

# Estimation of Evapotranspiration by Various Net Radiation Estimation Formulae for Non-Irrigated Grass in Brazil

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## Abstract

The objective of this study was to assess the accuracy of estimating evapotranspiration (ET) using the FAO-56 Penman-Monteith (FAO-56-PM) model, with measured and estimated net radiation ( $R_{n_{\text{measured}}}$  and  $R_{n_{\text{estimated}}}$ , respectively), the latter obtained via five different models. We used meteorological data collected between August 2005 and June 2008, on a daily basis and on a seasonal basis (wet vs. dry seasons). The following data were collected: temperature; relative humidity; global solar radiation ( $R_s$ ); wind speed and soil heat flux. The atmospheric pressure was determined by aneroid barograph, and sunshine duration was quantified with a Campbell-Stokes recorder. In addition to the sensor readings ( $R_{n_{\text{measured}}}$ ), five different models were used in order to obtain the  $R_{n_{\text{estimated}}}$ . Four of those models consider the effects of cloud cover: the original Brunt model; the FAO-24 model for wet climates; the FAO-24 model for dry climates, and the FAO-56 model. The fifth was a linear regression model based on  $R_s$ . In estimating the daily  $ET_0$  with the FAO-56-PM model,  $R_{n_{\text{measured}}}$  can be replaced by  $R_{n_{\text{estimated}}}$ , in accordance with the FAO-24 model for dry climates, with a relative error of 2.9%, or with the FAO-56 model, with an error of 4.9%, when  $R_s$  is measured, regardless of the season. The  $R_{n_{\text{estimated}}}$  obtained with the fifth model has a relatively high error. The original Brunt model and FAO-24 model for wet climates performed more poorly than did the other models in estimating the  $R_n$  and  $ET_0$ . In overcast conditions, the original Brunt model, the FAO-24 model for wet climates, the FAO-24 model for dry climates, the FAO-56 model and the model of linear regression with  $R_s$  as the predictor variable tended to overestimate  $R_n$  and  $ET$ , those estimates becoming progressively more accurate as the cloud cover diminished.

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## Keywords

**Evapotranspiration, Net Radiation, Solar Radiation, Cloud Cover, Empirical Models**

### 1. Introduction

The model employed in order to quantify the consumption of water by crops includes the concept of evapotranspiration (ET), which is the rate at which water is transferred into the air from a reference surface. The model uses the FAO-56 Penman-Monteith (FAO-56-PM) equation, with a grass height of 0.12 m, an albedo of 0.23 and a surface resistance of  $70 \text{ s}\cdot\text{m}^{-1}$  [1], with uniform height, actively growing, covering the entire surface of the soil and without any water shortage.

The application of the FAO-56-PM model requires measurements of net radiation ( $R_n$ ), soil heat flux, air temperature, humidity, atmospheric pressure and wind speed. Specifically in the case of  $R_n$ , there are procedures for estimating its value, as described by various authors [1] [2]. In many cases, because they are simple, empirical equations, the accuracy of the model in estimating  $R_n$  affects the value of ET. The uncertainty in estimating ET can be minimized by measuring  $R_n$  directly, which allows the measured and estimated values ( $R_{n_{\text{measured}}}$  and  $R_{n_{\text{estimated}}}$ , respectively) to be compared [3].

The net radiometer is the most widely used instrument for the measurement of  $R_n$ . However,  $R_n$  is not often measured in weather station networks [4] [5].

Various studies have evaluated measured or estimated ET on several times scales,  $R_n$  having been measured by different instruments or estimated by different models [6]-[9]. The choice of methodology depends on factors such as climatic conditions, accessibility of the necessary meteorological data, complexity of the model, grouping of the data considered and costs [10] [11].

Many researchers, in the absence of experimental observations, have estimated  $R_n$  from empirical relationships based on physical considerations or other meteorological data [12], using the correlations as a function of global solar radiation ( $R_s$ ). Thus, they have evaluated surfaces such as grass [13]-[16] and crops such as cotton, beans and soybeans [17], bananas [18], coffee [19], cowpeas [20], sunflowers [21], and grapes [22] [23], making the estimation of  $R_n$  simpler and more reliable because of the strong correlations found by these authors.

$R_n$  is the meteorological element that has the greatest influence on ET and represents the main source of energy used in various physical-biological processes. Furthermore, it is the main parameter used in many of the models that estimate the transfer of water from vegetated surfaces into the atmosphere. It is therefore important to measure or estimate  $R_n$  accurately. In the present study, we aimed to evaluate the accuracy of estimated evapotranspiration on a daily scale during dry and wet seasons, testing various  $R_n$  estimation formulae for non-irrigated grass in Brazil.

### 2. Material and Methods

Measurements were taken at the agrometeorological station of the São Paulo State University School of Agricultural and Veterinary Sciences, located in the city of Jaboticabal, Brazil ( $21^\circ 14' 05''\text{S}$ ;  $48^\circ 17' 09''\text{W}$ , altitude: 615.01 m). The surface studied was covered by grass. According to the Köppen climate classification system [24], the climate of the area is type Aw, which is defined as “tropical wet and dry”, or “tropical savanna” (annual climatological data: average air temperature of  $22.2^\circ\text{C}$ ; average relative humidity of 70.8%; rainfall of 1424.6 mm).

The experimental data were collected from August 2005 to June 2008—monthly meteorological data (Table 1) in an area of 0.56 ha ( $80 \times 70$  m) covered with non-irrigated grass (*Paspalum notatum* L.).

The months of January, February, March, October, November and December were considered the wettest months, whereas April, May, June, July, August and September were considered the driest months [25].

ET by the FAO-56-PM model, as described by [1]:

$$\text{ET} = \frac{0.408s(R_n - G) + \gamma \frac{900}{T + 273} U_2 (e_s - e_a)}{s + \gamma(1 + 0.34U_2)} \quad (\text{mm}^{-2} \cdot \text{day}^{-1}) \quad (1)$$

**Table 1.** Monthly meteorological data between August 2005 and June 2008.

Month	$T$ ( $^{\circ}\text{C}\cdot\text{day}^{-1}$ )	RH ( $\%\cdot\text{day}^{-1}$ )	P ( $\text{mm}\cdot\text{day}^{-1}$ )	$U_2$ ( $\text{m}\cdot\text{s}^{-1}\cdot\text{day}^{-1}$ )	$n$ ( $\text{h}\cdot\text{day}^{-1}$ )	Rn ( $\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ )
Jan	23.7	78.4	412.7	1.7	5.4	10.1
Feb	24.0	78.1	348.6	1.6	7.0	11.7
Mar	24.0	73.3	86.8	1.5	7.5	10.8
Ap	22.7	71.8	168.7	1.5	7.9	11.5
May	19.2	66.9	166.9	1.9	7.1	9.2
Jun	19.5	63.2	8.7	1.0	7.4	9.2
Jul	19.3	55.9	80.5	1.9	7.7	9.9
Aug	22.0	54.3	0.0	1.1	9.3	12.6
Sep	22.8	56.2	1.3	1.5	8.0	13.3
Oct	24.8	63.7	35.0	2.1	7.6	10.3
Nov	23.7	66.8	129.4	2.4	7.4	11.5
Dec	23.8	73.2	194.8	2.3	6.7	11.4
Full Period	22.5	66.9	1633.4	1.7	7.4	10.9

$T$ , air temperature; RH, air relative humidity; P, rainfall;  $U_2$ , wind speed—2 m;  $n$ , sunshine duration; Rn, net radiation.

where  $G$  is the soil heat flux ( $\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ ),  $\gamma$  is the psychrometric coefficient ( $\text{kPa}\cdot^{\circ}\text{C}^{-1}$ );  $T$  is the mean temperature ( $^{\circ}\text{C}$ );  $U_2$  is the mean wind speed at a height of 2 m ( $\text{m}\cdot\text{s}^{-1}$ ),  $e_s$  is the saturated vapor pressure (kPa), given by the expression:

$$e_s = 0.6108 \exp\left(\frac{17.27T}{T+237.3}\right) \quad (2)$$

$e_a$  is the actual vapor pressure (kPa), given by the expression:

$$e_a = e_s \text{RH} \quad (3)$$

where RH is relative humidity (%) and  $s$  is the slope of the curve of vapor pressure ( $\text{kPa}\cdot^{\circ}\text{C}^{-1}$ ), given by the expression:

$$s = \frac{4098e_s}{(T+237.3)^2} \quad (4)$$

An automated data logger (CR10X; Campbell Scientific, Logan, UT) was installed on the reference surface in order to collect the following data (from the following instruments): temperature and relative humidity at 1.5 m above the surface (CS500 probe; Vaisala, Helsinki, Finland);  $R_s$  (CM3 pyranometer; Kipp & Zonen, Delft, The Netherlands); wind speed at 2 m above the surface (014A-L-34 wind speed sensor; Met-One Instruments, Grants Pass, OR), and Rn (NR-Lite net radiometer; Kipp & Zonen). Measurements of Rn were corrected for the effects of wind according to the manufacturer's recommendation. The soil heat flux was obtained with a heat flux plate (HFT3; REBS Inc., Seattle, WA) installed at a depth of 3.5 cm. The atmospheric pressure was obtained by aneroid barograph (290; Lambrecht Meteorological Instruments, Göttingen, Germany), and sunshine duration was quantified with a Campbell-Stokes recorder (L-1603; Lambrecht Meteorological Instruments).

In addition to the  $Rn_{\text{measured}}$ ,  $Rn_{\text{estimated}}$  was obtained by combining the Angström-PreScott equations for short-wave radiation components with the Brunt equation for the longwave radiation component emitted by the atmosphere. Thus, the  $Rn_{\text{estimated}}$  values were obtained using four models that take into account the effects of cloud cover and a fifth model involving linear regression with  $R_s$  as the predictor variable:

$Rn_{\text{BRUNT}}$ : original equation of Brunt [26]:

$$Rn_{\text{BRUNT}} = [R_s(1-r)] - \left[ 4.8989 \times 10^{-9} T^4 (0.56 - 0.09\sqrt{ea}) \left( 0.1 + 0.9 \frac{n}{N} \right) \right] (\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}) \quad (5)$$

where  $R_s$  is the global solar radiation ( $\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ ),  $r$  is the reflection coefficient of grass,  $T$  is the mean temperature (K),  $ea$  is the actual vapor pressure in the air (mmHg),  $n$  is the number of hours of sunshine duration (h), and  $N$  is the photoperiod (h).

**Rn<sub>FAO-24W</sub>** and **Rn<sub>FAO-24D</sub>**: the Brunt equation, as adapted, in two forms [2]:

$$\text{Rn}_{\text{FAO-24W}} = [R_s(1-r)] - \left[ 4.903 \times 10^{-9} T^4 (0.56 - 0.25\sqrt{ea}) \left( 0.1 + 0.9 \frac{n}{N} \right) \right] \text{ (wet climates)} \quad (6)$$

$$\text{Rn}_{\text{FAO-24D}} = [R_s(1-r)] - \left[ 4.903 \times 10^{-9} T^4 (0.34 - 0.14\sqrt{ea}) \left( 0.1 + 0.9 \frac{n}{N} \right) \right] \text{ (dry climates)} \quad (7)$$

**Rn<sub>FAO-56</sub>**: FAO-56 equation [1]:

$$\text{Rn}_{\text{FAO-56}} = [R_s(1-r)] - \left[ 4.903 \times 10^{-9} T^4 (0.34 - 0.14\sqrt{ea}) \left( 1.35 \frac{R_s}{R_{so}} - 0.35 \right) \right] \quad (8)$$

where

$$R_{so} = [0.75 + 2 \times 10^{-5} z] Ra \quad (9)$$

$$Ra = \frac{1440}{\pi} G_{sc} d_r [w_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(w_s)] \quad (10)$$

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad (11)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (12)$$

$$w_s = \arccos[-\tan(\varphi) \tan(\delta)] \quad (13)$$

where  $R_{so}$  is the global solar radiation without the presence of clouds ( $\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ ),  $z$  is the altitude (m),  $Ra$  is the extraterrestrial radiation ( $\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ ),  $G_{sc}$  is the solar constant ( $0.0820 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{min}^{-1}$ ),  $d_r$  is the relative Earth-Sun distance (rad),  $\delta$  is the solar declination (rad),  $\varphi$  is latitude (rad),  $w_s$  is the solar hour angle (rad), and  $J$  is the Julian day of the year (1 to 365 or 366).

**Rn<sub>Rs</sub>**: equation for estimating the Rn at Jaboticabal linear regression with global solar radiation as the predictor variable, as proposed by André and Volpe [27]:

$$\text{Rn}_{R_s} = 0.67 + 0.78(R_s) \text{ (spring-summer)} \quad (14)$$

$$\text{Rn}_{R_s} = -3.85 + 0.94(R_s) \text{ (fall-winter)} \quad (15)$$

where  $R_s$  is the global solar radiation ( $\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$ ).

We adopted the cloud cover classification system proposed [28] using the clearness index ( $K_T$ ) which is the ratio between incident global solar radiation and extraterrestrial radiation:  $K_T < 0.35$  (overcast),  $0.35 \leq K_T < 0.55$  (broken clouds),  $0.55 \leq K_T \leq 0.65$  (scattered clouds) and  $K_T > 0.65$  (clear sky).

We compared the estimation of ET based on  $\text{Rn}_{\text{measured}}$  with that based on  $\text{Rn}_{\text{estimated}}$  using the five models mentioned previously, through the statistical indicators simple linear regression analysis through the origin ( $y = bx$ ), index of agreement ( $d$ ), mean relative error (MRE) and efficiency (EF) [29]:

$$d = 1 - \left[ \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \right] \quad (16)$$

$$\text{MRE} = \frac{1}{n} \sum_{i=1}^n (O_i - P_i) \quad (17)$$

$$EF = \frac{\sum_{i=1}^n (O_i - \bar{O})^2 - \sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (18)$$

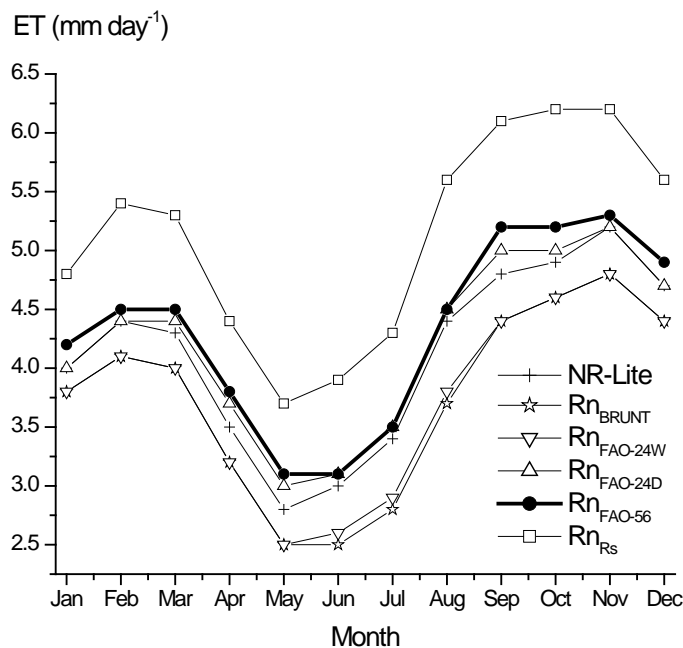
where  $d$  is the index of agreement,  $P_i$  is the ET estimated by the FAO-56-PM model with  $Rn_{\text{estimated}}$  via the model in question ( $Rn_{\text{BRUNT}}$ ;  $Rn_{\text{FAO-24W}}$ ;  $Rn_{\text{FAO-24D}}$ ;  $Rn_{\text{FAO-56}}$ ; or  $Rn_{\text{RS}}$ ),  $O_i$  is the ET estimated by the FAO-56-PM model with  $Rn_{\text{measured}}$  (the standard),  $\bar{P}$  is the mean ET obtained by the FAO-56-PM model with  $Rn_{\text{estimated}}$  via the alternative model in question,  $\bar{O}$  is the mean ET obtained by the FAO-56-PM model with  $Rn_{\text{measured}}$ , and  $n$  is the number of observations.

### 3. Results and Discussion

Analyzing the mean monthly ET values shown in **Figure 1**, which were obtained from the daily mean values, and comparing the  $Rn_{\text{measured}}$  ET with the  $Rn_{\text{estimated}}$  ET from the various models, we can see that the models in which the  $Rn_{\text{estimated}}$  most closely approximated the  $Rn_{\text{measured}}$  were the  $Rn_{\text{FAO-24D}}$  and  $Rn_{\text{FAO-56}}$  models. In addition, the  $Rn_{\text{RS}}$  equation was shown to have overestimated  $Rn$ , whereas there was an underestimation of  $Rn$  when the Brunt and FAO-24D equations were applied.

Initially, we analyzed the dry and wet months separately to determine the effect of seasonality of rainfall (**Table 2**).

Despite the similarity of the equations applied in the  $Rn_{\text{FAO-24D}}$  and  $Rn_{\text{FAO-56}}$  models, which differ only in the effect of cloud cover, there were significant differences between those two models. When we analyzed the dry months separately from the wet months, the  $Rn_{\text{FAO-56}}$  model underestimated the cloud cover, by 8.5% in the dry months and 22.9% in the wet months, resulting in the estimated ET being 1.6% and 2.8% higher in the dry and wet months, respectively, relative to the estimates obtained with the  $Rn_{\text{FAO-24D}}$  model. When we analyzed the dry and wet months together, the  $Rn_{\text{FAO-56}}$  model underestimated the cloud cover by 15.2%, increasing the estimated ET by 4.9% (**Table 3**). However, no statistically significant differences were observed between the separate and



**Figure 1.** Monthly variation in the evapotranspiration (ET) estimates obtained with the FAO-56 Penman-Monteith model, including net radiation ( $Rn$ ) measured with a net radiometer (NR-Lite) and  $Rn$  estimated via five different models:  $Rn_{\text{BRUNT}}$ ;  $Rn_{\text{FAO-24W}}$  (for wet climates);  $Rn_{\text{FAO-24D}}$  (for dry climates);  $Rn_{\text{FAO-56}}$ ; and linear regression with global solar radiation as the predictor variable ( $Rn_{\text{RS}}$ ).

**Table 2.** Comparative statistics for evapotranspiration (ET) estimates obtained with the FAO-56 Penman-Monteith model, for dry months and wet months, including net radiation (Rn) measured with a net radiometer ( $Rn_{measured}$ ) and Rn estimated ( $Rn_{estimated}$ ) via the five different models evaluated:  $Rn_{BRUNT}$ ;  $Rn_{FAO-24W}$  (for wet climates);  $Rn_{FAO-24D}$  (for dry climates);  $Rn_{FAO-56}$ ; and linear regression with global solar radiation as the predictor variable ( $Rn_{Rs}$ ).

<i>Rn estimation formulae</i>	<i>N</i>	ET with $Rn_{estimated}$ ( $mm \cdot day^{-1}$ )	<i>b</i>	$R^2$	<i>d</i>	MRE ( $mm \cdot day^{-1}$ )	EF
ET ( $Rn_{measured}$ ), dry month	1063	3.64c	-	-	-	-	-
ET ( $Rn_{measured}$ ), wet month		4.56C					
ET ( $Rn_{BRUNT}$ ), dry month	1063	3.19d	0.8787	0.9536	0.9942	0.45	0.9807
ET ( $Rn_{BRUNT}$ ), wet month		4.26D	0.9267	0.9391	0.9978	0.30	0.9917
ET ( $Rn_{FAO-24W}$ ), dry month	1063	3.21d	0.8852	0.9534	0.9947	0.43	0.9823
ET ( $Rn_{FAO-24W}$ ), wet month		4.30D	0.9339	0.9407	0.9981	0.26	0.9923
ET ( $Rn_{FAO-24D}$ ), dry month	1063	3.79c	1.0355	0.9827	0.9990	0.15	0.9955
ET ( $Rn_{FAO-24D}$ ), wet month		4.64C	1.0095	0.9628	0.9990	0.08	0.9950
ET ( $Rn_{FAO-56}$ ), dry month	1063	3.85b	1.0531	0.9746	0.9983	0.21	0.9918
ET ( $Rn_{FAO-56}$ ), wet month		4.77B	1.0374	0.9703	0.9985	0.20	0.9927
ET ( $Rn_{Rs}$ ), dry month	1063	4.69a	1.2804	0.9630	0.9829	1.05	0.9075
ET ( $Rn_{Rs}$ ), wet month		5.59A	1.2196	0.9668	0.9886	1.03	0.9413

*N*, number of observations; *b*, slope of the regression line;  $R^2$ , coefficient of determination; *d*, index of agreement; MRE, mean relative error; EF, efficiency. Means followed by the same letter in the same column do not differ at the 5% level by t-test.

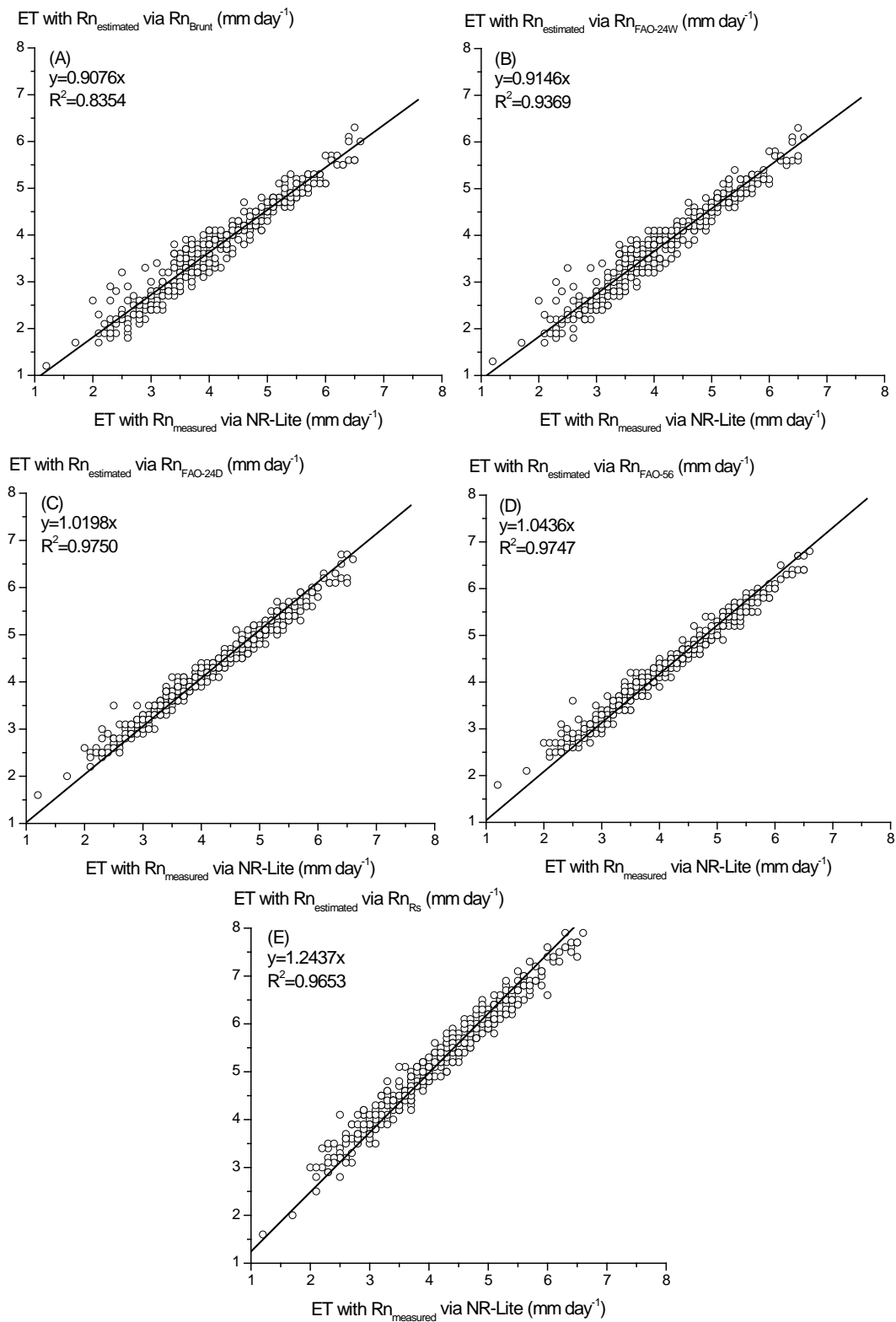
**Table 3.** Comparative statistics for evapotranspiration (ET) estimates obtained with the FAO-56 Penman-Monteith model, for the study period as a whole (August 2005 to June 2008), including net radiation (Rn) measured with a net radiometer ( $Rn_{measured}$ ) and Rn estimated ( $Rn_{estimated}$ ) via the five different models evaluated:  $Rn_{BRUNT}$ ;  $Rn_{FAO-24W}$  (for wet climates);  $Rn_{FAO-24D}$  (for dry climates);  $Rn_{FAO-56}$ ; and linear regression with global solar radiation as the predictor variable ( $Rn_{Rs}$ ).

<i>Rn estimation formulae</i>	<i>N</i>	ET (mm)	<i>b</i>	$R^2$	<i>d</i>	MRE (mm)	EF	$Rn$ ( $MJ \cdot m^{-2}$ )	<i>b</i>	$R^2$	<i>d</i>	MRE ( $MJ \cdot m^{-2}$ )	EF
ET ( $Rn_{medido}$ )	1063	4.1c	-	-	-	-	-	9.3e	-	-	-	-	-
ET ( $Rn_{BRUNT}$ )	1063	3.7d	0.908	0.835	0.996	0.4	0.986	7.7d	0.814	0.707	0.968	1.6	0.892
ET ( $Rn_{FAO-24W}$ )	1063	3.8d	0.915	0.937	0.996	0.3	0.987	7.9d	0.836	0.716	0.970	1.4	0.895
ET ( $Rn_{FAO-24D}$ )	1063	4.2bc	1.020	0.975	0.999	0.1	0.995	9.8c	1.013	0.842	0.986	0.5	0.905
ET ( $Rn_{FAO-56}$ )	1063	4.3b	1.044	0.975	0.998	0.2	0.992	10.2b	1.057	0.895	0.984	0.9	0.813
ET ( $Rn_{Rs}$ )	1063	5.1a	1.244	0.965	0.986	1.0	0.924	13.8a	1.425	0.801	0.949	4.4	0.589

*N*, number of observations; *b*, slope of the regression line;  $R^2$ , coefficient of determination; *d*, index of agreement; MRE, mean relative error; EF, efficiency. Means followed by the same letter in the same column do not differ at the 5% level by t-test.

joint analyses of dry and wet months, for any of the models. This, together with the values for slope, coefficient of determination, index of agreement, MRE and efficiency (Table 1), made it apparent that the separate analyses were not necessary, and we were able to group the data for the entire period (Table 3), thus simplifying the analysis.

When comparing the mean  $Rn_{measured}$  ET for the entire period ( $4.1 \text{ mm} \cdot \text{day}^{-1}$ , Table 3) with the mean  $Rn_{estimated}$  ET for the entire period obtained via the  $Rn_{BRUNT}$  and  $Rn_{FAO-24W}$  models, we found that those two models unde-



**Figure 2.** Relationship between the evapotranspiration (ET) estimates obtained with the FAO-56 Penman-Monteith model when net radiation ( $Rn$ ) is measured ( $Rn_{measured}$ ) with a net radiometer (NR-Lite) and when it is estimated ( $Rn_{estimated}$ ) via the five different models evaluated: (A)  $Rn_{BRUNT}$ ; (B)  $Rn_{FAO-24W}$  (for wet climates); (C)  $Rn_{FAO-24D}$  (for dry climates); (D)  $Rn_{FAO-56}$ ; and (E) Linear regression with  $R_s$  as the predictor variable ( $Rn_{R_s}$ ).

reestimated the ET by 10.8% and 7.9%, respectively, whereas ET was overestimated by 2.4%, 4.9% and 24.4%, respectively, when we used the models  $Rn_{FAO-24D}$ ,  $Rn_{FAO-56}$  and  $Rn_{R_s}$ . A slope of the regression equation that is closer to 1 indicates a better estimate of the ET. The best fit (slope = 1.020) was obtained with the  $Rn_{FAO-24D}$  model, as confirmed by t-test (**Table 3**) and scatterplot (**Figure 2**). According to the coefficient of determination, index of agreement, mean absolute error (MAE) and efficiency values, the best estimates of ET were obtained via the  $Rn_{FAO-24D}$  model, followed by the models  $Rn_{FAO-56}$  models,  $Rn_{FAO-24W}$ ,  $Rn_{BRUNT}$  and  $Rn_{R_s}$ . In the present study, the strongest correlation with the  $Rn_{measured}$  was achieved via the  $Rn_{FAO-24D}$  model. For the study period as a whole, the MRE of  $Rn$  ( $MJ \cdot m^{-2} \cdot day^{-1}$ ) was 1.6, 1.5, 0.5, 0.9 and 4.4, respectively, for the models  $Rn_{BRUNT}$ ,  $Rn_{FAO-24W}$ ,  $Rn_{FAO-24D}$ ,  $Rn_{FAO-56}$  and  $Rn_{R_s}$  (**Table 3**).

Some authors, such as [6] and [8], recommend using the FAO-56 equation [1] to calculate  $Rn$  when obtaining estimates of ET via the FAO-56-PM model, given that some other authors, such as [30] and [31], encountered difficulties with respect to the estimation of net longwave radiation in studies employing the FAO-24 equation. This is because the estimation of  $Rn$  requires the evaluation of several meteorological variables, including sunshine duration, which is not always possible due to the absence of measurements [32], which could make it more costly to estimate  $Rn$  than to measure it directly.

Given that estimates of ET obtained via the FAO-56-PM model are affected by the method employed in obtaining  $Rn$ , [15] recommend that  $Rn$  be obtained with the NR-Lite (Kipp & Zonen) sensor, whereas [33] stated that  $Rn$  can be obtained with either the NR-Lite (Kipp & Zonen) sensor or the Q-7.1 (REBS) sensor, provided that the sensor employed is properly calibrated against a CNR1 (Kipp & Zonen) sensor, which is considered the standard for its high accuracy [34].

For the Jaboticabal region, the  $Rn_{R_s}$  model André and Volpe [27] overestimated ET by 28.8% and 22.6% for dry and wet months, respectively, and by 24.4% for the study period as a whole (**Table 2** and **Table 3**). This is explained in part by the fact that the regression equation was devised in 1988, with  $Rn$  measured by a net exchange radiometer (Packard Bell model TCN-188), without dome and with ventilation, and  $R_s$  measured with an Eppley thermopile pyranometer (model 8-48), instruments quite different from those currently used. Most current net radiometers consist of thermopile covered by a dome of polyethylene to eliminate natural ventilation and reduce thermal convection from the body of the device. In view of the disadvantages regarding maintenance and operation of a net radiometer with a dome, the “dome-less” NR-Lite [34], in which the dome has been replaced by a black Teflon coating [35], is now widely used.

In the present study, despite the high correlation between  $Rn$  and  $R_s$ ,  $R_s$  overestimated  $Rn$  by 48.4% according to the methodology of André and Volpe [27] and, consequently, the FAO-56-PM model with  $Rn$  estimated by the  $Rn_{R_s}$  model overestimated the daily ET by 24.4% (**Table 3**). Many authors have identified such overestimation of ET, ranging from 6% to 29%, at various locations [15] [36]-[44].

Significant errors can be made in estimating the ET when  $Rn$  is not correctly measured or estimated, with differences of as much as  $2.2 MJ \cdot m^{-2} \cdot day^{-1}$  [45]. In the present study, when we analyzed the different cloud cover conditions, we found that the MRE for  $Rn_{estimated}$  was 0.2 -  $5.1 MJ \cdot m^{-2} \cdot day^{-1}$  for clear sky days, 0.01 -  $3.5 MJ \cdot m^{-2} \cdot day^{-1}$  for days with scattered clouds, 0.4 -  $3.1 MJ \cdot m^{-2} \cdot day^{-1}$  for days with broken clouds and 1.3 -  $2.7 MJ \cdot m^{-2} \cdot day^{-1}$  for overcast days (**Table 4**).

The model used in obtaining  $Rn$  and, specifically, the way in which the effect that cloud cover has on the longwave component is calculated, can cause significant errors in the estimation of daily ET by the Penman-Monteith model [15] [46].

The  $Rn$  depends heavily on the  $R_s$ , which is in turn dependent on other factors, such as the effect of cloud cover, increases in cloud cover decreasing the  $R_s$  and  $Rn$  fluxes and consequently decreasing the ET. This is because the clear sky condition reveals the dependence of  $Rn$  on cloud cover [47].

When ET is estimated by the Penman-Monteith model on the basis of  $Rn$  estimated by the  $Rn_{R_s}$  model, the effect of cloud cover is embedded in the term  $R_s$ , but varies slightly in comparison with that of the  $Rn$  estimation models in which the effect of cloud cover is taken into account. This is because cloud cover has a major influence on variations in net longwave radiation and consequently on estimates of ET. The  $Rn_{R_s}$  model limits variations that other models allow, because it sets fixed values for the seasons. [12] recommend that parameters such as  $R_s$ , surface albedo,  $K_T$  and air temperature, normally used to estimate  $Rn$ , be incorporated into new elements, such as  $R_s$  and pressure of water vapor, to improve the credibility of the estimates. As cloud cover decreases, the net longwave radiation balance becomes more negative and therefore has a greater effect on the calculation of the  $Rn_{estimated}$ , bringing it into closer proximity with the  $Rn_{measured}$  (**Table 5**).



**Table 4.** Comparative statistics for evapotranspiration (ET) estimates obtained with the FAO-56 Penman-Monteith model, under various cloud cover conditions, including net radiation (Rn) measured with a net radiometer ( $Rn_{\text{measured}}$ ) and Rn estimated ( $Rn_{\text{estimated}}$ ) via the five different models evaluated:  $Rn_{\text{BRUNT}}$ ;  $Rn_{\text{FAO-24W}}$  (for wet climates);  $Rn_{\text{FAO-24D}}$  (for dry climates);  $Rn_{\text{FAO-56}}$ ; and linear regression with global solar radiation as the predictor variable ( $Rn_{\text{Rs}}$ ).

Clearness Rn estimation formulae	<i>N</i>	ET (mm)	<i>b</i>	$R^2$	<i>d</i>	MRE (mm)	EF	Rn ( $\text{MJ}\cdot\text{m}^{-2}$ )	<i>b</i>	$R^2$	<i>d</i>	MRE ( $\text{MJ}\cdot\text{m}^{-2}$ )	EF
Clear sky													
ET ( $Rn_{\text{medido}}$ )	692	4.5bc	-	-	-	-	-	10.2c	-	-	-	-	-
ET ( $Rn_{\text{BRUNT}}$ )	692	3.9d	0.879	0.926	0.992	0.6	0.976	7.8d	0.775	0.806	0.964	2.4	0.912
ET ( $Rn_{\text{FAO-24W}}$ )	692	4.0d	0.886	0.927	0.993	0.5	0.978	7.9d	0.788	0.808	0.967	2.3	0.919
ET ( $Rn_{\text{FAO-24D}}$ )	692	4.6c	1.004	0.933	0.998	0.1	0.994	10.4c	0.998	0.816	0.994	0.2	0.974
ET ( $Rn_{\text{FAO-56}}$ )	692	4.7bc	1.025	0.960	0.999	0.1	0.993	10.8b	1.038	0.890	0.995	0.6	0.970
ET ( $Rn_{\text{Rs}}$ )	692	5.7a	1.250	0.917	0.983	1.2	0.903	15.3a	1.443	0.743	0.948	5.1	0.593
Scattered clouds													
ET ( $Rn_{\text{medido}}$ )	127	4.4bc	-	-	-	-	-	10.4c	-	-	-	-	-
ET ( $Rn_{\text{BRUNT}}$ )	127	4.0d	0.918	0.856	0.996	0.3	0.988	9.0d	0.857	0.605	0.985	1.4	0.959
ET ( $Rn_{\text{FAO-24W}}$ )	127	4.0d	0.924	0.859	0.997	0.3	0.989	9.1d	0.867	0.612	0.987	1.3	0.962
ET ( $Rn_{\text{FAO-24D}}$ )	127	4.4c	0.994	0.896	0.998	0.01	0.994	10.4c	0.988	0.698	0.995	0.01	0.979
ET ( $Rn_{\text{FAO-56}}$ )	127	4.5bc	1.030	0.932	0.990	0.2	0.993	11.1b	1.047	0.809	0.995	0.65	0.974
ET ( $Rn_{\text{Rs}}$ )	127	5.2a	1.184	0.910	0.991	0.8	0.954	13.9a	1.318	0.786	0.976	3.5	0.847
Broken clouds													
ET ( $Rn_{\text{medido}}$ )	155	3.2d	-	-	-	-	-	7.3e	-	-	-	-	-
ET ( $Rn_{\text{BRUNT}}$ )	155	3.3d	1.017	0.877	0.996	0.1	0.971	7.7e	1.028	0.633	0.989	0.4	0.932
ET ( $Rn_{\text{FAO-24W}}$ )	155	3.4d	1.021	0.880	0.996	0.1	0.971	7.8d	1.037	0.643	0.989	0.5	0.929
ET ( $Rn_{\text{FAO-24D}}$ )	155	3.5c	1.075	0.912	0.994	0.3	0.959	8.5c	1.137	0.746	0.984	1.2	0.873
ET ( $Rn_{\text{FAO-56}}$ )	155	3.6bc	1.103	0.928	0.992	0.4	0.947	8.9bc	1.184	0.817	0.979	1.6	0.799
ET ( $Rn_{\text{Rs}}$ )	155	4.0a	1.219	0.882	0.986	0.7	0.908	10.4a	1.410	0.767	0.962	3.1	0.726
Overcast													
ET ( $Rn_{\text{medido}}$ )	89	1.8c	-	-	-	-	-	3.7c	-	-	-	-	-
ET ( $Rn_{\text{BRUNT}}$ )	89	2.1ab	1.142	0.927	0.987	0.3	0.922	5.1b	1.223	0.760	0.932	1.3	0.530
ET ( $Rn_{\text{FAO-24W}}$ )	89	2.1ab	1.145	0.929	0.986	0.3	0.920	5.1b	1.231	0.766	0.930	1.4	0.516
ET ( $Rn_{\text{FAO-24D}}$ )	89	2.2ab	1.186	0.941	0.981	0.4	0.887	5.5b	1.325	0.818	0.909	1.8	0.278
ET ( $Rn_{\text{FAO-56}}$ )	89	2.4a	1.262	0.949	0.964	0.6	0.710	6.3a	1.448	0.866	0.874	2.5	0.826
ET ( $Rn_{\text{Rs}}$ )	89	2.4a	1.294	0.872	0.959	0.6	0.800	6.4a	1.628	0.777	0.888	2.7	0.120

*N*, number of observations; *b*, slope of the regression line;  $R^2$ , coefficient of determination; *d*, index of agreement; MRE, mean relative error; EF, efficiency. Means followed by the same letter in the same column do not differ at the 5% level by t-test.

As can be seen in **Table 5**, on days with overcast skies, all four of the Rn estimation models that took cloud cover into consideration overestimated the Rn in relation to the  $Rn_{\text{measured}}$ , because net shortwave radiation is directly dependent on  $R_s$ , the proportional contribution of net shortwave radiation increasing in parallel with increases in  $R_s$ . Determining the net longwave radiation depends on indices that correct for the effects of cloud

**Table 5.** Partition of net radiation estimated by the four models that take the effect of cloud cover into account, under various cloud cover conditions.

Clearness	$K_T$	$R_s$	Rns		Rnl			$Rn_{measured}$
			Rn	$Rn_{BRUNT}$	$Rn_{FAO-24W}$	$Rn_{FAO-24D}$	$Rn_{FAO-56}$	
Clear sky	0.83	20.13	15.50	-7.65	-7.51	-5.04	-4.66	10.25
Scattered clouds	0.60	17.50	13.48	-4.48	-4.36	-3.03	-2.39	10.44
Broken clouds	0.46	13.41	10.33	-2.62	-2.55	-1.78	-1.40	7.28
Overcast	0.26	7.50	5.77	-1.29	-1.26	-0.87	-0.02	3.05

$K_T$ , clearness index,  $R_s$ , global solar radiation; Rns, net shortwave radiation; Rnl, net longwave radiation, Rn, net radiation.

cover and pressure of water vapor. In the  $Rn_{BRUNT}$ ,  $Rn_{FAO-24W}$  and  $Rn_{FAO-24D}$  models, net longwave radiation has the same effect as cloud cover, changing only the indices that correct for pressure of water vapor in the air, which decreases the size of its effect, the index values being 0.47 for Equation (5), compared with 0.31 for Equation (6) and 0.20 for Equation (7).

Under conditions of clear sky, scattered clouds and broken clouds, the  $Rn_{estimated}$  values obtained with the  $Rn_{FAO-24D}$  and  $Rn_{FAO-56}$  models were comparable to the  $Rn_{measured}$ . Under overcast conditions, none of the models employed was able to adequately represent the  $Rn_{measured}$  or the ET obtained therefrom (Table 4). The  $Rn_{estimated}$  depends on the proportional contribution of net shortwave radiation and net longwave radiation. Under overcast conditions, the net longwave radiation share corresponded to only 15% - 22% of that of net shortwave radiation, which affected the estimation of Rn, because the net shortwave radiation was more prominent. Under conditions of clear sky, the net longwave radiation share corresponded to 30% - 49% of the net shortwave radiation share, having an even greater effect on the estimation of Rn (Table 5).

## 4. Conclusions

According to the coefficient of determination, index of agreement, MAE and efficiency values, the best estimates of ET were obtained via the  $Rn_{FAO-24D}$  model, followed by the models  $Rn_{FAO-56}$ ,  $Rn_{FAO-24W}$ ,  $Rn_{BRUNT}$  and  $Rn_{R_s}$ . The  $Rn_{estimated}$  obtained with the  $Rn_{FAO-24D}$  and  $Rn_{FAO-56}$  models more closely approximated the  $Rn_{measured}$  than did that obtained with the other models. Despite the similarity of the equations applied in the  $Rn_{FAO-24D}$  and  $Rn_{FAO-56}$  models, which differ only in the effect of cloud cover, there were significant differences between the two models. The  $Rn_{FAO-56}$  model underestimated the cloud cover, thereby increasing the estimated ET.

Under conditions of clear sky, scattered clouds and broken clouds, the  $Rn_{estimated}$  values obtained with the  $Rn_{FAO-24D}$  and  $Rn_{FAO-56}$  models were comparable to the  $Rn_{measured}$  value. As cloud cover decreases, the net longwave radiation balance becomes more negative and therefore has a greater effect on the calculation of the  $Rn_{estimated}$ , bringing it into closer proximity with the  $Rn_{measured}$ .

The Rn is the meteorological element that has the greatest influence on ET and can cause significant errors in the estimation of ET when not correctly measured or estimated.

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