanner, 1960).

In the EB method, an energy balance equation is applied to a soil-crop land area using remote or tower-mounted atmospheric boundary layer sensors and near-surface soil sensor measurements of the system variables (Bhattarai et al., 2016; Cammalleri et al., 2012). In this approach, ET (expressed as latent heat flux, *LE*) is estimated as the residual term of the energy balance equation when other fluxes in the equation are either measured or calculated. Typically, the sensible heat

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[*] Corresponding author.
*E-mail address:* saseendran.anapalli@ars.usda.gov (S.S. Anapalli).

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flux (*H*) is quantified assuming an air-diffusion (flow) resistance to heat and water transport across the turbulent atmospheric boundary layer above the plant canopy (also known as bulk transfer approach), and soil heat flux is measured using buried heat flux plates, adjusted to estimate the soil surface heat flux ($G_o$) (Allen et al., 2007a,b; Heilman and Kanemasu, 1976; Su 2002). Many models and methods for estimating land surface ET from satellite remote sensing data (SEBAL – surface energy balance algorithm for the land model, for example), make use of the general EB approach (Brunet et al., 1991; Bastiaanssen et al., 1998; Cammalleri et al., 2012; McShane et al., 2017). Verma et al. (1976) developed a resistance-energy balance (resistance refers to the method for computing sensible heat flux) procedure for monitoring ET from sorghum (*Sorghum bicolor* L.) and millet *(Panicum melimeurn* L.) cropping systems that compared well with lysimetric measurements. Heilman and Kanemasu (1976) developed an EB based ET model that uses the diffusion resistance to heat transport in the energy balance equation. They obtained ET estimates within 4% and 15% bias on a seasonal basis of lysimetric measurements for soybean (*Glycine Max* L.) and sorghum, respectively. Simultaneous measurements of energy flux data with EB and EC approach reported comparable results in estimated ET in a boreal forest system (Amiro, 2009). Kimball et al. (1999, 1995, 1994) and Triggs et al. (2004) used the EB approach for comparing free-air $CO_2$ enrichment effects on ET from cotton (*Gossypium hirsutum* L.), sorghum, and wheat *(Triticum estivum* L.) crops. In these studies, in general, the values of sensible heat (*H*) in the EB procedure were derived from the measurements of the air and crop canopy temperature differential and modeling the aerodynamic resistance ($r_a$). In vegetated land surfaces, plant-soil surface temperature should represent the temperature of the apparent source/sink of sensible heat flux within in the plant canopy. As such, it should form the base measurement for quantification of the air and canopy temperature differential (Blonquist et al., 2009). This apparent temperature, known as aerodynamic temperature ($T_o$) is not a directly measurable variable, so crop canopy surface radiative temperature ($T_s$) is commonly measured using an infrared thermometer and used as a surrogate for $T_o$ in the computations of *H* in cropping systems. In relatively homogenous surfaces, the difference between $T_s$ and $T_o$ may not be substantial, but in heterogeneous crop canopy surfaces the differences can be substantial, and this can lead to significant errors in the estimation of *H*, which in turn leads to unreliable *LE* estimates using the EB method (Chávez et al., 2010, 2005). The variable $T_o$ is defined as the temperature at the zero-plane displacement height (*d*, the level to which the ground surface must be raised for the wind profile to follow a logarithmic shape) plus the surface roughness length (height at which wind velocity becomes zero) for sensible heat transfer ($Z_h$) i.e. ($d + Z_h$). Thus, $T_o$ results from the interactions of $T_s$ with the complex canopy characteristics linked to its architecture. As such, no known physical relationships exist between the two that can be used for predicting the value of one from the other. In this context, empirical relationships were derived and used in the literature for computing the value of $T_o$ from plant canopy and environmental variables in energy balance studies (Chávez et al., 2005). For computations of $T_o$ in this study, we used the equation developed by Chávez et al. (2010) for corn and Chávez et al. (2005) for cotton crops. Such empirical relationships linking crop-specific characteristics with environmental variables were applied for simulating crop processes in cropping system models across the globe; Examples include the CERES-rice model (Ritchie, 1998), APSIM model (Robertson and Carberry, 1998), CropSyst model (Stöckle et al., 2003), and in modeling ecosystems (Norby et al., 2016; Rogers, 2014).

Intensive, ground-based continuous monitoring of all the EB components in a cropped field are required for quantifying ET based on the EB approach (Brown and Rosenberg, 1973; Amiro, 2009). As such, application of this technology for quantifying ET in cropping systems remained sporadic, possibly due to the difficulties in making these continuous measurements and their storage and transmission for developing algorithms for computing resistances customized to those measurements. With the advent of the modern fast response sensors, data loggers, and wireless communication system, this is no longer considered a hindrance in adopting this technology in field research.

Recently corn growers in the Mississippi (MS) Delta region planted an estimated 750,000 acres (303,500 ha) of corn and produced about 134 bushels per acre (5400 kg $ha^{-1}$) grain yield and 97.82 million bushels (6,140,161 Mg) in 2010 (Mississippi State University Extension service, http://msucares.com/crops/soybeans/index.html). The long-term average annual rainfall received over the Mississippi Delta region was approximately 1300 mm, with about 30% received during the core crop growing periods from April to August (Saseendran et al., 2016a). The crop growing season rainfall is also characterized by large inter- and intra- seasonal variabilities in their amounts and temporal distributions. To stabilize returns from crops raised in the region, farmers often provide supplementary irrigations, drawing water from the Mississippi River Valley Alluvial Aquifer. In the absence of reliable information on the water needs of the crops, farmers often provide arbitrary irrigations. Agricultural water use from this aquifer has been reported to far exceed its long-term recharge rates (Powers, 2007). Global warming associated with increasing anthropogenic greenhouse gasses in the atmosphere was also reported to increase pressure on irrigation water requirements in the region (Saseendran et al., 2016b). Accurate, timely quantification of water requirements (or ET) of major crops (cotton, corn, soybeans, and rice) grown in the region is essential for scheduling irrigations for optimizing water use efficiency (WUE) in these cropping systems and to match irrigation withdrawals with the recharge rates of the aquifer.

In these contexts, our objectives were to provide a synthesis of components in the EB approach and (1) develop a state-of-the-science algorithm for computation of ET based on the EB approach, (2) test the ET quantified using this algorithm with cotton ET measured using a large-scale field lysimeter at Bushland, TX, USA, and (3) use the EB algorithm to v quantify ET in corn at Stoneville, MS, USA, for the first time in the history of MS Delta, and compare it with grass and alfalfa reference crop ET computed from climatological data for the location.

## 2. Methodology

### 2.1. The energy balance (EB) approach for estimating evapotranspiration (ET)

An energy balance equation for a crop-soil surface can be written as

$$R_n = LE + G_0 + H + \Delta S_{air} + \Delta S_{bm} + \Delta S_{ph} \tag{1}$$

where $R_n$ is the $R_n$ (positive downward), *LE* is the latent heat flux (positive upward), $G_o$ is the soil heat flux (positive downward), *H* is the sensible heat flux (positive upward), $S_{bm}$ is the energy stored in the biomass, $S_{air}$ is the energy stored in the air layer, and $S_{ph}$ is the energy used in photosynthesis, where Δ denotes the change per unit time (s). Units are $Wm^{-2}$ for energy flux and J $m^{-2}$ for energy storage. Based upon previous work (Meyers and Hollinger, 2004) and screening calculations, we assume that in summer crops (3–4 months duration) like corn and cotton, $S_{air}$, $S_{bm}$, and $S_{ph}$ are negligible compared with other terms in Eq. (1). Meyers and Hollinger (2004) estimated the solar energy stored in the carbohydrate bonds from photosynthesis, in the biomass, and in the soil under corn. When these processes were considered independently, each component was found to be insignificant ($< 5\%$) (Meyers and Hollinger, 2004). However, when these losses were combined, the total loss comprised 8–14% of the net solar energy. Energy stored in the soil and plant canopy accounted for majority of this change in energy storage. In the present study, however, heat storage changes in the soil water and minerals were included in Eq. (3). We did not compute the storage changes in crop-biomass based on observations from past studies: Leuning et al. (2012) and Anderson and Wang (2014) reported no net energy gain or loss due to heat storage changes in the biomass because, on a daily basis, energy stored in the plant-biomass in the morning is returned to the air in the afternoon and evening hours. In this study, though we initially computed energy fluxes on a half-hour interval, we accumulated those fluxes for the whole day to calculate daily ET at the end of the day, cancelling out the gains of energy with its losses.

The ET is calculated from Eq. (1) by dividing *LE* by the latent heat of vaporization of water ($\lambda = 2.501\ \text{MJ kg}^{-1}$):

$$ET = (R_n - G_0 - H)/\lambda \tag{2}$$

We employed the resistance to the turbulent exchange of energy and matter between different layers of the atmosphere and the ground surface to compute ET using Eq. (2) (Foken, 2008). The crop surface is considered a big leaf and energy (latent heat of water vapor) is transferred across an atmospheric layer against a turbulent resistance; this process is analogous to Ohm's law for current flow in electrical conductors. Energy flow across the turbulent boundary layer takes place analogous to the Fick's law: net flux of energy is proportional to its concentration gradient.

### 2.1.1. Estimation of ground heat flux, $G_o$

The heat flux at the ground surface, $G_o$ ($\text{W m}^{-2}$), is estimated using the following equation (Kimball et al., 1999):

$$G_0 = G_8 + Cs\Delta z\left(\frac{\Delta T}{\Delta t}\right) \tag{3}$$

where, $G_8$ the soil heat flux at 8 cm depth, $\Delta z$ the soil depth above the heat flux plate (8 cm), $\Delta T$ the change in temperature in $\Delta z$ during $\Delta t$, $\Delta t$ the time between two consecutive soil temperature measurements; CS *the* volumetric heat capacity of soil in the $\Delta z$ computed as

$$C_s = \%M*C_m + \%OM*C_{om} + \%SWC*C_{sw} \tag{4}$$

where, $M$ is the mineral, OM the organic matter, and SWC the volumetric water content in $\Delta z$; $C_m$, $C_{om}$, and $C_{swc}$ are volumetric heat capacities of minerals, organic matter and soil water in $\Delta z$, respectively. Thus, $C_S$ is calculated following De Vries (1963) with values of $C_m = 1.9$, $C_{om} = 2.5$, and $C_{sw} = 4.2\ \text{MJ m}^{-3}\ {}^{\circ}\text{C}^{-1}_{.}$

### 2.1.2. Estimation of sensible heat flux, H

The aerodynamic resistance approach to quantifying $H$ ($\text{W m}^{-2}$) is analogous to Ohm's law for electric current in conductors, following Triggs et al. (2004),

$$H = \rho_a C_p(T_0 - T_a)/r_a \tag{5}$$

where $\rho_a$ is the density of air ($\text{kg m}^{-3}$) calculated from the ideal gas equation, $C_p$ is the specific heat of air assumed constant at $1005\ \text{J kg}^{-1}\ \text{K}^{-1}_{,}$ $T_{ais}$ the air temperature at the sensor height above the crop canopy, and $r_a$ the bulk aerodynamic resistance to sensible heat transfer ($\text{s m}^{-1}$).

$T_0$ is the aerodynamic temperature (K) calculated from Chávez et al. (2010) for cotton:

$$T_0 = 0.5T_s + 0.14T_a + 0.81\ \ LAI - 0.97u + \ {}_{14.9} \tag{6}$$

$T_0$ for corn is calculated based on Chávez et al. (2005):

$$T_0 = 0.534T_s + 0.39T_a + 0.224\ \ LAI - 0.192u + \ {}_{1.67} \tag{7}$$

where $T_S$ is surface radiometric temperature, $u$ is the wind speed at temperature sensor height in $\text{m s}^{-1}$, and *LAI* the leaf area index. Chávez et al. (2005) reported a coefficient of determination ($R^2$) of 0.9 for regression between H values computed using $T_0$ estimated with the above method and $T_0$ obtained by inverting the energy balance equation. Based on Triggs et al. (2004),

$$\rho_a = \left[\frac{P_d}{R_d T_a}\right] + \left[\frac{P_v}{R_v T_a}\right] \tag{8}$$

where $T_a$ is air temperature at 2 m above the canopy (K); $P_d$ is the partial pressure of dry air (kPa); $P_v$ is the partial pressure of water vapor (kPa); Rd is the gas constant for dry air = $287.05\ \text{J kg}^{-1}\ \text{K}^{-1}$; $R_v$ = gas constant for water vapor = $461.495\ \text{J kg}^{-1}\ \text{K}^{-1}$;

$$P_d = P - P_v \tag{9}$$

where $P$ is atmospheric pressure (kPa),

$$P_v = P_{sat}*RH \tag{10}$$

where $RH$ is relative humidity, and

$$P_{sat} = 6.1078*10^{\left(\frac{7.5T_a - 2048.625}{T_a - 35.85}\right)} \tag{11}$$

The following procedure was employed for estimating $r_a$:

The main factors affecting $r_a$ are wind speed and stability of the air layer above the plant canopy and canopy characteristics linked to the canopy architecture. The atmosphere can be characterized as stable, unstable, or neutral if $T_s$ is less than, greater than, or approximately equal to $T_a$, respectively.

When air is neutrally stable (i.e., $|T_s - T_a| < 0.1\,^{\circ}\text{C}$), and $u < 0.1\ \text{m s}^{-1}$ (calm wind), $r_a$ is set to a maximum value of $1720\ \text{s m}^{-1}$ following Triggs et al. (2004). However, when the wind speed is low ($u < 0.1\ \text{m s}^{-1}$) but the absolute value of temperature difference between $T_s$ and $T_a$ is greater than 0.1 °C (air is unstable), the formula from the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHARE, 1972) was used to compute $r_a$:

$$r_a = \frac{\rho_a C_p}{1.52|T_s - T_a|^{1/3}} \tag{12}$$

When $u > 0.1\ \text{m s}^{-1}$ and the temperature difference between $T_s$ and $T_a$ is greater than 0.1 °C (unstable air), $r_a$ was computed following Jackson et al. (1987):

$$r_a = \frac{1}{u}\left\{\frac{1}{k}ln\left[\frac{z - d + z_0}{z_0}\right]\right\}^2 \varphi \tag{13}$$

where the von Karman's constant, $k = 0.41$, $z$ is the wind speed measurement height (m), $d$ is the zero-plane displacement height (m), $z_o$ is the roughness length for heat transfer (m), and $\varphi$ is the stability correction factor.

Values of $z_o$ and d were estimated from plant height, $h$ (m), according to relationships presented by Jacobs and Van Boxe (1988) for corn:

$$z_0 = 0.25(h - d) \tag{14}$$

$$d = 0.84h - 0.14 \tag{15}$$

For bare soil, $z_0$ and $d$ were estimated from Monteith and Unsworth (1990) as 0.005 and 0.05, respectively.

The stability correction term, $\varphi$, was calculated using the equation from Mahrt and Ek (1984) for stable conditions ($T_s < T_a$):

$$\varphi = \frac{1 + 15R_i}{\sqrt{1 + 5R_i}} \tag{16}$$

where, $R_i$ is the Richardson number calculated based upon Mahrt and Ek (1984) as:

$$R_i = \frac{g(T_a - T_s)(z - d)}{(T_a + 273.16)u^2} \tag{17}$$

where, $g$ is the acceleration due to gravity ($9.81\ \text{m s}^{-2}$) for unstable conditions (Mahrt and Ek, 1984) (i.e., $Ts > Ta$),

$$\phi = \frac{1 - 15R_i}{1 + K\sqrt{-R_i}} \tag{18}$$

where,

$$K = 75k^2\frac{\sqrt{(z - d + z_o)/z_o}}{\{\ln[(z - d + z_o)/z_o]\}^2} \tag{19}$$

### 2.2. Experimental data

#### 2.2.1. Lysimeter and energy balance experiments in cotton (Bushland experiment)

Experiments to estimate cotton crop ET using both lysimeter and energy balance methods were conducted simultaneously in 2008 at the USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX (35° 11′N, 102 °06′W, 1170 m amsl) in a Pullman clay loam soil. Cotton crop ET was estimated in a large (3 × 3 × 2.3 m) precision, weighing lysimeter, located in the middle of a 4.7 ha irrigated cotton field (Southeast lysimeter; Evett et al., 2015). Changes in lysimeter mass were recorded as 5-min means and used to compute daily ET. Details of lysimeter installation, data collection procedures, and calibration and maintenance are available in Howell et al. (1995) and Evett et al. (2015). The lysimetric measurement site was also equipped with instruments for measuring $R_n$ (CNR4, Kipp & Zonen), air temperature and relative humidity (HMP 155, Vaisala), wind speed (CSAT3 3D sonic anemometer), and canopy surface radiative temperature (SI-111, Apogee) mounted to view the ground at 60° zenith angle at 1 m above ground level in the center of the lysimeter field (Chávez et al., 2009). The site was also instrumented for measuring soil heat flux using HP01SC self-calibrating heat flux sensor (Hukseflux) at 8 cm depth and soil water and temperature monitored above the flux plate. Both the lysimeter and energy balance components (micrometeorological) data were recorded on a data logger (CR-7X, Campbell Scientific Inc., Logan, UT).

The required micrometeorological data at Bushland were collected using techniques detailed by Chávez et al. (2010, 2009). Quality control and assurance of lysimeter and weather data were maintained through daily graphing and visual inspection for obvious errors, missing values, and exceedance of physically possible values. Daily lysimeter ET data were computed as the difference between midnight centered, 5-min average lysimeter mass values, expressed as an equivalent depth of water in mm. When necessary, adjustments to daily ET values were performed to address gains in lysimeter mass corresponding to dew and frost accumulation, and rainfall and irrigation events using techniques detailed by Marek et al. (2014). Irrigation treatments were applied to refill the soil to field capacity based on weekly neutron probe measurements to maintain the soil water content above the 50% level of maximum plant available water depletion.

Cotton was planted on May 21, 2008, and harvested on December 14, 2008. However, continuous measurements of energy balance data were made only from June 7 to August 20, 2008.

Periodic measurements of biomass and LAI, pooled from four subsamples were made employing a destructive sampling method. Plant height was monitored simultaneously. An exponential equation,

$$LAI = 0.0024e^{0.0926t_p} \tag{20}$$

was fitted ($R^2 = 0.99$) to the measured data to obtain continuous values of LAI from the time after planting ($t_p$, days). The cotton LAI did not change substantially after about 90 days. A polynomial equation,

$$h = 0.00005t_p{}^2 + 0.0078t_p - 0.185 \tag{21}$$

was fitted ($R^2 = 0.97$) to the measured data to obtain continuous values of $h$ (m) from $t_p$ for computing aerodynamic temperature using Eqs. (6) and (7).

#### 2.2.2. Corn energy balance experiment (Stoneville experiment)

Measurements of the energy balance for computing ET in corn, the experiment in 2016 was conducted on a Dundee silt loam (fine-silty mixed, thermic Aeric Ochraqualf) at Stoneville, MS (33.42° N, 90.92° W, 32 amsl) located in the Lower Mississippi Delta region. Corn hybrid DKC66-97 was planted on March 23, 2016, with 102 cm row spacing, at a rate of 33,174 seeds ha$^{-1}$. The crop was furrow irrigated, and irrigation amounts were adjusted to refill soil water contents back to field capacity based on weekly soil water content measurements to maintain the soil water content always above the 50% level of maximum plant available water in the soil. Approximately 40 mm of water was applied at each irrigation event. Nitrogen was applied at the rate of 224 kg ha$^{-1}$ as UAN at planting. The field size for the experiment was 1.5 ha with dimensions of 200 m in the north-south direction and 75 m in the east-west direction. The tower for measuring energy balance components was in the middle of the plot. The sensors for measuring air temperature and relative humidity (Vaisala, HMP 155), $R_n$ using NR-LITE2 Net radiometer sensor (Kipp & Zonen), infrared canopy surface temperature sensor installed to view of the ground at 60° zenith angle using SI-111 Standard View Infrared Sensor (Apogee), and wind direction and speed using Windsonic4 2D-Sonic wind sensor (Gill Instruments) were maintained at 1 m above the plant canopy. The sensor heights were adjusted manually to maintain this height whenever there is an increase in crop height exceeding 5 cm. There was adequate fetch (ratio of 100:1 for distance from the edge of the crop field to the tower to the sensor height above the crop canopy) in the north-south direction, which is also the prevailing wind direction during the crop season. The fetch in the east-west direction was not adequate but winds from this direction occur very rarely. Four soil heat flux sensors (HP01SC self-calibrating heat flux sensor, Hukseflux) were installed at 8 cm depth. Water content and temperature in the 8 cm soil layer above the heat flux were monitored using Stevens HydraProbe (Steven Water Monitoring Systems Inc.).

**Table 1**
Mean monthly minimum ($T_{min}$) and maximum ($T_{max}$) temperatures and monthly total rainfall and irrigation for the Bushland cotton experiment (2008) and the Stoneville corn experiment (2016).

| | $T_{max}$ °C | $T_{min}$ °C | Rain mm | Irrigation mm | ET lysimeter mm |
|---|---|---|---|---|---|
| | Cotton season, Bushland, TX (2008) | | | | |
| May | 27.0 | 9.3 | 37 | 31 | 72 |
| June | 33.4 | 15.4 | 74 | 57 | 125 |
| July | 31.2 | 17.4 | 76 | 103 | 211 |
| August | 29.9 | 16.6 | 138 | 93 | 239 |
| September | 26.5 | 11.4 | 16 | 0 | 158 |
| Total | | | 304 | 284 | 805 |
| | Corn season, Stoneville, MS (2016) | | | | |
| April | 28.1 | 8.7 | 47 | 0 | |
| May | 27.8 | 16.2 | 65 | 51 | |
| June | 32.7 | 22.5 | 158 | 35 | |
| July | 34.1 | 23.5 | 160 | 40 | |
| Total | | | 430 | 126 | |

The LAI of corn was measured every other week using AccuPAR LP-80 Ceptometer (Decagon Devices Inc.). Plant heights were monitored every week. Plant biomass was measured by removing plants in 1 m$^2$ areas twice during the crop season: one at tasseling (R1 stage) and another at physiological maturity (R6 stage). All the plant measurements were replicated at four random locations in the field and used in the calculation of standard error (SE) of measurements. Phenology observations were recorded every week.

A second-order polynomial equation

$$LAI = -0.0009t_p{}^2 + 0.1156t_p + 0.693 \tag{22}$$

was fitted ($R^2 = 0.99$) to the measured LAI data to interpolate continuous values of LAI as a function of $t_p$. Similarly, another polynomial equation,

$$h = -0.0001t_p{}^2 + 0.0402t_p - 0.6893 \tag{23}$$

was fitted ($R^2 = 0.97$) to the measured data to interpolate continuous values of $h$ (m) as a function of $t_p$ for computing $z_o$ and $d$ in Eqs. (14) and (15).

#### 2.2.3. Reference crop ET

Alfalfa (0.50 m tall) reference crop ET ($ET_r$) and short grass (0.12 m

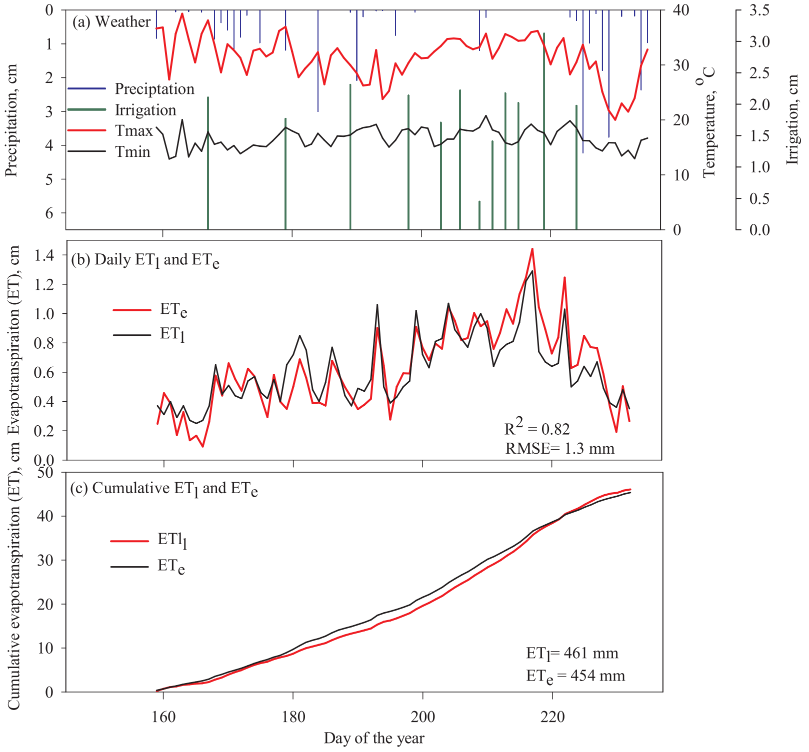

**Fig. 1.** (a) Daily maximum (Tmax) and minimum (Tmin) temperature(°C), rainfall and irrigation amounts (mm $d^{-1}$), (b) evapotranspiration (ET) measured by lysimeter ($ET_l$) and computed with the energy balance method ($ET_e$), and (c) cumulative ET, and $ET_e$ in the Bushland cotton experiment in 2008. RMSE is root mean squared error, and $R^2$ is the coefficient of determination – fraction of variations in the daily lysimeter ET explained by the ET estimated using the energy balance approach.

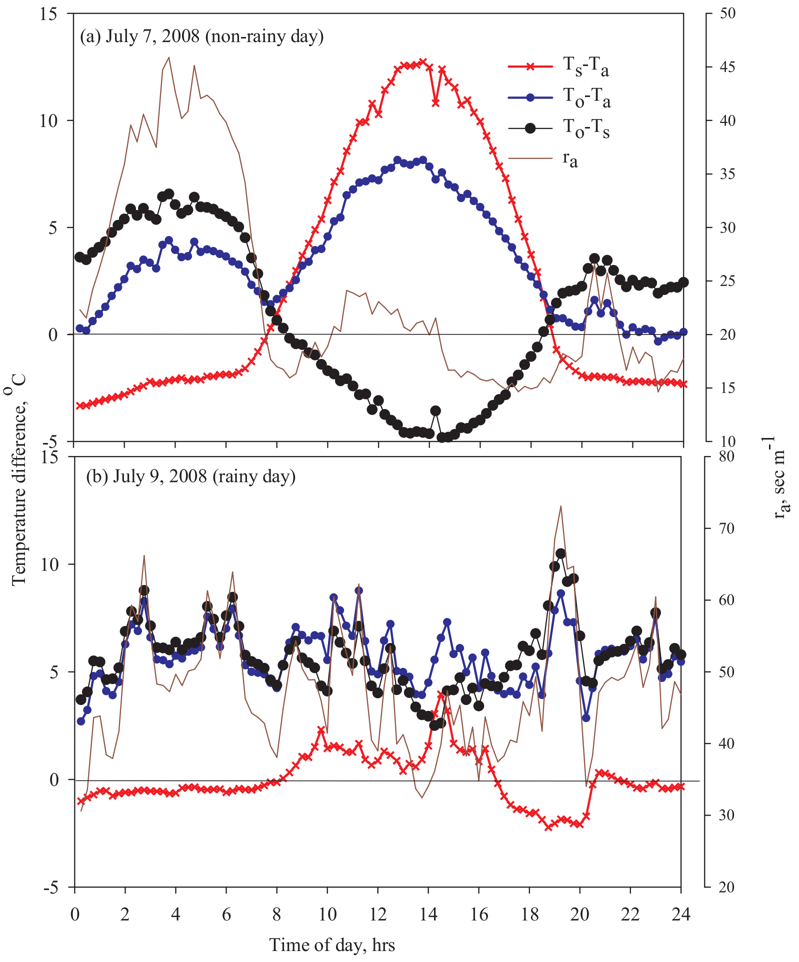

**Fig. 2.** Time series of temperature differences between measured corn canopy radiative temperature ($T_s$), air temperature ($T_a$) and computed canopy aerodynamic temperature ($T_o$), and aerodynamic resistance ($r_a$) in the Bushland cotton experiment for representative days (a) without rain and (b) with rain in 2008.

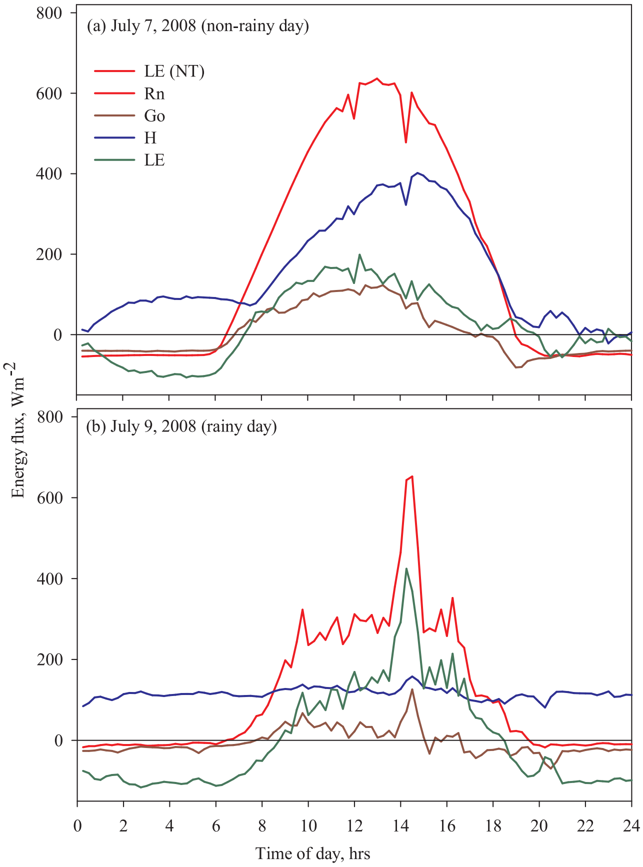

**Fig. 3.** Diurnal patterns of energy fluxes on (s) July 7, 2008 (non-rainy day) and (b) July 9, 2008 (rainy day) during the Bushland cotton experiment. Fluxes were computed and plotted in the graph at 15 m intervals.

tall) reference crop ET ($ET_o$) were computed using the ASCE Environmental and Water Resources Institute (ASCE-EWRI, 2005) and FAO Irrigation and Drainage Paper no. 56 (Allen et al., 1998; Pereira et al., 2015), respectively, from weather data collected at the location by assigning fixed resistances for the reference crop surfaces.

## 3. Results and discussion

### 3.1. *Evaluation of the EB method for quantifying ET in the Bushland experiment*

During the cotton growing season (May to September) in 2008, the mean daily minimum temperature varied between 9.3 °C in May to 17.4 °C in July and maximum temperatures between 26.5 °C in September to 33.4 °C in June (Table 1; Fig. 1a). Cotton grown in this region, on average, requires about 670 mm of water to meet its ET demand (Chávez et al., 2009), water received from rains during the 2008 season was 325 mm – measured monthly total rainfall varied between 37 mm in May to 138 mm in August. Irrigation applied during the 2008 crop season was 284 mm with monthly total applications varying between 31 mm in May to 103 mm in July. Monthly total lysimeter measured ET fluctuated between 72 mm in May to 23.9 mm in July, totaling to 805 mm during the four months. On average, the location receives about 560 mm of rainfall in a year.

In the Bushland experiment, substantial differences were noticed between the measured $T_s$, and computed $T_o$. For instance, during the daytime on a non-rainy day, July 7, 2008, the computed $T_o$ remained less than $T_s$ ($T_o - T_s$ is negative in Fig. 2a). This difference peaked at 4.62 °C at 1:25 PM However, during the nighttime, the $T_o$ values were higher than $T_s$ ($T_o - T_s$ is positive), where the highest difference of 6.56 °C occurred at 3:25 AM On July 9, 2008, a rainy day with contrasting weather conditions, $T_o$ remained above $T_s$ throughout the day with the temperature difference ranging from 2.6 to 10.4 °C (Fig. 2b). Chávez et al. (2010) reported differences between $T_o$ and $T_s$ ranging from 2 °C to 3 °C for uniform canopy covers and from 10 °C to 15 °C for partial surface vegetation cover.

As explained in the methodology section, $r_a$ decreases with solar radiation and solar heating induced wind speed increases in the atmosphere during the daytime. As such, as expected, the computed $r_a$ decreased at sunrise and increased at sunset mainly due to increased wind speed and more unstable air brought by the increased heating associated with increased solar radiation (Fig. 2a and b). The maximum computed $r_a$ on a non-rainy day was 45.1 s m$^{-1}$ during the night time and 15.2 s m$^{-1}$ during the day time (Fig. 2a).

The $R_n$ is the primary input energy term in the energy balance equation used for quantification of ET using the EB procedure. Thus, the accuracy of the estimated ET depends on accurate measurements of $R_n$ (Eq. (2)). The $R_n$ data plotted in Fig. 3a represents a non-rainy day on July 7, 2008, and those plotted in Fig. 3b represent a rainy day two days later on July 9, 2008. The cotton crop was at R4 stage, average LAI was 3.5, and average $h$ was 65 cm. During the non-rainy day on July 7, the maximum value of $R_n$ (637 W m$^2$ s$^{-1}$) was measured at 1:00 PM, local time. This value is realistic for the location and time of the year, illustrating the high accuracy of the energy inputs into the system. On July 9, the location received 21 mm of rainfall and the sky was overcast most of the day. Thus, $R_\mathrm{n}$ remained below 300 W m$^2$ s$^{-1}$, and when the sun reappeared after the clouds dissipated in the sky around 2:15 PM, the measured $R_\mathrm{n}$ went up to 652 W m$^2$ s$^{-1}$ (Fig. 3b).

On the non-rainy day, with less water available for ET, compared to that of the rainy-day, more of the $R_n$ received was partitioned towards H than LE. And on the rainy day with more water available for ET, the situation reversed; more of the $R_n$ was partitioned towards *LE* than *H*. On the non-rainy day on July 7, 2008, with more $R_n$ (Fig. 3a and b), $G_o$ fluxes into the soil were also higher in magnitude during the day hours compared to those on the rainy day. On the rainy day, when the $R_n$ went up during a brief cloud free period around 02:15 PM, the computed $G_o$ became more positive (Fig. 3b). The magnitude of the components of the energy balance equation (2) during these two contrasting weather

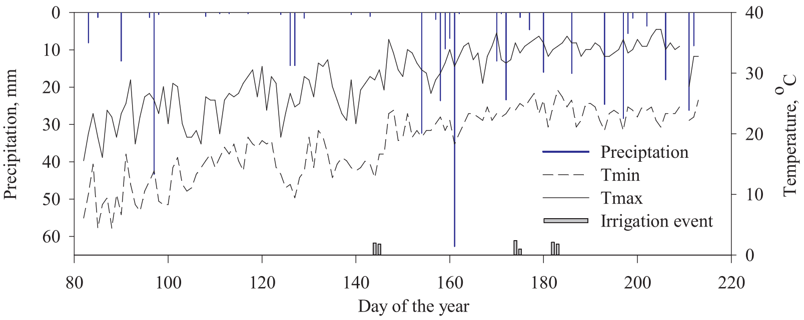

**Fig. 4.** Daily temperature maximum (Tmax) and minimum (Tmin), irrigation and rainfall recorded during the Stoneville corn experiment in 2016.

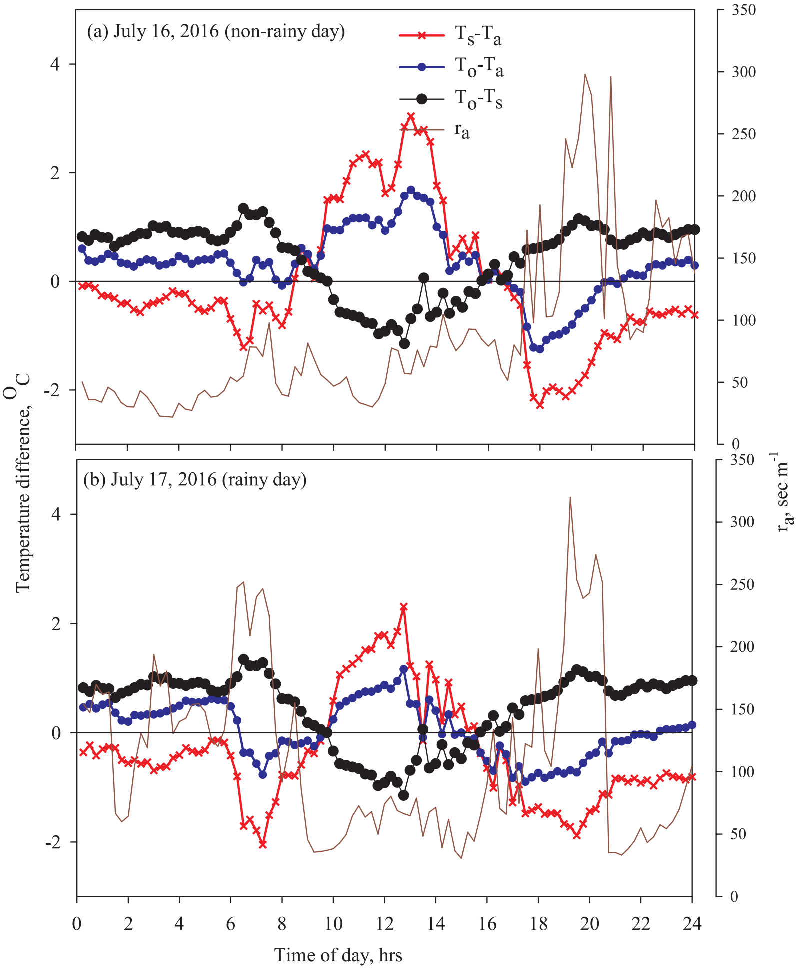

**Fig. 5.** Measured corn canopy radiative temperature ($T_s$), and computed canopy aerodynamic temperature ($T_o$) and aerodynamic resistance ($r_a$) in the Stoneville corn experiment for representative days (a) without rain and (b) with rain in 2016. The difference between $T_o$ and $T_s$ also presented.

periods (non-rainy vs. rainy day) are representative of the measurements during the whole cotton growth season. Adequate responses of the sensors with changing weather, both diurnal and across days, give confidence in the accuracy of the sensors used in monitoring the energy balance components in the field. Adequate responses in the computed $G_o$, $H$, and $LE$ across changing weather conditions – a rainy versus a non-rainy day – illustrated the correctness of the equations implemented in the methods developed for quantifying the components of the crop surface energy balance equation.

Though the cotton crop in the experiment was planted on May 21, 2008, and harvested on December 14, 2008, measurements of energy balance data could be conducted only from June 7 to August 20, 2008. Daily $ET_e$ computed using the EB method during this period matched and correlated well with the lysimeter measured $ET_l$, with an $R^2$ (coefficient of determination computed as the squared value of the Pearson's correlation coefficient, r) value of 0.86. The total $ET_e$ computed during this period was 426 mm versus a measured $ET_l$ value of 433 mm. In other words, the difference between $ET_l$ and $ET_e$ during this 105-day period was only 6.5 mm. The root mean squared error in (RMSE) daily $ET_l$ relative to $ET_e$ was 1.3 mm. From these results, we propose that the energy balance procedure developed above using Eq. (6) for computing $T_0$ is capable of quantifying ET comparable to direct measurements of ET using large-scale field lysimeters. Hence, the EB method for indirectly computing ET from measurements of energy balance components in the cropping system has the potential to provide a viable alternative to more directly measuring ET as a change in mass in large-scale field lysimeters. Though simple in concept and science, lysimeters are expensive and difficult to install and maintain for long-term data collection. The energy balance closure problems associated with the EC method are not apparent with the EB method, and no closure correction is applied. The errors involved in the measurements of different energy balance components, however, can reduce the accuracies of the residual energy computed and attributed to latent heat energy. Most of the uncertainty in the EB method is associated with estimation of the sensible heat component. Even so, modern highly accurate sensors for monitoring environmental variables and parameters, data storage and their real-time communication and automated data processing facilities available today can render the EB approach as employed in this study to be a reliable accurate alternative approach with portable instrumentation for quantifying ET in crop fields for irrigation water management applications.

### 3.2. *Corn experiment*

The EB method developed in this study can be considered fully mechanistic, except for the empirical equation used in the computation of $T_o$. Both Eqs. (6) and (7) used to compute $T_o$ for cotton and corn crops, respectively, are crop-specific empirical equations.

The location for the corn crop experiment near Stoneville, MS receives an average annual rainfall of about 1300 mm, of which about 36% (452 mm) is received during the four months of the corn growth period between April and in July (Saseendran et al., 2016a,b). During this period in 2016, the location received 433 mm of rainfall, characterizing the season as an average rainfall season (Table 1). The crop

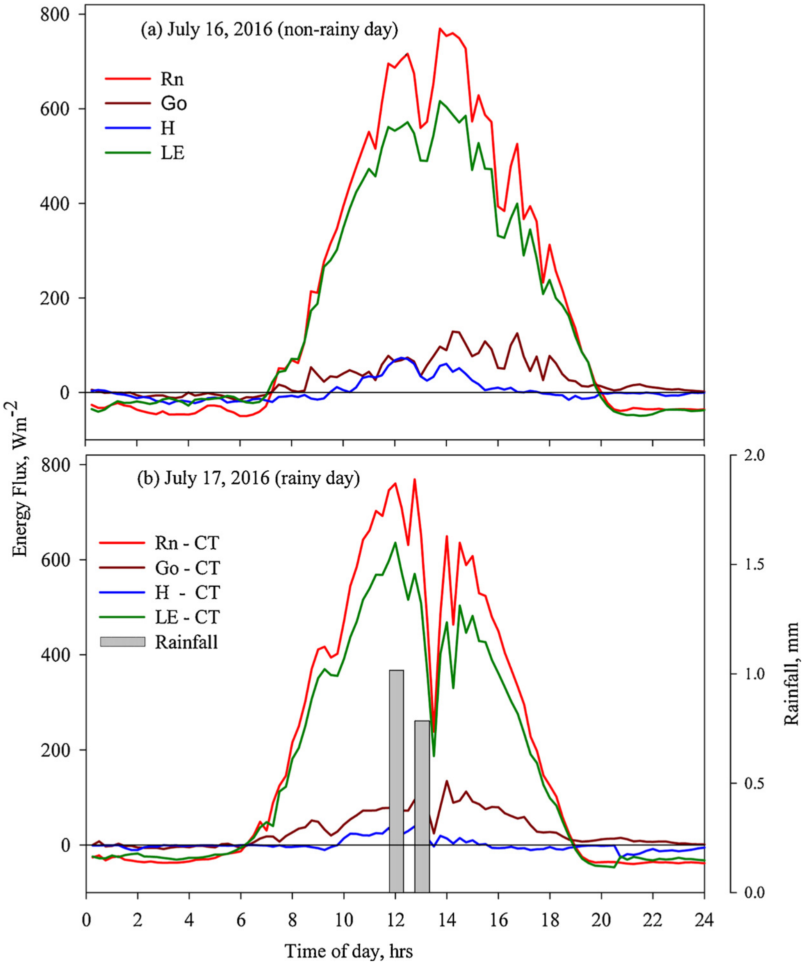

**Fig. 6.** Diurnal patterns of energy fluxes on July 15, 2016 (rainy day) and on July 17, 2016 (non-rainy day) during the Stoneville corn experiment. Fluxes were computed and plotted in the graph at 15 m intervals.

was planted on March 23, and it reached physiological maturity on August 2. Maximum crop height averaged 1.9 m with an average maximum *LAI* of 5.5. The ET$_o$ for this season computed from weather data collected on the EB tower was 559 mm, and ET$_r$ was 666 mm. We furrow irrigated the crop with 126 mm of water in three irrigation events − each irrigation event lasted two days (Fig. 4). Daily temperatures varied between 8.7 and 28.1 °C in April, between 16.2 and 27.8 °C in May, between 22.5 and 32.7 °C in June, and between 23.5 and 34.1 °C in July. Harvested grain yield in this season was 10,467 kg ha$^{-1}$.

As explained in the methods, *H* was computed by measuring the canopy air temperature differential and computing r$_a$ from Eq. (5). As in the case of cotton, $T_s$ in corn also was monitored using an infrared thermometer mounted on the energy balance tower maintained at 1 m above the corn canopy. We used Eq. (7) for computing $T_o$ from measurements of $T_s$, *LAI* and *u* representing the corn crop canopy (Chávez et al., 2005).

As in the case of cotton, substantial differences were seen between measured $T_s$ and the computed $T_o$. Looking at a typical non-rainy day on July 16, 2016, during the corn growth season when LAI was on average 5.0 and plant height over an average of 1.9 m, the computed $T_o$ remained less than $T_s$ (i.e., $T_o - T_s$ is negative in Fig. 5a) during the day-hours with a minimum value of −1.2 °C at 01:00 PM The computed $T_o$ went above $T_s$ at sunset (i.e., $T_o - T_s$ is positive in Fig. 5a) with the maximum value of 1.3 °C at 06:30 PM The general pattern in computed $T_o$ relative to $T_s$ was similar on a rainy day, July 17, 2016, as well (Fig. 5b). These differences in $T_o$ relative to $T_s$ computed for corn in the warm and humid climate of Stoneville, MS, are much smaller than similar differences between $T_o$ and *Ts* computed in the case of cotton in a semi-arid climate at Bushland, TX as presented earlier. Computed $r_a$ in corn at Stoneville, MS, on non-rainy day varied between 16 s m$^{-1}$ at 16:30 and 45 s m$^{-1}$ at 4:45 AM(Fig. 5a). On the rainy-day on July 17, 2016, $r_a$ varied 22 s m$^{-1}$ at 1:45 PM and 298 s m$^{-1}$ 07:45 PM (Fig. 5b).

The data plotted in Fig. 6a represents the computed energy fluxes on the EB tower on the non-rainy day on July 16, 2016, and those plotted in Fig. 6b represent similar fluxes on a rainy day on July 17, 2016, at Stoneville, MS. The crop was at R5 (Dent) stage, average LAI was 5.5, and average plant height was about 190 cm. During the non-rainy day on July 17, R$_n$ peaked at 770 W m$^2$ s$^{-1}$ at 1:25 PM This value is typical for the location and time of the year; however, this value is higher than that measured in July at Bushland, TX, due to the warmer, humid climate of Stoneville, MS. Though the day was without rain, there were clouds in the sky continuously masking the sun's radiation from reaching the ground surface, as detected in the depressions in the $R_n$ curve. On the next day (July 18, 2016), the location received 2.6 mm of rainfall, and the sky was overcast for part of the day. The maximum $R_n$ measured remained close to the previous non-rainy day at 769 W m$^2$ s$^{-1}$ at 0:45 PM, but when clouds masked the sun in the next hour, the recorded $R_n$ went down to a minimum of 238 W m$^2$ s$^{-1}$ at 1:30 PM (Fig. 6b). On both days (non-rainy and rainy days), enough water was available for evapotranspiration from rains that occurred in the previous days; as such, most of the $R_n$ received was partitioned towards *LE* rather than *H*. On both days, $G_o$ flux into the soil (-ve values) was higher during the day hours than the night hours.

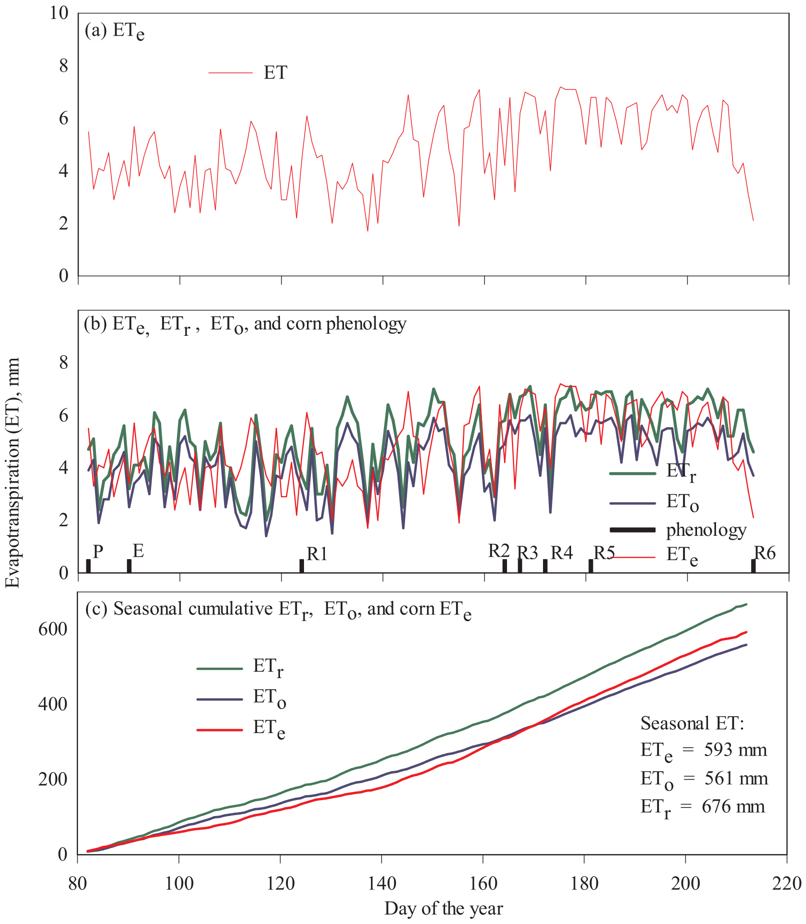

**Fig. 7.** (a) Corn evapotranspiration computed using the energy balance method (ET$_e$), and (b) grass reference crop evapotranspiration (ET$_o$) and alfalfa reference crop evapotranspiration (ET$_r$) computed from climate data in the Stoneville corn experiment in 2016. Symbols P, E, R1, R2, R3, R4, R5, and R6 represent the dates of occurrences of corn phenological stages: planting, emergence, silking, blister, milk, dough, dent, and physiological maturity, respectively. (c) Cumulative seasonal ET$_e$, ET$_r$ and ET$_o$.

The corn crop was planted on March 23, 2016, reached physiological maturity (R6 stage) on August 02, 2016, and was harvested three weeks later on August 23, 2016. Between planting and physiological maturity, the crop growth duration was 131 days. Energy balance data were collected during the whole crop season without a break. During the crop period, the estimated $ET_e$ ranged between 1.7 and 7.2 mm d$^{-1}$ (Fig. 7a, b). The lowest value occurred 56 days after planting (May 17, 2016) due to nearly overcast skies. The values of $ET_o$ and $ET_r$ computed using climatological data collected at the location with values 1.9 and 2.3 mm, respectively, did not deviate substantially from the energy balance computed value. The highest value of $ET_e$ occurred 94 days after planting (June 24, 2016) with clear skies and warm weather (no rainfall or cloud with a daytime maximum temperature of 33.3 °C). The ET$_o$ and ET$_r$ computed using weather data for this day were 6.6 and 5.7 mm d$^{-1}$, respectively, both less than the estimated $ET_e$. Notwithstanding, there were some days when $ET_e$ values lower than the computed $ET_o$ and $ET_r$ values.

On an average seasonal basis, the $ET_e$ values were higher than $ET_o$ and less than $ET_r$ computed from weather data from an Agrometeorological weather station within 2 km from the experiment site. The average daily $ET_e$, $ET_o$, and $ET_r$ values during the corn growth period were 4.8, 4.2, and 5.1 mm d$^{-1}$, respectively. The root mean squared error (RMSE) between daily $ET_o$ and $ET_r$ values versus daily $ET_e$ values were 1.4 and 1.5 mm, respectively. The computed weekly total (irrigation decisions in this region are taken mostly on a weekly basis) values of both $ET_o$ and $ET_r$ were correlated with $ET_e$ with Pearson's correlation coefficient (r) values of 0.81 (coefficient of determination, $R^2 = 0.66$) and 0.70 ($R^2 = 0.61$), respectively (Fig. 8a and b). Likewise, though the daily $ET_o$ and $ET_r$ values deviated substantially from $ET_e$ estimates (Fig. 7b), seasonal total values of $ET_e$ and $ET_r$ were close to one other (Fig. 7c). Seasonal cumulative $ET_e$, $ET_o$, and $ET_r$ were 593, 561, and 676 mm, respectively. Therefore, in the absence of direct measurements of crop ET (for example, lysimeters, eddy covariance, or energy balance estimates), $ET_r$ computed from climatological data representing the crop conditions can be the best alternative for irrigation management applications where water is typically not the limiting factor.

## 4. Conclusions

A residual energy balance (EB) procedure for quantifying daily evapotranspiration (ET) from cropping systems based on measurements of the various components of heat energy balance of a land-crop canopy system was developed from components studied previously in the literature. In the present EB method, estimated ET (ET$_e$) is expressed as latent heat flux, computed as the residual energy from a crop surface energy balance equation when $R_n$ and soil heat flux are measured, and sensible heat flux is estimated from measurements of plant surface radiative temperature, air temperature, relative humidity, and wind speed at a constant height above the canopy. A flux gradient approach was employed for computation of sensible heat, which requires quantification of the aerodynamic resistance to water flux across the 1-m air layer between the sensors and canopy surface. The computed aerodynamic resistance was modified for wind conditions and air stability effects. Details of the EB components are evaluated using 15-min average values of the high-resolution data, which are illustrated on selected days with and without rain.

For a cotton field in Bushland, TX, ET$_e$ compared well with ET measured concurrently in a lysimeter. The present EB methodology was then used to quantify ET for irrigated corn in Stoneville, MS. On a weekly total basis, the energy balance computed ET$_e$ was strongly correlated with reference crop ET for alfalfa (ET$_r$) and grass (ET$_o$)

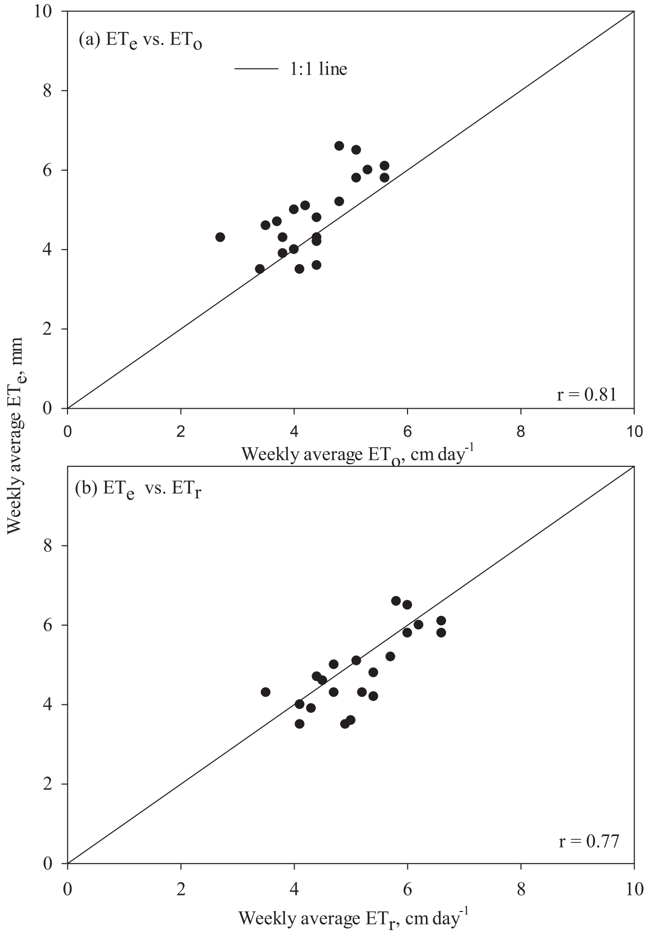

**Fig. 8.** Comparison between corn evapotranspiration computed using the energy balance method ($ET_e$), grass reference crop evapotranspiration ($ET_o$) and alfalfa reference crop evapotranspiration ($ET_r$) using 2016 climate data in the Stoneville corn experiment. r is the Pearson's correlation coefficient.

computed from weather data at the location. The cumulative seasonal values of $ET_r$ compared better with $ET_e$ than $ET_o$. From these results, we conclude that the EB procedure presented here, using movable instrumentation, constitutes a viable alternative method to lysimeters and eddy covariance systems for quantifying ET quickly in cropping systems for irrigation water management applications. Additional testing of the EB method is recommended under a broader range of climatic, agronomic, and soil conditions. Case studies on the use of the $ET_e$ in irrigation scheduling applications are planned to further demonstrate the utility of the present EB method.

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