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Estimating daily net radiation in the FAO Penman–Monteith method

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Abstract In this work, we evaluate the procedures of the *Manual No. 56* of the FAO (United Nations Food and Agriculture Organization) for predicting daily net radiation using measures collected in Tandil (Argentina) between March 2007 and June 2010. In addition, a new methodology is proposed for estimating daily net radiation over the reference crop considered in the FAO Penman–Monteith method. The calculated and observed values of daily net radiation are compared. Estimation errors are reduced from ±22 to ±12 W m^{-2} considering the new model. From spring–summer data, estimation errors of less than ±10 % were observed for the new physical model, which represents an error of just ±0.4 mm d^{-1} for computing reference evapotranspiration. The new model presented here is not restricted to a climate regime and is mainly appropriate for application in the FAO Penman–Monteith method to determine the reference crop evapotranspiration.

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1 Introduction

Net radiation, R_n, is the radiant energy available at the surface to drive biological and physical processes (Rosenberg et al. 1983). It is the balance between the energy absorbed, reflected, and emitted by the Earth's surface (Jobson 1982). R_n is normally positive during the daytime and negative during the nighttime, and its daily average value is almost always positive, except in extreme conditions at high latitudes (Allen et al. 1998). Quantification of R_n is required in numerous practical applications in agricultural crop planning and management and at various scales in crop-yield modeling studies, plant, and nutrient cycling assessments and agricultural water management (Kjaersgaard and Cuenca 2009). In general, its magnitude is required at daily time steps (Jensen et al. 1990; Allen et al. 1998; Kjaersgaard and Cuenca 2009). Considering incoming and outgoing contributions of shortwave and longwave radiation fluxes at the surface, R_n is expressed as (Allen et al. 2011; Carmona 2014):

$$R_n = R_{ns} + R_{nl} = \left[R_{s\downarrow} - R_{s\uparrow}\right] + \left[R_{l\downarrow} - \left(R_{l\uparrow S} + (1-\varepsilon_s)R_{l\downarrow}\right)\right] \quad (1)$$

Where $R_{ns} = [R_{s\downarrow} - R_{s\uparrow}]$ is the net shortwave radiation, with $R_{s\downarrow}$ the incoming solar radiation and $R_{s\uparrow}$ the fraction of incoming solar radiation reflected at the surface; $R_{nl} = [R_{l\downarrow} - (Rl_{\uparrow S} + (1 - \varepsilon_s)\, R_{l\downarrow})]$ is the net longwave radiation, with $R_{l\downarrow}$ the incoming longwave radiation flux emitted by the atmosphere; $Rl_{\uparrow S}$ is the radiation emitted by the surface; and ε_s is the surface emissivity.

Net radiation data are rarely available due to the technical and economical limitations associated with direct measurements (Carmona et al. 2015). Net radiometers require frequent maintenance and calibration, and providing a standard surface

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for measuring net radiation represents an additional problem (Monteith and Unsworth 1990; Alados et al. 2003). Therefore, due to difficulties in obtaining net radiation measurements, for practical applications, models based on easily accessed meteorological information have been developed. For example, multiple linear regression models have been applied to estimate net radiation using meteorological data (Irmak et al. 2003; Kjaersgaard et al. 2007; Ocampo and Rivas 2013).

A widely used method of estimating R_n over short grass is described in Manual No. 56 of the United Nations Food and Agriculture Organization (FAO) (Allen et al. 1998; ASCE-EWRI 2005). This method is recommended to determine the reference crop evapotranspiration (ET_o) by means of the FAO Penman–Monteith equation (which closely resembles the evaporation from an extensive surface of green grass, of uniform height, completely shading the ground, growing actively, and adequately watered). Procedures for application of the method are described in Manual No. 56 of the FAO (Allen et al. 1998), where the method requires not only a set of meteorological data but also the use of ad hoc equations (Ocampo and Rivas 2013). The equation for estimating net radiation in the FAO Penman–Monteith method, $R_{n\ \mathrm{FAO\ PM}}$, is expressed as:

$$R_{n\,\mathrm{FAO\,PM}} = R_{ns} + R_{nl} = R_{s\downarrow}(1-\alpha) + R_{nl} \tag{2}$$

With

$$R_{nl} = -\sigma\left[\frac{T^4_{\max,K} + T^4_{\min,K}}{2}\right]\left(a_1 + b_1\, e_a^{1/2}\right)\left(a_c\frac{R_{s\downarrow}}{R_{s\downarrow 0}} + b_c\right) \tag{3}$$

Where α = 0.23 is the surface albedo, σ is the Stefan-Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4}), $T_{\max,K}$ and $T_{\min,K}$ are the daily maximum and minimum air temperatures (K) at screen height (2 m), respectively, $e_{a.}$ is the water vapor pressure (kPa), $R_{s\downarrow 0}$ is clear-sky solar radiation (W m^{-2}), and a_l, b_l, a_c, and b_c are calibration coefficients (dimensionless). The term ($a_l + b_l\, e_a^{1/2}$) expresses the correction for air humidity, and will be smaller if the humidity increases. The effect of cloudiness is expressed by (a_c ($R_{s\downarrow}/R_{s\downarrow 0}$) + b_c). The term becomes smaller if the cloudiness increases and hence $R_{s\downarrow}$ decreases (Allen et al. 1998).

For the application of the FAO Penman–Monteith method, values of $a_l = 0.34$, $b_l = -0.14$, $a_c = 1.35$, and $b_c = -0.35$ have been recommended (Allen et al. 1998), using data from an arid climate for its calibration (Wright and Jensen 1972). However, if measurements of incoming and outgoing short and longwave radiation are available, calibration of these coefficients should be carried out for each climatic condition. For example, Jensen et al. (1990) found the best results with ac and bc values of [1.2, −0.2], [1.1, −0.1], and [1.0, 0.0] for arid, semiarid, and humid areas, respectively (Kjaersgaard and Cuenca 2009). Most users do not know these details, and significant errors in the estimation of net radiation are generated.

The objectives of this study are (a) to evaluate Eqs. (2) and (3) for estimating net radiation in the FAO Penman–Monteith method and (b) to develop a new method that is not restricted to a particular climate regime. The calculated values of daily net radiation are compared to observed values for the reference crop using meteorological data registered in Tandil, Argentina.

2 Model

For estimating the net radiation, the reference crop of the FAO Penman–Monteith method considers values of α = 0.23 and ε_s = 0.98 and a surface temperature T_S equal to air temperature, T_a. Figure 1 shows the radiation terms over the reference crop in the FAO Penman–Monteith method.

The FAO Penman–Monteith method considers empirical equations for estimating R_{nl}. However, considering the reference crop characteristics, if T_a, $R_{s\downarrow}$, and $R_{l\downarrow}$ are measured, the net radiation can be obtained by means of the following equation:

$$R_{n\ \mathrm{ref\ crop}} = 0.77 R_{s\downarrow} + 0.98\left(R_{l\downarrow} - \sigma T_a^4\right) \tag{4}$$

Where $R_{n\ \mathrm{ref.\ crop}}$ is the observed net radiation over the reference crop. Due to the absence of pyrgeometers in weather stations, Eq. (4) cannot be used directly. Several researchers have proposed using simple models for estimating $Rl_{\downarrow}$ (Carmona et al. 2014). These models make some assumptions regarding the vertical structure of the atmosphere. In some cases, these assumptions are explicitly presented, while in other cases, they are implicitly considered through the use of local experimental coefficients. From the viewpoint of thermal atmospheric irradiance, the atmosphere can be considered as a gray body with an effective emissivity defined as $\varepsilon_a = R_{l\downarrow}/\sigma.T_a^4$ (Jobson 1982; Brutsaert 1984). Under clear-sky conditions, ε_a can be modeled as a function of T_a and/or vapor pressure, $e_{a.}$ (see Eq. (3)). Then, the incoming longwave radiation is calculated as:

$$R_{l\downarrow 0} = \varepsilon_{a0}(T_a, e_a)\,\sigma T_a^4 \tag{5}$$

Where the subscript “0” indicates clear-sky conditions. There are numerous formulations for estimating $R_{l\downarrow 0}$ from basic meteorological data. Given the general scheme presented in Eq. (5), several researchers have proposed different models (Brunt 1932; Swinbank 1963; Idso and Jackson 1969; Brutsaert 1975; Prata 1996, among others). Other researchers estimated the experimental coefficients to adapt the preexistent equations to different local conditions (Bilbao and de Miguel 2007; Lhomme et al. 2007; Choi et al. 2009; Marthews et al. 2011; Alados et al. 2012; Carmona et al.

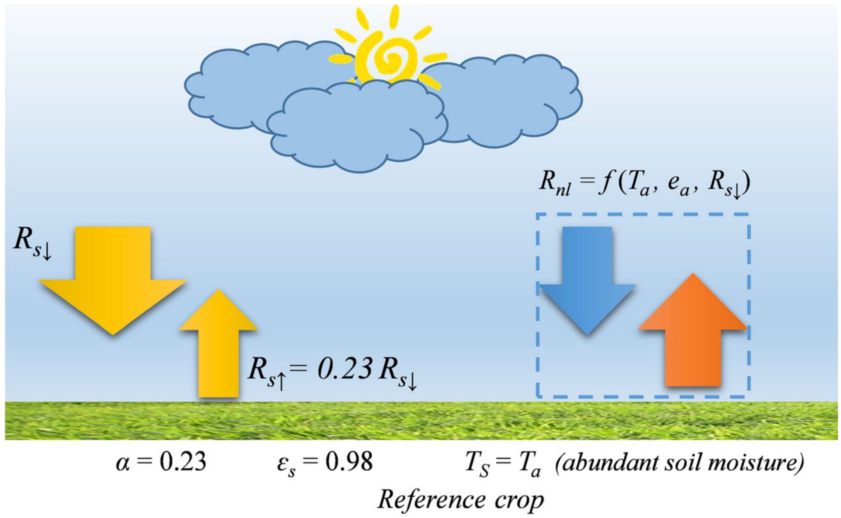

Fig. 1 Scheme of the radiation terms over the reference crop of the FAO Penman–Monteith method

2014, among others). On the other hand, for cloudy-sky conditions, the longwave radiation flux received at the surface is substantially modified. The liquid water and ice absorb and emit longwave radiation more effectively than water in the vapor phase (the most important atmospheric gas contributing to thermal radiation in the atmosphere), increasing $R_{l\downarrow}$. This is the reason why the cloud cover plays an important role in estimating $R_{l\downarrow}$ (Lhomme et al. 2007). Then, a more general formulation for estimating $R_{l\downarrow}$ can be written as:

$$R_{l\downarrow} = \varepsilon_a(T_a, e_a, P_c)\,\sigma T_a^4 = \varepsilon_a(\varepsilon_{a0}, P_c)\,\sigma T_a^4 \quad (6)$$

Where P_c is the cloud fraction. In this case, several researchers have proposed equations for estimating $R_{l\downarrow}$ under cloudy-sky conditions, generally using ε_{a0} and P_c as inputs (i.e., Sridhar and Elliott 2002; Iziomon et al. 2003; Duarte et al. 2006; Lhomme et al. 2007; De Bruin et al. 2010, among others). Carmona et al. (2014) showed that effective emissivity can be obtained by considering a sky emissivity, ε_{a0}, and a cloud emissivity, ε_c, with proportions of sky, P_s, and cloud, P_c. Then, the expression for estimating ε_a is given by:

$$\varepsilon_a = \varepsilon_{a0}P_s + \varepsilon_c P_c = \varepsilon_{a0}P_s + \varepsilon_c(1-P_s) \quad (7)$$

Where $\varepsilon_c = 1$ (since clouds behave as a black body) and P_s is defined as the ratio between the measured incoming solar radiation, $R_{s\downarrow}$, and the theoretical incoming clear-sky solar radiation, $R_{s\downarrow 0}$ (Allen et al. 1998; Lhomme et al. 2007; Carmona et al. 2014).

Combining Eqs. (4) to (7), we propose to estimate the net radiation by means of the following equation:

$$R_{n\,\mathrm{model}} = 0.77R_{s\downarrow} + \left(\frac{R_{s\downarrow}}{R_{s\downarrow 0}}\right)(\varepsilon_{a0}-1)\,0.98\,\sigma T_a^4 \quad (8)$$

Among the numerous formulations for estimating ε_{a0} from basic meteorological data, we choose to use the equation proposed by Brutsaert (1975), because it is based on analytical equations using radiative transfer theory and data from several authors. It is a function of vapor pressure and temperature at screen level and is given by:

$$\varepsilon_{a0} = 1.24\left(\frac{10\,e_a}{T_a}\right)^{1/7} \quad (9)$$

Where T_a is expressed in Kelvin and $e_{a.}$ in kilopascals. The vapor pressure, $e_{a.}$, is obtained as function of T_a and the air relative humidity, *RH* (Allen et al. 1998). Therefore, combining Eqs. (8) and (9), the proposed model is expressed as:

$$R_{n\,\mathrm{model}} = 0.77R_{s\downarrow} + \left(\frac{R_{s\downarrow}}{R_{s\downarrow 0}}\right)\left(1.24\left(\frac{10\,e_a}{T_a}\right)^{1/7} - 1\right)0.98\,\sigma T_a^4 \quad (10)$$

Where $R_{n\ \mathrm{model}}$ (W m^{-2}) is the net radiation over the reference crop of the FAO Penman–Monteith method. Figure 2 shows the scheme of the model proposed by means of Eq. (10).

3 Materials and methods

3.1 Experimental site and field measurements

Meteorological data collected in Tandil by means of an Energy Balance Station were used in this study (Carmona et al. 2014). Located in the central-southeastern area of Buenos Aires province (Argentina), Tandil is a department of 4935 km^2. The study area has a temperate and sub-humid climate regime. Representative vegetation types over this area are soybean and corn crops and native grassland, including *Dactylis glomerata*, *Festuca arundinacea*, and *Lolium multiflorum*. The soil is Typic Argiudoll, and the soil texture is silty loam and silty clay loam in deep soil horizons. The mean annual temperature is 14 °C, with a maximum monthly

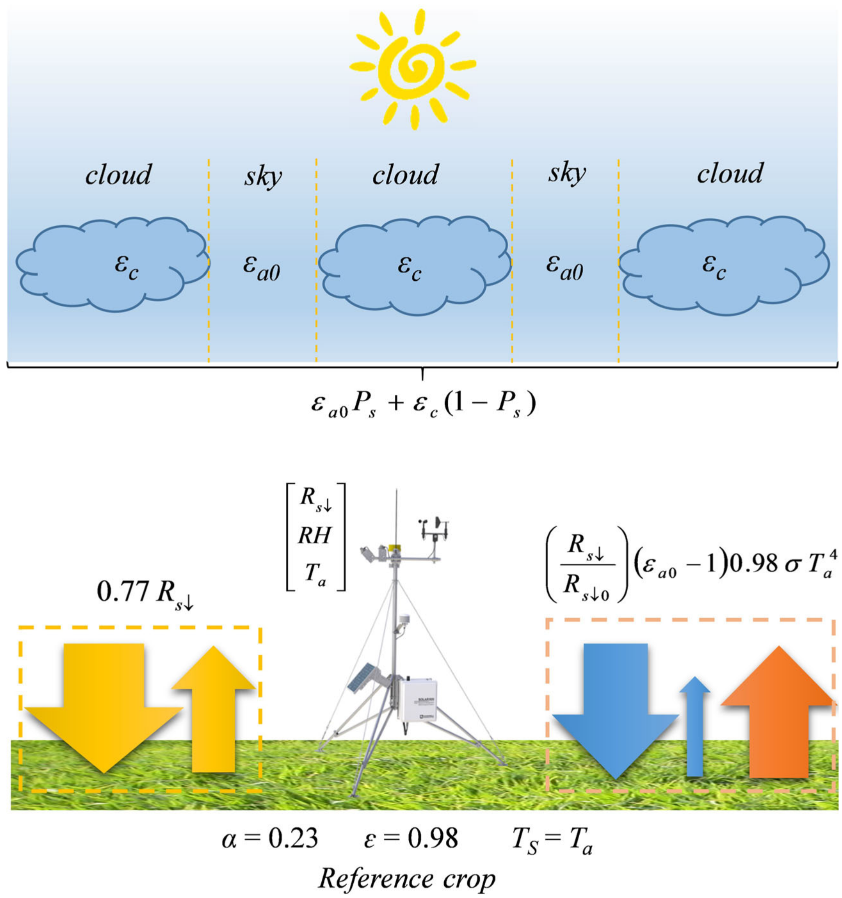

Fig. 2 Scheme of proposed model to estimate the net radiation over the reference crop

temperature of 22 °C in January and minimum of 8 °C in the coldest months of the year (June, July, and August). Average annual rainfall is 900 mm (Tandil Station of the Argentinean National Meteorological Network, 37°14′ S, 59°15′ W, 175 m); the maximum monthly value is in March (105 mm) and the minimum is in August (45 mm).

Measures of incoming shortwave and longwave radiation and air temperature/relative humidity were used. Incoming shortwave (0.305–2.800 μm) and longwave (5–50 μm) radiation components were measured with a CNR-1 net radiometer (Kipp & Zonen). The radiometer calibration was provided by the manufacturer. The CNR-1 radiometer was visually inspected during campaigns and was recalibrated bi-annually. Air temperature and relative humidity were also measured with a CS215-L16 probe (Campbell Scientific). All sensors were installed at about 2 m above the ground. Data were acquired by a CR10X data-logger (Campbell Scientific), and 15-min averages were recorded on a storage module for later processing. The station was continuously powered by a 12 V battery connected to a 20 W solar panel (Carmona et al. 2014).

3.2 Methods

The Tandil dataset included observations from March 2007 to June 2010, corresponding to measures conducted in different experimental campaigns within a 50 km radius of Tandil city (37° 19′ S, 59° 05′ W). A dataset of 840 days was available for analysis. Measures of T_a, RH, $R_{s\downarrow}$, and $R_{l\downarrow}$ were used to

Table 1 Cases evaluated for estimating the daily net radiation over the reference crop

Case	Model (equation)	Calibration	Coefficients			
			a_c	b_c	a_1	b_1
(*1*)	$R_{n\ \mathrm{FAO\ PM}}$ (Eqs. (2) and (3))	(Allen et al. 1998)	1.35	−0.35	0.34	−0.14
(*2*)	$R_{n\ \mathrm{FAO\ PM}}$ (Eqs. (2) and (3))	(Jensen et al. 1990)[a]	1.00	0.00	0.34	−0.14
(*3*)	$R_{n\ \mathrm{model}}$ (Eq. (10))	Calibration coefficients are not required	–	–	–	–

[a] a_c and b_c coefficients for humid climate regime

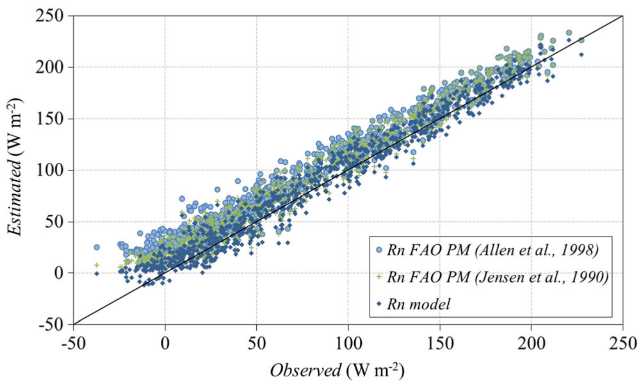

Fig. 3 Comparison of predicted and measured values of daily net radiation. The 1:1 line is shown on the plot

calculate the daily values of net radiation. The values of clear-sky solar radiation were estimated from:

$$R_{s\downarrow 0} = \left[0.75 + 2 \times 10^{-5} z\right] R_a \tag{11}$$

Where z is the station elevation above sea level (m) and R_a is the extraterrestrial radiation calculated following procedures described by Allen et al. (1998). The $e_{a.}$ (kPa) was obtained by means of the following equations:

$$e_a = \frac{e^0(T_{\min})\dfrac{RH_{\max}}{100} + e^0(T_{\max})\dfrac{RH_{\min}}{100}}{2} \tag{12}$$

With

$$e^0(T_a) = 0.6108 \ \ \exp\left[\frac{17.27\ T_a}{T_a + 237.3}\right] \tag{13}$$

Where $RH_{\min}$ and $RH_{\max}$ are the daily minimum and maximum relative humidities, and $e^0(T_{\min})$ and $e^0(T_{\max})$ are the saturation vapor pressures at daily minimum and maximum temperatures, $T_{\min}$ and $T_{\max}$, respectively. T_a is expressed in degrees Celsius and RH as a percentage (%).

Three alternatives were evaluated: *Cases* (*1*), (*2*), and (*3*) (Table 1). The first two cases correspond to Eqs. (2) and (3) recommended in the FAO Penman–Monteith method. In *Case* (*1*), we considered the calibration coefficients (a_l, b_l, a_c, b_c) that are recommended in Manual No. 56 of the FAO for estimating R_{nl} (Allen et al. 1998; ASCE-EWRI 2005), and in *Case* (*2*), we considered the calibration coefficients recommended by Jensen et al. (1990) for humid areas. *Case* (*3*) corresponds to the net radiation calculated by means of Eq. (10), according to the methodology proposed in this work.

The predicted and observed values of the daily net radiation over the reference crop were compared, where the observed values correspond to the daily net radiation obtained with Eq. (4). For the analysis of the results, the following statistics were considered: the mean bias error (MBE), mean absolute error (MAE), root mean square error (RMSE), and determination coefficient (r^2) with the slope (b) and the intercept (a) of the linear regression.

4 Results and discussion

The whole dataset of Tandil ($N = 840$, with N being the number of data days) was used in this study. In Fig. 3, the comparisons between predicted and measured values of net radiation are presented. The statistical results are summarized in Table 2.

In addition to analyzing the results using the whole Tandil dataset ($N = 840$), the data subsets of *spring–summer* ($N = 416$) and *autumn–winter* ($N = 424$) were studied. Because similar errors between the two data subsets were observed, we decided to analyze the statistical results of the whole dataset.

Table 2 Statistical results of the comparisons between predicted and measured values of daily net radiation for the reference crop. (*a*) *All* data: $N = 840$, $Rn_{\text{ref crop}} = 79$ W m^{-2}; (*b*) *autumn–winter* data: $N = 424$, $Rn_{\text{ref crop}} = 33$ W m^{-2}; (*c*) *spring–summer* data: $N = 416$, $Rn_{\text{ref crop}} = 126$ W m^{-2}

Model	Calibration	*MBE* (W m^{-2})	*MAE* (W m^{-2})	*RMSE* (W m^{-2})	*a* (W m^{-2})	*b*	r^2
(*a*)							
$R_{n\ \text{FAO PM}}$	(Allen et al. 1998)	19	20	±22	25	0.92	0.96
$R_{n\ \text{FAO PM}}$	(Jensen et al. 1990)	13	14	±17	15	0.96	0.96
$R_{n\ \text{model}}$	–	5	10	±12	7	0.97	0.97
(*b*)							
$R_{n\ \text{FAO PM}}$	(Allen et al. 1998)	20	21	±24	26	0.80	0.85
$R_{n\ \text{FAO PM}}$	(Jensen et al. 1990)	13	15	±18	18	0.87	0.85
$R_{n\ \text{model}}$	–	4	10	±12	8	0.88	0.87
(*c*)							
$R_{n\ \text{FAO PM}}$	(Allen et al. 1998)	18	18	±21	33	0.88	0.94
$R_{n\ \text{FAO PM}}$	(Jensen et al. 1990	12	13	±16	16	0.97	0.95
$R_{n\ \text{model}}$	–	5	9	±12	15	0.92	0.95

The estimated values of daily net radiation show significant overestimations using the method recommended by Manual No. 56 of the FAO. The results show the highest errors when using the calibration coefficients proposed by Allen et al. (1998), with values of MBE of 19 W m^{-2}, MAE of 20 W m^{-2}, and RMSE of ±22 W m^{-2}. An improvement in the performance of FAO Penman–Monteith method for estimating daily net radiation occurred when the coefficients proposed by Jensen et al. (1990) for humid areas were considered, with MBE, MAE, and RMSE of 13, 14, and ±17 W m^{-2}, respectively. The results confirm that the coefficients a_c and b_c should be chosen properly according to the climate regime (arid climate, semiarid, humid…). Similar values of a_c and b_c proposed by Jensen et al. (1990) were also found by Kjaersgaard et al. (2007) for humid areas.

On other hand, we tested a new methodology for estimating daily net radiation over the reference crop. The results show better performance of the proposed model with respect to the FAO Penman–Monteith equation, with values of 5, 10, and ±12 W m^{-2} for MBE, MAE, and RMSE, respectively.

Unlike other researchers, we do not use measures of outgoing shortwave and longwave radiation to obtain the predicted values of daily net radiation. These terms can be modeled according to assumptions about the reference crop presented in the FAO Penman–Monteith method (Eq. (4)). The outgoing shortwave radiation is given by $0.23{*}R_{s\downarrow}$, and the longwave radiation emitted by the surface is equal to $0.98\sigma T_a^{\ 4}$, with the air temperature being equal to the reference crop temperature. Our interpretation is that this is the correct way to test the models. Another methodology consists of using measures of net radiation over a surface similar to the reference crop to test the models. However, we must be certain to keep the surface conditions same as the reference crop all the time, which is hardly possible.

Considering that the observed daily net radiation over the reference crop is 79 ± 62 W m^{-2} (mean value ± standard deviation), the percentage RMSE (PRMSE) is reduced from ±28 % (*Case* (*1*)) and ±22 % (*Case* (*2*)) to less than ±15 % (*Case* (*3*), proposed model). As the net radiation represents much of the available energy for the evapotranspiration process, it is interesting to analyze the performances of models mainly in spring–summer, where the PRMSE is reduced to ±10 % for the proposed model in this study.

5 Conclusions

In this work, the procedures outlined in the manual No. 56 of the United Nations Food and Agriculture Organization (FAO) for predicting daily net radiation have been evaluated. In addition, we propose a new physical model that does not require the calibration of experimental coefficients for the applied climate area. From a dataset of 840 days, we found that the proposed model shows better results than typical equations recommended by Allen et al. (1998) and Jensen et al. (1990). The estimation errors are reduced from 19, 20, and ±22 to 5, 10, and ±12 W m-2 for MBE, MAE, and RMSE, respectively. From the spring–summer data, estimation errors of less than ±10 % were observed for the new physical model, representing an error of just ±0.4 mm d^{-1} for computing reference evapotranspiration. In summary, the methodology presented here is mainly appropriate for application in the FAO Penman–Monteith method to determine the reference crop evapotranspiration.

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