

# Predicting Daily Net Radiation Using Minimum Climatological Data<sup>1</sup>

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**Abstract:** Net radiation ( $R_n$ ) is a key variable for computing reference evapotranspiration and is a driving force in many other physical and biological processes. The procedures outlined in the Food and Agriculture Organization Irrigation and Drainage Paper No. 56 [FAO56 (reported by Allen et al. in 1998)] for predicting daily  $R_n$  have been widely used. However, when the paucity of detailed climatological data in the United States and around the world is considered, it appears that there is a need for methods that can predict daily  $R_n$  with fewer input and computation. The objective of this study was to develop two alternative equations to reduce the input and computation intensity of the FAO56- $R_n$  procedures to predict daily  $R_n$  and evaluate the performance of these equations in the humid regions of the southeast and two arid regions in the United States. Two equations were developed. The first equation [measured- $R_s$ -based ( $R_{s-M}$ )] requires measured maximum and minimum air temperatures ( $T_{max}$  and  $T_{min}$ ), measured solar radiation ( $R_s$ ), and inverse relative distance from Earth to sun ( $d_r$ ). The second equation [predicted- $R_s$ -based ( $R_{s-P}$ )] requires  $T_{max}$ ,  $T_{min}$ , mean relative humidity ( $RH_{mean}$ ), and predicted  $R_s$ . The performance of both equations was evaluated in different locations including humid and arid, and coastal and inland regions (Gainesville, Fla.; Miami, Fla.; Tampa, Fla.; Tifton, Ga.; Watkinsville, Ga.; Mobile, Ala.; Logan, Utah; and Bushland, Tex.) in the United States. The daily  $R_n$  values predicted by the  $R_{s-M}$  equation were in close agreement with those obtained from the FAO56- $R_n$  in all locations and for all years evaluated. In general, the standard error of daily  $R_n$  predictions (SEP) were relatively small, ranging from 0.35 to 0.73 MJ m<sup>-2</sup> d<sup>-1</sup> with coastal regions having lower SEP values. The coefficients of determination were high, ranging from 0.96 for Gainesville to 0.99 for Miami and Tampa. Similar results, with approximately 30% lower SEP values, were obtained when daily predictions were averaged over a three-day period. Comparisons of  $R_{s-M}$  equation and FAO56- $R_n$  predictions with the measured  $R_n$  values showed that the  $R_{s-M}$  equations' predictions were as good or better than the FAO56- $R_n$  in most cases. The performance of the  $R_{s-P}$  equation was quite good when compared with the measured  $R_n$  in Gainesville, Watkinsville, Logan, and Bushland locations and provided similar or better daily  $R_n$  predictions than the FAO56- $R_n$  procedures. The  $R_{s-P}$  equation was able to explain at least 79% of the variability in  $R_n$  predictions using only  $T_{max}$ ,  $T_{min}$ , and RH data for all locations. It was concluded that both proposed equations are simple, reliable, and practical to predict daily  $R_n$ . The significant advantage of the  $R_{s-P}$  equation is that it can be used to predict daily  $R_n$  with a reasonable precision when measured  $R_s$  is not available. This is a significant improvement and contribution for engineers, agronomists, climatologists, and others when working with National Weather Service climatological datasets that only record  $T_{max}$  and  $T_{min}$  on a regular basis.

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## Introduction

Net radiation ( $R_n$ ) is a key variable for computing reference evapotranspiration ( $ET_o$ ) and is a driving force in many other physical processes.  $R_n$  is the difference between total upward and downward radiation fluxes and is a measure of the energy available at the ground surface. This quantity of energy is available to drive the processes of evaporation, evapotranspiration, air, and soil fluxes as well as other, smaller energy-consuming processes such as photosynthesis (Rosenberg et al. 1983).  $R_n$  is normally positive during the daytime and negative during the nighttime. The total daily value for  $R_n$  is almost always positive except in extreme conditions at high latitudes (Allen et al. 1998).

In many biological, agronomic, and engineering applications, including  $ET_o$  predictions,  $R_n$  rather than the total solar radiation ( $R_s$ ) is required. For example; the International Commission for Irrigation and Drainage and the Food and Agriculture Organization of the United Nations (FAO) Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements (Smith et al. 1991) have recommended that the FAO56-Penman-Monteith (FAO56-PM) method be used as the standard method to estimate  $ET_o$ . This widely used method requires  $R_n$  values. Historically, little attention has been given to the routine measurement of  $R_n$  in the United States and around the world. Due to financial, theoretical, and other reasons,  $R_n$  is measured infrequently, usually by scientists in short-term studies. Many attempts have been made to relate  $R_n$  to  $R_s$ , air temperature, and other variables such as relative humidity, and extraterrestrial radiation ( $R_a$ ) (Reddy 1971; Wright 1982; Dong et al. 1992).

An increasingly widely used approach for predicting  $R_n$  is the procedure outlined by Allen et al. (1998) in the FAO Irrigation and Drainage Paper No. 56. The  $R_n$  calculation procedures outlined in FAO Paper No. 56 have also been recommended for estimating  $ET_o$  in the FAO56-PM method. These  $R_n$  calculation procedures are as follows:

$$R_n = R_{ns} - R_{nl} \quad (1)$$

where  $R_n$ =net radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ );  $R_{ns}$ =incoming net shortwave radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ); and  $R_{nl}$ =outgoing net longwave radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ).

The incoming net shortwave radiation ( $R_{ns}$ ), a result of the balance between incoming and reflected solar radiation, is

$$R_{ns} = (1 - \alpha)R_s \quad (2)$$

where  $\alpha$ =albedo or canopy reflection coefficient (0.23 for a grass reference crop surface) and  $R_s$ =total incoming solar radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ).

The rate of outgoing net longwave radiation  $R_{nl}$  is proportional to the absolute temperature of the surface raised to the fourth power. This relation is expressed quantitatively as

$$R_{nl} = \sigma \left[ \frac{T_{\max,K}^4 + T_{\min,K}^4}{2} \right] (0.34 - 0.14\sqrt{e_a}) \left( 1.35 \frac{R_s}{R_{so}} - 0.35 \right) \quad (3)$$

where  $\sigma$ =Stefan-Boltzmann constant ( $4.903 \times 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{d}^{-1}$ );  $T_{\max,K}$ =daily maximum absolute temperature ( $^{\circ}\text{K} = ^{\circ}\text{C} + 273.16$ );  $T_{\min,K}$ =daily minimum absolute temperature ( $^{\circ}\text{K} = ^{\circ}\text{C} + 273.16$ );  $e_a$ =actual air vapor pressure (kPa); and  $R_{so}$ =calculated clear sky solar radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ).

The actual vapor pressure  $e_a$  (kPa) is calculated as

$$e_a = 0.6108 \exp \left[ \frac{17.27T_{\text{dew}}}{T_{\text{dew}} + 237.3} \right] \quad (4)$$

where  $T_{\text{dew}}$ =dew point temperature ( $^{\circ}\text{C}$ ). Depending on the availability of the data,  $e_a$  can be calculated using relative humidity (RH) and/or minimum air temperature ( $T_{\min}$ ).

Doorenbos and Pruitt (1977) developed an equation to calculate daily values of clear sky solar radiation  $R_{so}$  as a function of station elevation  $z(m)$ , and the extraterrestrial radiation  $R_a$  ( $\text{MJ m}^{-2} \text{d}^{-1}$ ) as

$$R_{so} = (0.75 + 2 \times 10^{-5}z)R_a \quad (5)$$

$R_a$  can be calculated on a daily basis as a function of day of the year, solar constant, solar declination, and latitude as

$$R_a = \frac{1,440}{\pi} G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \quad (6)$$

where  $G_{sc}$ =solar constant ( $0.0820 \text{ MJ m}^{-2} \text{min}^{-1}$ );  $d_r$ =inverse relative distance from Earth to sun;  $\omega_s$ =sunset hour angle (rad);  $\varphi$ =latitude (rad); and  $\delta$ =solar declination (rad).

In Eq. (6), the daily values of  $\varphi$ ,  $d_r$ ,  $\delta$ , and  $\omega_s$  are given by the following equations:

$$\text{Rad} = \frac{\pi}{180} [\text{decimal degrees}] \quad (7)$$

$$d_r = 1 + 0.033 \cos \left( \frac{2\pi}{365} \text{JD} \right) \quad (8)$$

$$\delta = 0.409 \sin \left( \frac{2\pi}{365} \text{JD} - 1.39 \right) \quad (9)$$

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \quad (10)$$

where JD=day of the year.

After application of Eqs. (2)–(10), the daily values of  $R_n$  can be determined using Eq. (1). With the development of automatic dataloggers,  $ET_o$  predictions are being made continuously for real-time irrigation scheduling, agricultural water management, and other engineering/agronomic applications. Also, the calculation of  $ET_o$  using computer programs and spread sheets are being practiced extensively. However, the calculations of the above coefficients are tedious steps that are time consuming and may lead to implementation errors that are unacceptable. An alternative approach is to develop a simple equation to predict daily values of  $R_n$  that is suitable for  $ET_o$  calculations. The proposed equation, however, should provide reliable and consistent predictions of  $R_n$  for a given location. In addition, considering the paucity of detailed climatological data in the United States and around the world, there is a need for methods that can predict  $R_n$  with limited data.

Most of the  $R_n$  equations predict daily or longer-term  $R_n$  values from measured  $R_s$ . However, the major difficulty in these equations is that the  $R_s$  term is not routinely measured in many states in the United States and around the world. If  $R_n$  could be predicted in an accurate manner from  $T_{\max}$  and  $T_{\min}$  observations, this would be a great improvement and contribution for engineers, agronomists, climatologists, and others who work routinely with National Weather Service climatological data that only record  $T_{\max}$ ,  $T_{\min}$ , and rainfall on a regular basis.

The objectives of this study were to (1) develop an equation to reduce the input and computation intensity of the FAO56- $R_n$  procedures to predict daily  $R_n$  from  $T_{\max}$ ,  $T_{\min}$ , measured  $R_s$ , and  $d_r$ ; (2) evaluate the performance of the proposed equation by comparing its daily  $R_n$  predictions with the FAO56- $R_n$  method and with the measured  $R_n$  values; and (3) to develop an equation

to predict daily  $R_n$  (when measured  $R_s$  is not available) from only  $T_{\max}$ ,  $T_{\min}$ ,  $RH_{\text{mean}}$ , and predicted  $R_s$ , and evaluate the performance of this equation in the humid regions of the southeast and two arid regions in the United States.

## Climate Data and Procedures

Six locations in the humid regions of the southeast and two locations in arid regions of the United States were studied. They were Gainesville, Florida (latitude 29° 38' N, longitude 82° 22' W, elevation=29.3 m); Tifton, Georgia (latitude 31° 50' N, longitude 83° 53' W, elevation=116 m); Watkinsville, Georgia (latitude 33° 87' N, longitude 83° 45' W, elevation=241 m); Mobile, Alabama (latitude 30° 41' N, longitude 88° 15' W, elevation=7 m); Miami, Florida (25° 48' N, 80° 16' W, elevation=2 m); Tampa, Florida (latitude 27° 58' N, longitude 82° 32' W, elevation=3 m); Logan, Utah (latitude 41° 07' N, longitude 111° 8' W, elevation=1,350 m); and Bushland, Texas (latitude 35° 11' N, longitude 35° 06' W, elevation=1,169 m). The Mobile, Miami, and Tampa locations were considered to represent coastal regions, the others were inland locations. Daily measured and carefully screened weather data for a 23-year period (January 1, 1978 through January 31, 2000) for Gainesville, and for a six-year period for Miami, Tampa, Tifton, and Mobile locations were used (1995 through 2000 for Tifton, and 1985 through 1990 for Mobile, Miami, and Tampa). Daily weather variables measured at these stations included rainfall, maximum and minimum air temperature, relative humidity, wind speed and direction, and total incoming solar radiation. Measured values of  $R_n$  were not available in any of these stations. Measured  $R_n$  and other climate variables were available only for Gainesville [data obtained from Florida Ameriflux Network website (<http://public.ornl.gov/ameriflux/>); for Austin Carey which is located at five miles north of Gainesville, Fla. and this location was assumed to represent Gainesville's climate conditions] (1998 and 1999), Bushland (1998 and 1999), Logan (1988, only from May through October), and Watkinsville (1999, 2000, and 2001). The relative humidity (RH) data for Bushland was not available, thus, the RH data for the two-year period was predicted from air temperature data for this location.

The  $R_s$  data in Bushland was measured using an Epply PSP pyranometer and  $R_n$  was measured with a REBS Q7 net radiometer over tall fescue grass. In Austin Carey and Watkinsville, the  $R_s$  was measured using a Li-Cor LI-200 pyranometer and  $R_n$  was measured using a REBS Q7 net radiometer. A Li-Cor LI-200 pyranometer and REBS Q4 net radiometer were used to measure  $R_s$  and  $R_n$ , respectively, in Logan.

### Equation Development to Predict Daily $R_n$ Using Measured $R_s$ (Measured- $R_s$ -Based Equation, $R_{s-M}$ )

Because of the limited availability of long-term measured  $R_n$  data, the FAO56- $R_n$  calculation procedure was used as a standard method to predict daily values of  $R_n$ , and the  $R_n$  values obtained from the  $R_{s-M}$  equation were compared against the FAO56- $R_n$  values in Gainesville, Miami, Tampa, Tifton, and Mobile. The  $R_{s-M}$  equation was developed using a multilinear regression with input parameters of  $T_{\max}$ ,  $T_{\min}$ , measured  $R_s$ , and  $d_r$ . The performance of the equation was evaluated by comparing its daily and three-day average  $R_n$  predictions with those obtained from the FAO56- $R_n$  procedure. The equation was developed for Gainesville, Fla. using 17 years of measured daily weather data. It

was validated using six years of daily data for other locations (Gainesville, Miami, Tampa, Tifton, and Mobile). To compare the performance of the  $R_{s-M}$  equation for validation years on a daily and three-day average basis, the standard error of prediction (SEP) between the proposed equation and FAO56- $R_n$  was computed. These SEP values were used as an indicator of how well the  $R_{s-M}$  equation predicted daily  $R_n$ . Thus, lower SEP indicated a better performance of the equation. For three-day average comparisons, daily  $R_n$  values were averaged over the three-day period and graphed against those values obtained from the FAO56- $R_n$  method. The coefficient of determination ( $r^2$ ), and the average ratio of the FAO56- $R_n$  to  $R_{s-M}$  equation  $R_n$  values were computed in order to quantify the over- and underpredictions.

### Equation Development to Predict $R_n$ Using Predicted $R_s$ (Predicted- $R_s$ -Based Equation, $R_{s-P}$ )

A  $R_{s-P}$  equation was developed using a multilinear regression with input parameters of  $T_{\max}$ ,  $T_{\min}$ ,  $RH_{\text{mean}}$ , and predicted  $R_s$ . The performance of the equation was evaluated by comparing its daily and weekly average  $R_n$  predictions with measured and FAO56- $R_n$  values for Gainesville, Fla., Watkinsville, Ga., Logan, Utah, and Bushland, Tex. To compare the performance of the  $R_{s-P}$  equation, on a daily and weekly average basis, the SEP between the  $R_{s-P}$  equation  $R_n$  values and measured  $R_n$  values was computed. For the weekly average comparisons, daily  $R_n$  values were averaged over a one week period and graphed against measured values. The  $r^2$  values and the average ratio of the  $R_{s-P}$  equation to measured  $R_n$  were computed in order to quantify the over- and underpredictions.

## Results

### Multilinear Regression Approach

#### Proposed Equation to Predict $R_n$ Using Measured $R_s$ (Measured- $R_s$ -Based Equation, $R_{s-M}$ )

The  $R_n$  values from January 1, 1978 through December 31, 1994 were computed using Eqs. (1)–(10). In the multilinear regression analyses, the FAO56- $R_n$  values were used as dependent variables and daily  $T_{\max}$  and  $T_{\min}$ ,  $R_s$ , and the inverse relative distance Earth-sun ( $d_r$ ) values were used as independent variables to determine the coefficients in the proposed equation to predict  $R_n$ . The main reason for using  $T_{\max}$  and  $T_{\min}$  as independent variables rather than cloud cover, and/or actual duration of sunshine in the development of the proposed equation was that the  $T_{\max}$  and  $T_{\min}$  are more routinely measured in most locations. Also, air temperature is a strong function of  $R_s$ . On a cloudy day, less  $R_s$  will reach the earth surface compared with a day with clear sky conditions. Thus, the air temperature will increase more in a day with a clear sky than for a cloudy day. This is an indication that the daily  $T_{\max}$  and  $T_{\min}$  are strongly related to the daily  $R_s$  (Cengiz et al. 1981). The coefficients for the proposed  $R_n$  equation were determined for  $T_{\max}$ ,  $T_{\min}$ , measured  $R_s$ , and  $d_r$  to obtain the best fit to the FAO56- $R_n$  values. Daily values of  $d_r$  were calculated using Eq. (8); all other variables were measured. Although it is known that the coastal and inland stations might behave differently (due to the maritime-inland effects), in the equation development, it was assumed that the coastal-inland effects on  $R_n$  were negligible and the same equation could be used to predict  $R_n$  in both locations. The form of the multilinear equation that relates a dependent variable ( $R_n$ ) to a set of quantitative independent vari-

ables ( $T_{max}$ ,  $T_{min}$ , measured  $R_s$ , and  $d_r$ ) is a direct extension of a polynomial regression model with one independent variable

$$R_n = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 \quad (11)$$

where  $R_n$  = net radiation as dependent variable;  $\beta_0$  = intercept;  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ , and  $\beta_4$  = slopes of the regression line for each independent variable; and  $X_1$ ,  $X_2$ ,  $X_3$ , and  $X_4$  = independent variables ( $T_{max}$ ,  $T_{min}$ , measured  $R_s$ , and  $d_r$ , respectively). The first-order multilinear regression equation to predict  $R_n$  on a daily basis was found as

$$R_n = (-0.054T_{max}) + (0.111T_{min}) + (0.462R_{s(\text{measured})}) + (-49.243d_r) + 50.831 \quad (12)$$

where all variables have been previously defined. In Eq. (12), all dependent variables, including the intercept, were statistically significant ( $p < 0.05$ ). The units of the  $R_n$ ,  $T_{max}$ ,  $T_{min}$ , and measured  $R_s$  are:  $\text{MJ m}^{-2} \text{d}^{-1}$ ,  $^{\circ}\text{C}$ ,  $^{\circ}\text{C}$ , and  $\text{MJ m}^{-2} \text{d}^{-1}$ , respectively. Another independent variable, mean relative humidity ( $\text{RH}_{\text{mean}}$ ), was also included in the initial equation development procedure. However, because it did not have any significant positive effect in the prediction of the final  $R_n$  value, it was not included in Eq. (12). It is important to note that although surface albedo ( $\alpha$ ) is not included in Eq. (12), the albedo effect is reflected, to some degree, in the final value of  $R_n$ . The albedo value of 0.23 for a grass surface in the Eq. (2) was used in the FAO56- $R_n$  calculation and calibration procedures. One advantage of using Eq. (12) is that it requires fewer inputs than the FAO56- $R_n$  method. The FAO56- $R_n$  method requires additional inputs of measured dew point temperature and/or relative humidity data, depending on which method is used to calculate actual vapor pressure of air ( $e_a$ ).

#### Proposed Equation to Predict $R_n$ Using Predicted $R_s$ ( $R_{s-p}$ )

The same statistical procedures were used to develop the  $R_{s-p}$  equation. The Hargreaves and Samani (1982)  $R_s$  equation was substituted into the proposed equation. The coefficients of the  $R_{s-p}$  equation were determined for  $T_{max}$ ,  $T_{min}$ ,  $\text{RH}_{\text{mean}}$ , and predicted  $R_s$  to obtain the best fit to the daily measured  $R_n$  values. The form of the multilinear equation that relates a dependent variable ( $R_n$ ) to a set of quantitative independent variables ( $T_{max}$ ,  $T_{min}$ ,  $\text{RH}_{\text{mean}}$ , and predicted  $R_s$ ) was found to be

$$R_n = (-0.09T_{max}) + (0.203T_{min}) - (0.101\text{RH}_{\text{mean}}) + (0.687R_{s(\text{predicted})}) + 3.97 \quad (13)$$

where all the variables have been previously defined. Theoretically, Eq. (13) predicts  $R_n$  from only  $T_{max}$  and  $T_{min}$  because RH can always be predicted using air temperature with a sufficient accuracy when measured RH data are not available. In Eq. (13), all dependent variables, including the intercept, were statistically significant ( $p < 0.05$ ). Another independent variable  $d_r$  was also included in the initial equation development procedure, however, because it did not have any significant positive effect in the prediction of the final  $R_n$  value, it was not included in Eq. (13). In the development of Eq. (13), because of the limitations in availability of long-term measured daily  $R_n$  values, only two years of measured  $R_n$  values for the Gainesville location were used to determine the coefficients. The SEP of  $R_n$  predictions of Eq. (13) for the calibration curve was found to be  $0.74 \text{ MJ m}^{-2} \text{d}^{-1}$  ( $r^2 = 0.80$ ,  $n = 730$ ). It is important to note that the coefficient of the predicted  $R_s$  (0.687) in Eq. (13) is specific to the Hargreaves and Samani (1982)  $R_s$  equation since this equation was used to predict

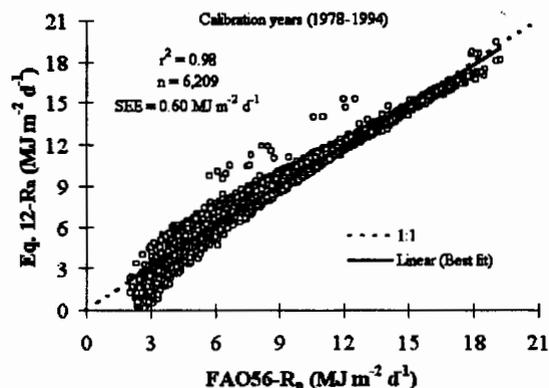


Fig. 1. Regression analyses for calibration of measured- $R_s$ -based equation [Eq. (12)] for Gainesville, Fla.

$R_s$  in Eq. (13) in the calibration against measured  $R_n$ . Hargreaves and Samani (1982) developed a simple equation to predict solar radiation ( $R_s$ )

$$R_s = (KT)(R_a)(\text{TD})^{0.5} \quad (14)$$

where  $\text{TD}$  = maximum daily temperature minus minimum daily temperature ( $^{\circ}\text{C}$ );  $R_a$  = extraterrestrial radiation ( $\text{MJ m}^{-2} \text{d}^{-1}$ ); and  $\text{KT}$  = empirical coefficient. Allen et al. (1997) suggested using  $\text{KT} = 0.17(P/P_0)^{0.5}$  for interior regions and  $\text{KT} = 0.2(P/P_0)^{0.5}$  for coastal regions (for elevations  $< 1,500$  m) to account for proximity to a large body of water and elevation effects on the volumetric heat capacity of the atmosphere, where  $P$  = mean monthly atmospheric pressure of the site (kPa) and  $P_0$  = mean monthly atmospheric pressure at sea level (kPa) (Samani 2000). Another equation to calculate  $\text{KT}$  values from  $\text{TD}$  was later suggested by Samani (2000). Hargreaves (1994) recommended using  $\text{KT} = 0.162$  for interior regions and  $\text{KT} = 0.19$  for coastal regions. The procedures suggested by Allen (1997) were used to calculate  $\text{KT}$  values in this study. The average  $\text{KT}$  values for Gainesville, Watkinsville, Logan, and Bushland were found to be 0.170, 0.168, 0.157, and 0.159, respectively.

#### Performance of Measured- $R_s$ -Based Equation [Eq. (12)]

A comparison of Eq. (12) and FAO56- $R_n$  is shown in a 1:1 plot in Fig. 1 for Gainesville, Fla. The fitted model resulted in remarkably good agreement between FAO56- $R_n$  and Eq. (12)- $R_n$  for the

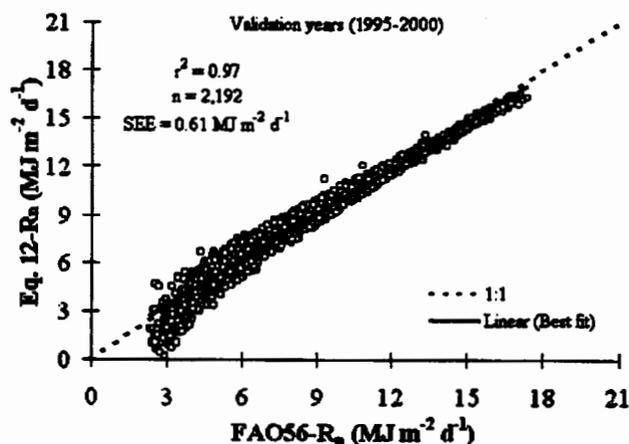


Fig. 2. Regression analyses for validation of measured- $R_s$ -based equation [Eq. (12)] for Gainesville, Fla.

**Table 1.** Standard Error of Daily and Three-Day Average  $R_n$  Predictions (SEP), Coefficient of Determination ( $r^2$ ), Average Ratio of FAO56- $R_n$  to Eq. (12)- $R_n$ , and Annual Total Rainfall for Five Locations for Validation Years

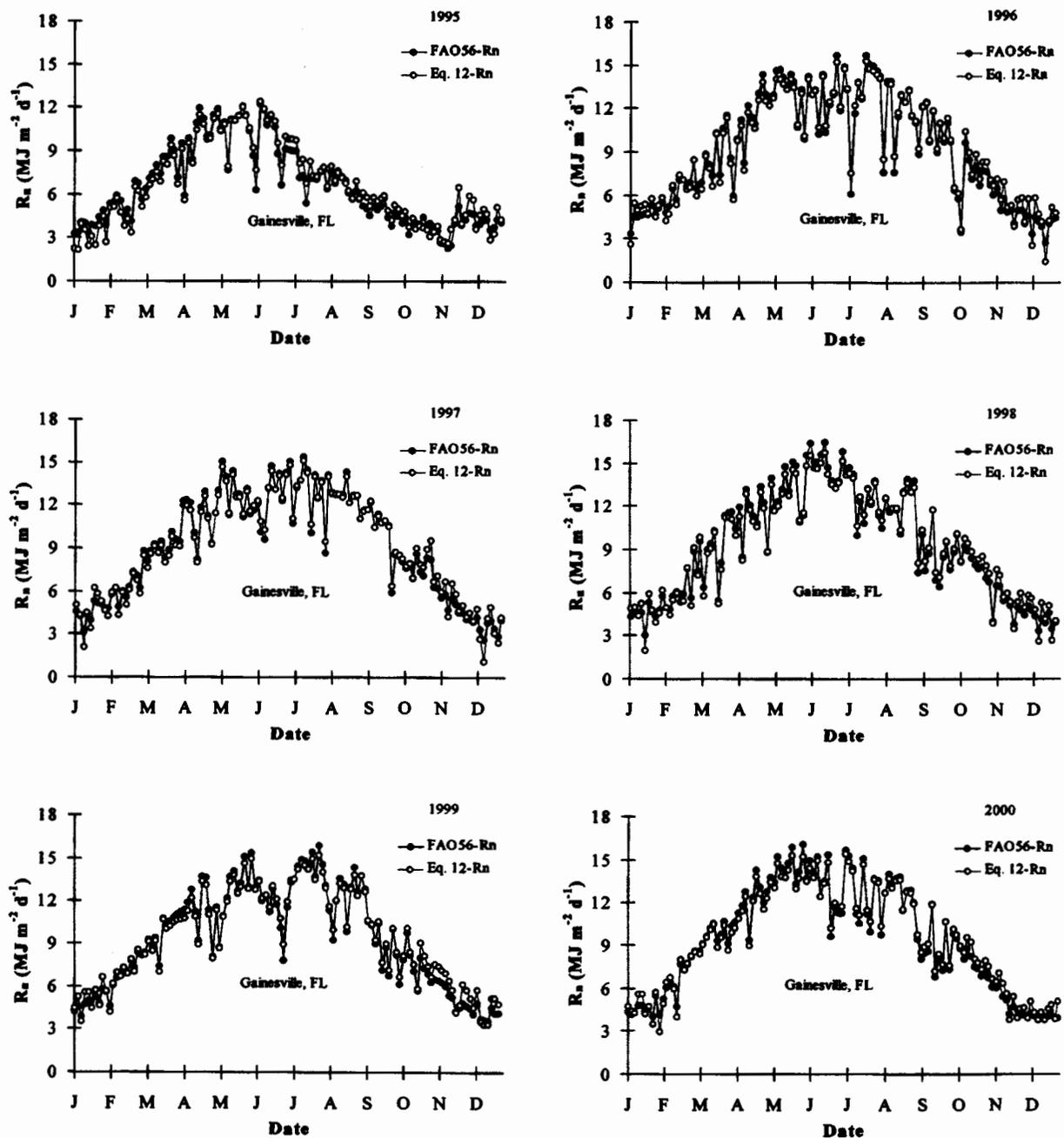
Location	Valid. year	Rainfall (mm year <sup>-1</sup> )	Daily prediction			Three-day average		
			Standard error of daily $R_n$ predictions (MJ m <sup>-2</sup> d <sup>-1</sup> )	$r^2$	Average ratio of FAO56- $R_n$ / Eq. (12)- $R_n$	Standard error of daily $R_n$ predictions (MJ m <sup>-2</sup> d <sup>-1</sup> )	$r^2$	Average ratio of FAO56- $R_n$ / Eq. (12)- $R_n$
Gainesville, Fla.	1995	1,337	0.72	0.96	1.04	0.60	0.96	1.03
	1996	1,387	0.57	0.98	1.01	0.46	0.98	0.99
	1997	1,585	0.57	0.98	1.03	0.42	0.98	1.01
	1998	1,425	0.55	0.98	1.02	0.42	0.98	1.00
	1999	1,185	0.49	0.98	0.99	0.38	0.98	0.98
	2000	1,097	0.58	0.98	1.05	0.38	0.98	0.99
Tifton, Ga.	1995	857	0.70	0.97	1.03	0.47	0.97	0.99
	1996	1,002	0.64	0.98	1.02	0.48	0.98	0.98
	1997	1,091	0.69	0.97	1.05	0.54	0.97	1.02
	1998	1,120	0.67	0.98	1.03	0.52	0.98	1.00
	1999	805	0.64	0.98	1.01	0.49	0.98	0.97
	2000	920	0.73	0.97	1.04	0.59	0.97	1.00
Mobile, Ala.	1985	1,780	0.58	0.98	1.00	0.46	0.98	0.99
	1986	1,506	0.51	0.98	1.00	0.37	0.98	0.99
	1987	1,705	0.62	0.98	0.99	0.48	0.98	0.98
	1988	1,581	0.56	0.98	0.99	0.44	0.98	0.98
	1989	1,626	0.56	0.98	1.01	0.44	0.98	0.99
	1990	1,422	0.54	0.98	1.00	0.44	0.98	0.99
Miami, Fla.	1985	1,429	0.52	0.97	1.00	0.44	0.97	1.00
	1986	1,680	0.38	0.99	1.02	0.31	0.99	1.02
	1987	1,277	0.35	0.99	1.02	0.27	0.99	1.02
	1988	1,133	0.42	0.99	1.02	0.35	0.99	1.02
	1989	1,083	0.40	0.99	1.03	0.34	0.99	1.03
	1990	1,313	0.39	0.99	1.02	0.33	0.99	1.02
Tampa, Fla.	1985	1,133	0.40	0.99	1.01	0.28	0.99	1.00
	1986	1,057	0.38	0.99	1.01	0.31	0.99	1.01
	1987	1,247	0.39	0.99	1.00	0.30	0.99	1.00
	1988	1,329	0.42	0.99	1.00	0.34	0.99	1.00
	1989	1,108	0.41	0.99	1.01	0.31	0.99	1.00
	1990	873	0.40	0.99	1.00	0.31	0.99	1.00

17-year period for Gainesville with points scattering very close to 1:1 line. In Eq. (12), the correlation coefficient ( $r^2$ ) value was 0.98 for the calibration years (1978–1994). The regression coefficients for each independent variable ( $T_{max}$ ,  $T_{min}$ ,  $R_s$ , and  $d_r$ ) were significant ( $p < 0.001$ ,  $n = 6,209$ ) with the standard error of daily prediction (SEP) of 0.60 MJ m<sup>-2</sup> d<sup>-1</sup> over the 17-year period (Fig. 1).

Fig. 2 shows the validation results for Gainesville from 1995 to 2000. For these years, both  $R_n$  values agreed very well with a similar correlation coefficient value (0.97,  $n = 2,192$ ) to the calibration years. The SEP value was also low (0.61 MJ m<sup>-2</sup> d<sup>-1</sup>) for the six-year period. One should note that the deviations between the FAO56- $R_n$  and Eq. (12)- $R_n$  (Figs. 1 and 2) were slightly higher at lower  $R_n$  values (approximately 0 to 8.5 MJ m<sup>-2</sup> d<sup>-1</sup> and 0 to 8 MJ m<sup>-2</sup> d<sup>-1</sup>, for calibration and validation years, respectively). The deviations between the two methods decreased as  $R_n$  values increased. This, in part, might indicate that these relatively low  $R_n$  values are associated with rainy days and the cloud cover observed on rainy days which might have a greater influence on  $R_n$ . Further analyses showed that the SEP value averaged 0.11 MJ m<sup>-2</sup> d<sup>-1</sup> higher than the original SEP value of 0.60

MJ m<sup>-2</sup> d<sup>-1</sup> (for the 17-year average for all values) when only the  $R_n$  values from 0 to 8.5 MJ m<sup>-2</sup> d<sup>-1</sup> were considered. A SEP value of 0.73 MJ m<sup>-2</sup> d<sup>-1</sup> was obtained when only from 0 to 8 MJ m<sup>-2</sup> d<sup>-1</sup>  $R_n$  range was considered for the validation years. The larger SEP values for smaller  $R_n$  than for larger  $R_n$  in Figs. 1 and 2 might also be due to using noncalibrated values of the parameters  $a_s + b_s$  in the calculation of clear sky solar radiation ( $a_s + b_s =$  fractions of extraterrestrial radiation  $R_o$  reaching the Earth on overcast days) in Eq. (5). Noncalibrated values of  $a_s$  and  $b_s$  were used in Eq. (5) ( $a_s = 0.75$  and  $b_s = 2 \times 10^{-5}$ ). Although turbidity and water vapor have some effects, especially for the smaller  $R_n$  values in the winter months (Allen et al. 1998), this effect was also neglected in the  $R_{so}$  calculations. Thus, as a result, it appears that Eq. (12) does not fully account for environmental factors described in net shortwave ( $R_{ns}$ ) and net longwave ( $R_{nl}$ ) radiation calculations, resulting in greater deviations from the FAO56- $R_n$  at smaller  $R_n$  range. However, these deviations were not significant.

Overall, validation results showed that Eq. (12) can be used to predict  $R_n$  with sufficient accuracy and consistency at the Gainesville location. However, the SEP values of Eq. (12) obtained in



**Fig. 3.** Comparison of three-day average  $R_n$  predictions of measured- $R_s$ -based equation [Eq. (12)] with the FAO56- $R_n$  for validation years (1995–2000), Gainesville, Fla.

Figs. 1 and 2 are the average values of 17- and six-year periods, respectively. In order to conclude that Eq. (12) provides reliable predictions of  $R_n$ , the validity of the equation should also be evaluated for individual annual datasets and for other locations.

Table 1 summarizes the SEP of Eq. (12) relative to the FAO56- $R_n$  method, coefficients of determination ( $r^2$ ) of predictions, and the annual average of the ratio of FAO56- $R_n$  to Eq. (12)- $R_n$  by validation year for Gainesville, Tifton, Mobile, Miami, and Tampa. The coastal regions (Mobile, Miami, and Tampa) are included to test the performance of Eq. (12) under maritime conditions. In Table 1, the annual total rainfall values for all locations were also included. This is particularly important since the amount of rainfall can be used as a qualitative indication of cloud cover. Thus, this allowed us to evaluate the performance of the

$R_{s-M}$  equation in both dry and wet years. Validation years showed significant variations in terms of rainfall. The annual total rainfall of validation years ranged from 805 mm year<sup>-1</sup> in 1999 in Tifton to 1,780 mm year<sup>-1</sup> in 1985 in Mobile (Table 1).

When predictions are compared on a daily basis, it is clear from Table 1 that the Eq. (12)- $R_n$  values were in very good agreement with those obtained from the FAO56- $R_n$  method in all locations and all validation years. In general, the SEP values were relatively small ranging from 0.49 to 0.72 MJ m<sup>-2</sup> d<sup>-1</sup> for Gainesville, 0.64 to 0.73 MJ m<sup>-2</sup> d<sup>-1</sup> for Tifton, 0.58 to 0.62 MJ m<sup>-2</sup> d<sup>-1</sup> for Mobile, 0.35 to 0.52 MJ m<sup>-2</sup> d<sup>-1</sup> for Miami, and 0.38 to 0.42 MJ m<sup>-2</sup> d<sup>-1</sup> for Tampa. The maximum SEPs were 0.73 and 0.72 MJ m<sup>-2</sup> d<sup>-1</sup> in Tifton and Gainesville for 2000 and 1995, respectively. The lowest SEP values were obtained from coastal loca-

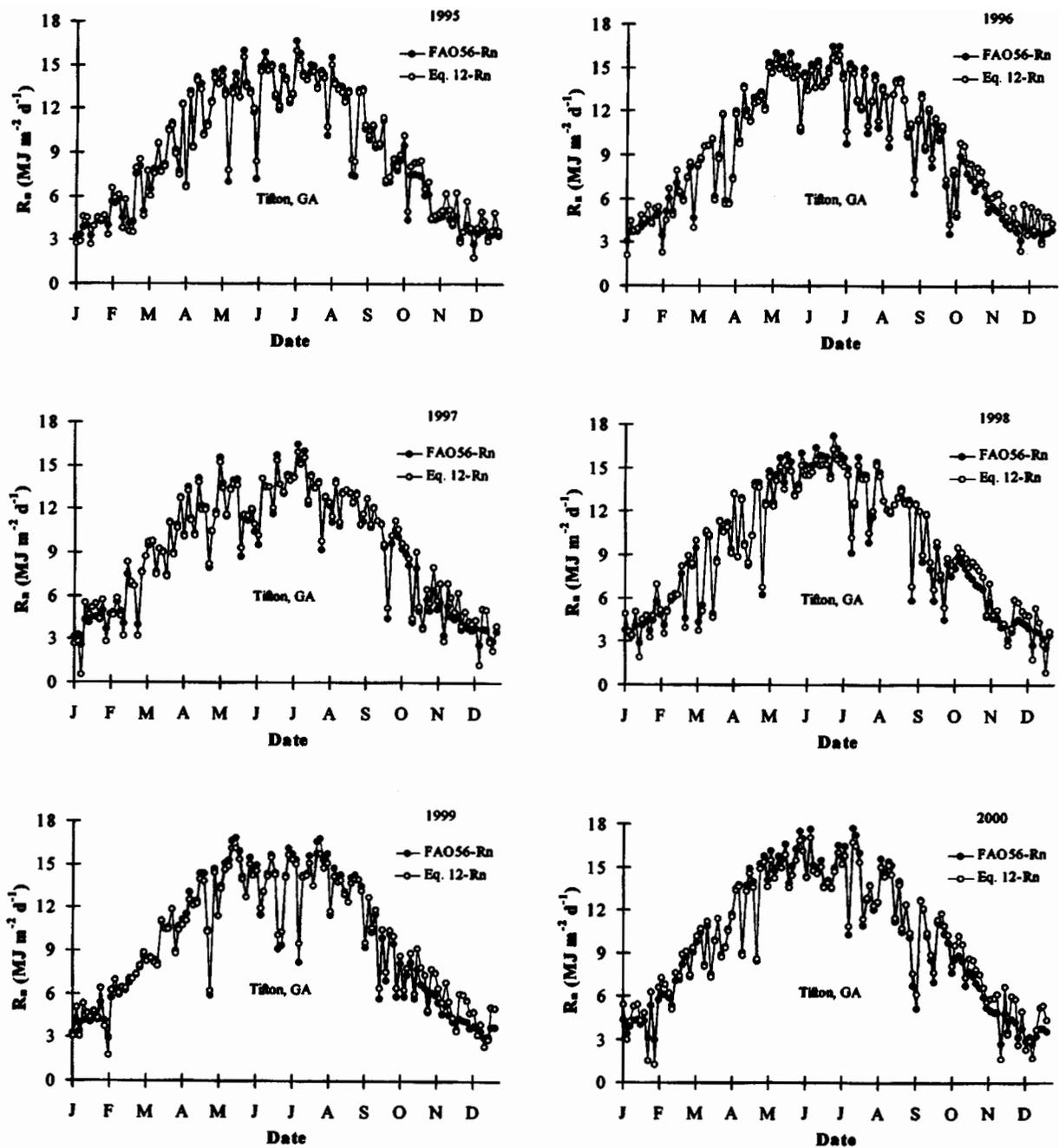


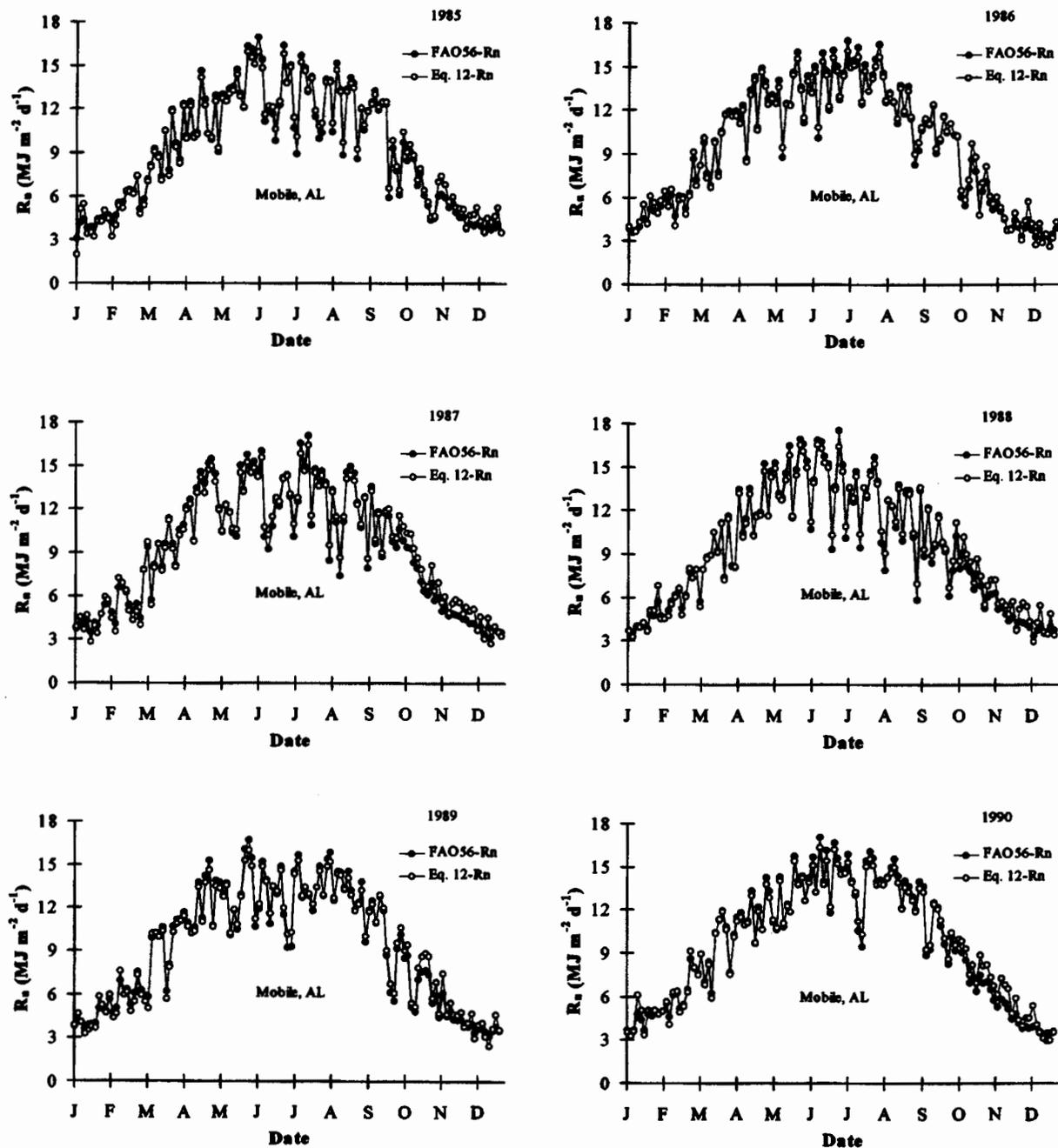
Fig. 4. Comparison of three-day average  $R_n$  predictions of measured- $R_n$ -based equation [Eq. (12)] with FAO56- $R_n$  for validation years (1995–2000), Tifton, Ga.

tions. These coastal locations also had the lowest six-year average SEP values of 0.54, 0.41, and 0.40  $\text{MJ m}^{-2} \text{d}^{-1}$ , respectively, while Tifton had the largest six-year average SEP of 0.68  $\text{MJ m}^{-2} \text{d}^{-1}$ . It is evident in Table 1 that the SEP values are smaller for the coastal locations than for those inland locations. This is because the same equation [Eq. (12)] was used to predict  $R_n$  in both coastal and inland locations and, in the equation development, it was assumed that the coastal-inland effects on  $R_n$  were negligible for simplifications. The six-year average SEP for Gainesville was 0.58  $\text{MJ m}^{-2} \text{d}^{-1}$ . All locations in all years had high  $r^2$  values, ranging from 0.96 (for Gainesville in 1995) to 0.99 in other locations. The average ratio of FAO56- $R_n$  to Eq. (12)- $R_n$  were very close to 1.00 for all locations and validation

years, indicating that the Eq. (12) did not bias the predicted daily  $R_n$  values. The average ratios were consistently higher than 1.00 for Tifton.

Similar results were obtained from the three-day average predictions of  $R_n$ . The SEP of three-day average predictions were usually 30% lower than those daily SEP values. The average ratios of FAO56- $R_n$  to Eq. (12)- $R_n$  were very close to 1.00, and all locations had high  $r^2$  values, ranging from 0.96 (for Gainesville in 1995) to 0.99 for other locations.

In order to better visualize the over- and underpredictions and the distribution of  $R_n$  values over the year, the three-day average  $R_n$  values for validation years were graphed in Figs. 3–7 for Gainesville, Tifton, Mobile, Miami, and Tampa, respectively. In



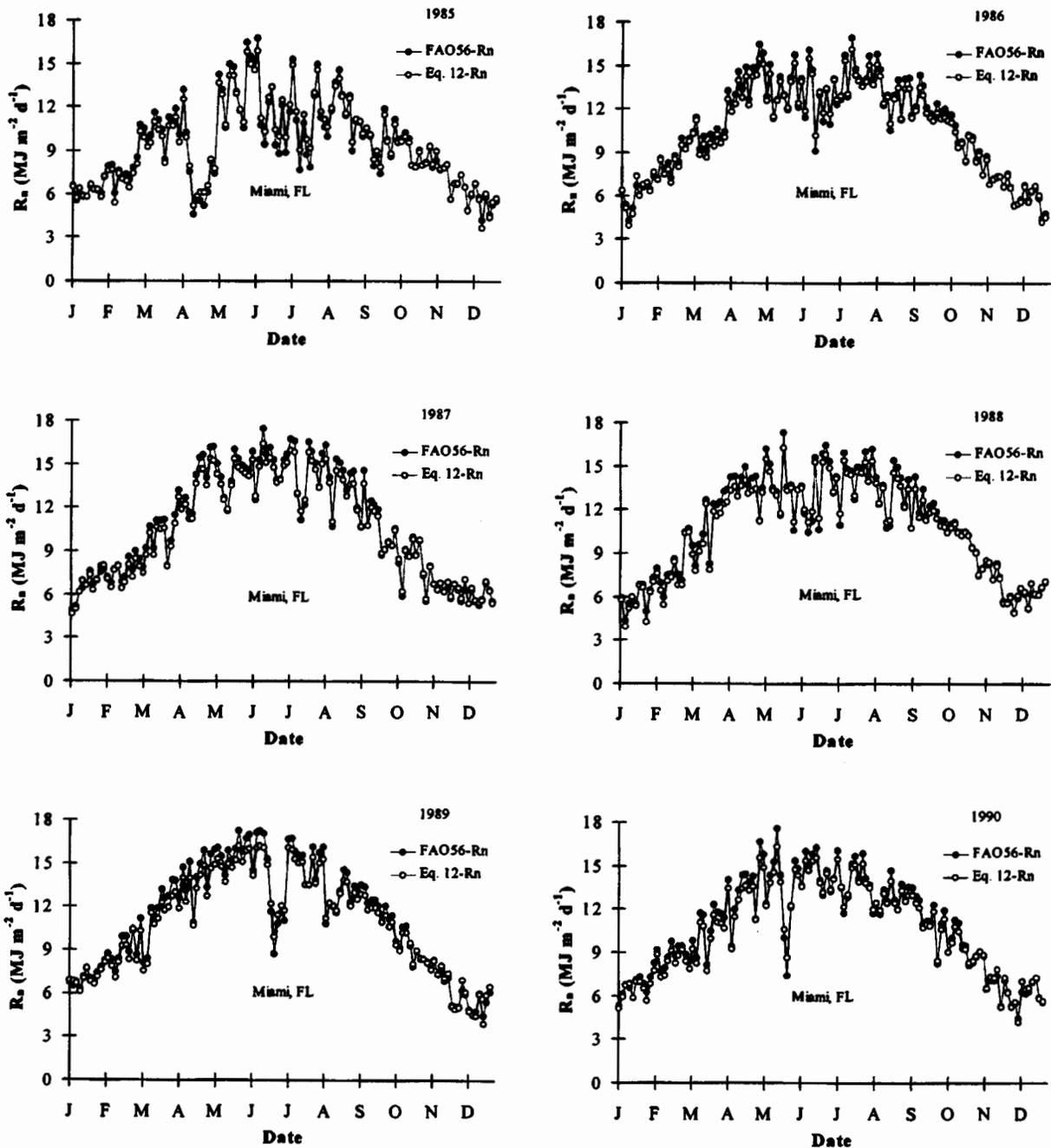
**Fig. 5.** Comparison of three-day average  $R_n$  predictions of measured- $R_s$ -based equation [Eq. (12)] with FAO56- $R_n$  for validation years (1985–1990), Mobile, Ala.

general, Eq. (12) was in a very good agreement with the FAO56- $R_n$  throughout the year for all validation years in all locations. However, in some locations, Eq. (12) overpredicted  $R_n$  in winter months for low- $R_n$  values. For example; Eq. (12) slightly overpredicted  $R_n$  for almost all validation years for Gainesville, Tifton, and Mobile locations in winter months. However, analyses for the winter months showed that the maximum limit for the overprediction was not more than  $1.2 \text{ MJ m}^{-2} \text{ d}^{-1}$  for any location. For the two coastal locations (Miami and Tampa) Eq. (12) did not overpredict  $R_n$ . The three-day average  $R_n$  predictions ranged from  $1.1$  to  $15.7 \text{ MJ m}^{-2} \text{ d}^{-1}$  for Gainesville (Fig. 3), from  $0.53$  to  $17.1 \text{ MJ m}^{-2} \text{ d}^{-1}$  for Tifton (Fig. 4), from  $2.0$  to  $16.6 \text{ MJ m}^{-2} \text{ d}^{-1}$  for Mobile (Fig. 5), from  $3.7$  to  $16.5 \text{ MJ m}^{-2} \text{ d}^{-1}$  for Miami (Fig. 6), and from  $2.9$  to  $16.6 \text{ MJ m}^{-2} \text{ d}^{-1}$  for Tampa (Fig.

7) locations, with coastal regions having considerably higher three-day average  $R_n$  values in the winter months compared with the inland regions. Overall results showed that Eq. (12) can successfully be used to predict daily  $R_n$  values in the humid climate conditions of the southeast United States without further calibration.

#### Daily Comparisons of $R_{s,M}$ Equation [Eq. (12)] and FAO56- $R_n$ Predictions with Measured $R_n$ Values

Figs. 8(A and B) and 9(A and B) show the comparison of predicted  $R_n$  values [using Eq. (12) and FAO56 procedures] versus measured  $R_n$  values for Gainesville, Watkinsville, Logan, and Bush-land, respectively. In the figures, the predicted  $R_n$  data from multiple years (except for Logan, Utah, where only one year of



**Fig. 6.** Comparison of three-day average  $R_n$  predictions of measured- $R_n$ -based equation [Eq. (12)] with FAO56- $R_n$  for validation years (1985–1990), Miami, Fla.

data was available) were combined (pooled) and plotted against measured  $R_n$  data. The SEP of daily  $R_n$  predictions, average ratio of Eq. (12) or FAO56- $R_n$  to measured  $R_n$ , and regression coefficients between the predicted and measured  $R_n$  values for the same locations and for individual years are given in Table 2.

Overall, Eq. (12) and FAO56- $R_n$  predictions (using measured  $R_n$  data) correlated well with the measured  $R_n$  values for Gainesville [Fig. 8(A)] with  $r^2$  values of 0.91 and 0.93 in 1998 for Eq. (12) and 0.90 and 0.91 in 1999 for FAO56- $R_n$  equations, respectively. In 1998, the SEP of daily  $R_n$  predictions for Eq. (12) and FAO56, respectively, were 1.42 and 1.29  $\text{MJ m}^{-2} \text{d}^{-1}$ , and in 1999, they were same (1.37  $\text{MJ m}^{-2} \text{d}^{-1}$ ). None of the equations resulted in significant over- or underpredictions because the aver-

age ratio of Eq. (12) or FAO56- $R_n$  to measured  $R_n$  was very close to 1.0 in both years as it is shown in Fig. 8(A) and Table 2 ( $n = 730$ ).

In general, both Eq. (12) and FAO56- $R_n$  equations resulted in reasonable predictions of  $R_n$  for Watkinsville, Ga., in all three years (1999, 2000, and 2001) [Fig. 8(B)] with Eq. (12) having lower SEP and higher  $r^2$  values (Table 2). Thus, proposed equations' performance in predicting  $R_n$  was slightly better than FAO56- $R_n$  predictions. However, both equations overpredicted  $R_n$ . The average ratios of Eq. (12) to measured  $R_n$  were 1.25, 1.22, and 1.20 in 1999, 2000, and 2001, respectively. The average ratios of FAO56- $R_n$  to measured  $R_n$  were 1.01, 1.50, and 1.20 in 1999, 2000, and 2001, respectively.

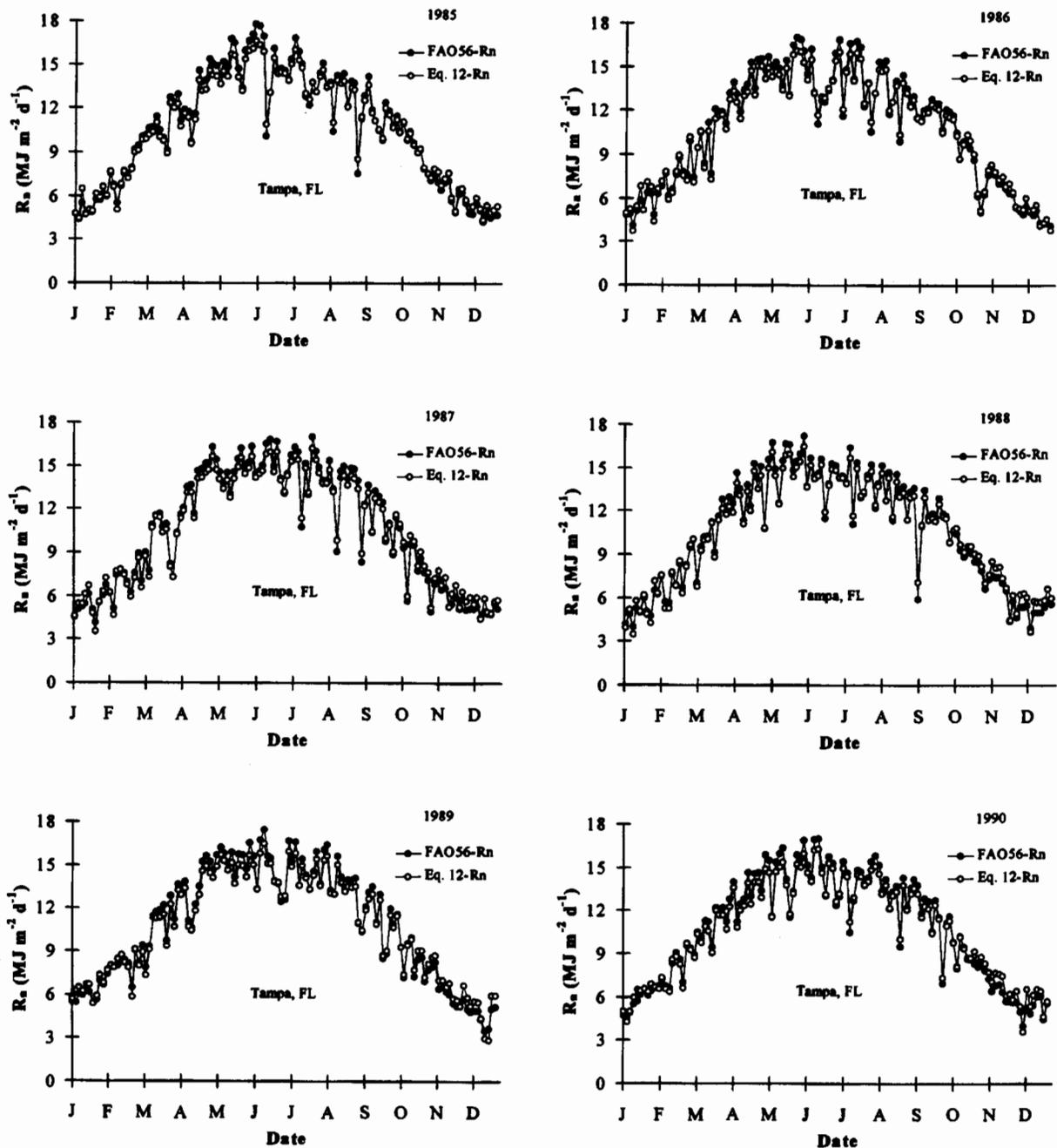
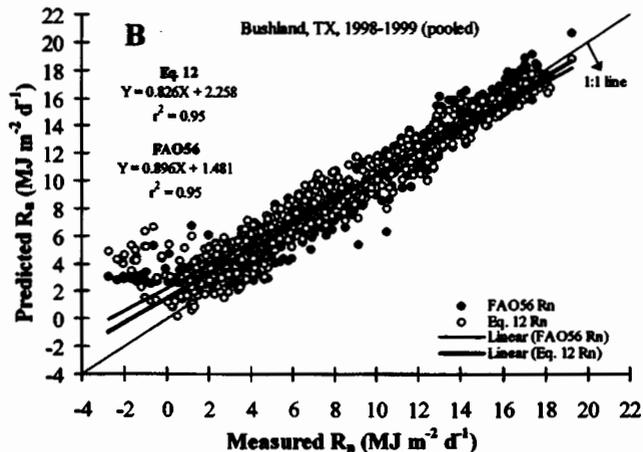
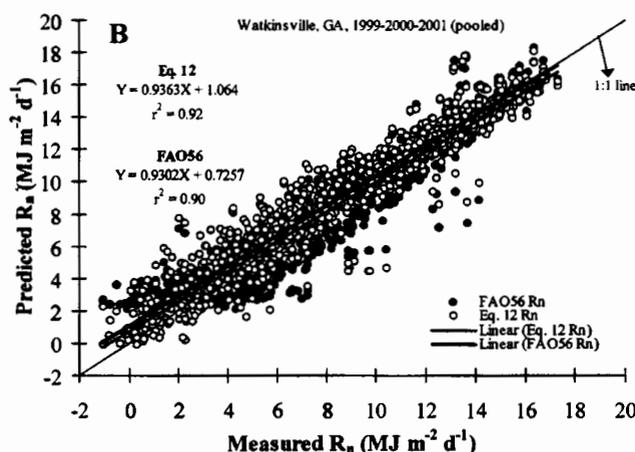
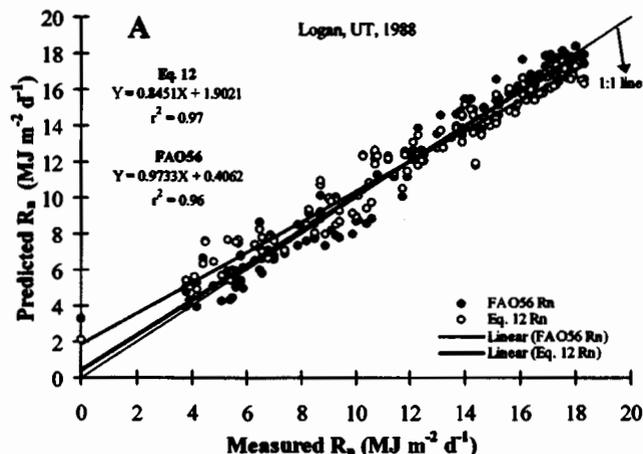
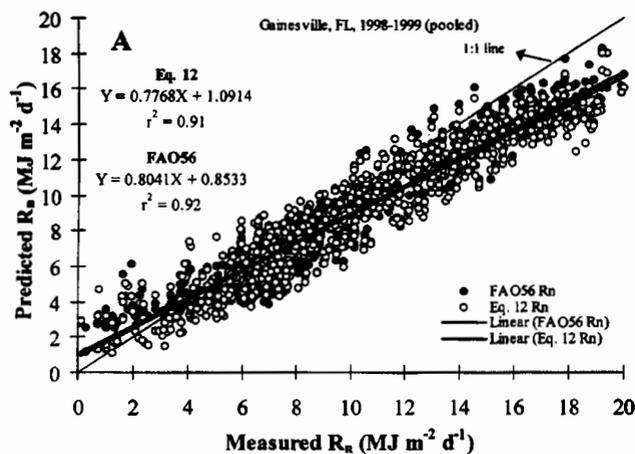


Fig. 7. Comparison of three-day average  $R_n$  predictions of measured- $R_n$ -based equation [Eq. (12)] with FAO56- $R_n$  for validation years (1985–1990), Tampa, Fla.

Logan, Utah, was the only location that did not have complete year of measured dataset. The dataset for this location was from May 6, 1988 to October 27, 1988. Fig. 9(A) clearly shows that both Eq. (12) and FAO56- $R_n$  equations resulted in good predictions of  $R_n$  for this location. The proposed equation had the lowest SEP ( $0.84 \text{ MJ m}^{-2} \text{ d}^{-1}$ ) (Table 2) of daily  $R_n$  values for Logan, Utah, among all locations evaluated with a high  $r^2$  of 0.97. The predictions of the FAO56- $R_n$  equations was poorer compared with the proposed equation and had higher-daily SEP value ( $0.95 \text{ MJ m}^{-2} \text{ d}^{-1}$ ) and lower  $r^2$  of 0.96 (Table 2). Relatively low-SEP values for Logan may be due to the smaller dataset used. The average ratios of Eq. (12) and FAO56- $R_n$  to measured  $R_n$  were 1.04 and 1.02, respectively.

Fig. 9(B) compares Eq. (12) and FAO56- $R_n$  equations predictions with the measured  $R_n$  values for Bushland, Tex. Agreement between the two equations and measured  $R_n$  is good, with some overpredictions by both equations when the  $R_n$  values were low ( $R_n < 0$ ). The daily SEP of Eq. (12) for 1988 and 1999, respectively, were  $0.96$  and  $1.34 \text{ MJ m}^{-2} \text{ d}^{-1}$  with  $r^2$  of 0.97 and 0.95, respectively (Table 2). The daily SEP of the FAO56 for the same years were  $1.02$  and  $1.26 \text{ MJ m}^{-2} \text{ d}^{-1}$  with  $r^2$  of 0.96 and 0.95, respectively (Table 2). The overpredictions by the two equations in the Bushland location might be due to the fact that there is no provision in FAO56- $R_n$  procedures to adjust for wintertime. Because Eq. (12) was calibrated against the  $R_n$  values calculated from the FAO56- $R_n$  equations, it showed a similar trend as the



**Fig. 8.** Comparison of measured- $R_s$ -based equation [Eq. (12)] performance with measured daily  $R_n$  values for (A) Gainesville, Fla. and (B) Watkinsville, Ga.

**Fig. 9.** Comparison of measured- $R_s$ -based equation [Eq. (12)] performance with measured daily  $R_n$  values for (A) Logan, Utah and (B) Bushland, Tex. locations

FAO56- $R_n$  equation for the low- $R_n$  range in Fig. 9(B). The FAO56- $R_n$  procedure does not account for changes in surface albedo with lower-sun angles and changes in effective sky emittance during wintertime (Wright, personal communication, 2001). It should be noted that in the FAO56- $R_n$  calculations, a constant albedo value of 0.23 was used for green vegetation to calculate the net shortwave radiation,  $R_{ns}$  [Eq. (2)] for all seasons. However, it is important to note in Fig. 9(B) that the overpredictions of both equations were apparent in winter months when the ground surface in Bushland, Tex. might have been covered by snow or the grass might have been frozen (dormant grass will also affect the albedo value). It is known that snow is a very effective reflector, particularly when new and the albedo value of fresh snow is much higher ranging from 0.80 to 0.95 and the albedo of the old snow ranging from 0.42 to 0.70 (Rosenberg et al. 1983). Thus, in the FAO56- $R_n$  calculations, the albedo value of 0.23 underpredicted the actual albedo when snow cover existed in winter months. A higher albedo would decrease  $R_{ns}$  and, consequently, decrease the predicted  $R_n$  values of both Eq. (12) and the FAO56- $R_n$  in wintertime resulting in better agreements with the measured  $R_n$  values. This, in part, would suggest the necessity of adjusting or modifying the FAO56- $R_n$  equations to account for snow cover when it exists. The similar conditions might be valid for Logan, Utah. However, this location's measured  $R_n$  data were

evaluated only from May through the end of October when the snow cover was not present on the ground surface.

#### Daily Comparisons of $R_{s,p}$ Equation [Eq. (13)] Predictions with Measured $R_n$ Values

A comparison of predicted daily  $R_n$ , using Eq. (13), and measured  $R_n$  for four locations is shown in Table 3. The FAO56- $R_n$  predictions, using predicted  $R_s$ , are also given in Table 3 for comparison. In general, Eq. (13) resulted in reasonable predictions of  $R_n$  using predicted  $R_s$ . In all locations and all years evaluated with the exception of Bushland, Tex., Eq. (13) provided much better predictions than the FAO56- $R_n$ . The FAO56- $R_n$  procedure produced slightly lower-SEP values in Bushland. Note that the RH data for Bushland were not available, thus, RH data for the two-year period were predicted from  $T_{min}$  data for this location and this might have contributed to the poorer performance of Eq. (13). Note that if the winter  $R_n$  values (from December to February) had been excluded for Bushland, the  $R_{s,p}$  equation would have resulted in better predictions. The SEP values between Eq. (13) and measured  $R_n$  varied from 1.75  $\text{MJ m}^{-2} \text{d}^{-1}$  for Logan, Utah, in 1988 to 2.64  $\text{MJ m}^{-2} \text{d}^{-1}$  for Bushland, Tex., in 1999. The SEP values between FAO56- $R_n$  procedures and measured  $R_n$  varied from 1.77  $\text{MJ m}^{-2} \text{d}^{-1}$  for Logan, Utah, to 2.50  $\text{MJ m}^{-2} \text{d}^{-1}$  for Gainesville, Fla. The  $r^2$  values of Eq. (13) were higher than FAO56- $R_n$  procedures in most cases varying from 0.79 for Bushland in 1999 to 0.86 in the same location in 1998.

**Table 2.** Daily Comparison of Proposed Equations' [Measured- $R_s$ -Based, Eq. (12)] Predictions with Measured  $R_n$  Values: Standard Error of Daily  $R_n$  Prediction (SEP), Average Ratio of Eq. (12) or FAO56- $R_n$  to Measured  $R_n$ , and Regression Coefficients Between Measured and Predicted  $R_n$  Values for Four Locations in the United States

Location, year	Measured- $R_s$ -based [Eq. (12)]- $R_n$					FAO56- $R_n$				
	SEP of daily prediction <sup>a</sup> (MJ m <sup>-2</sup> d <sup>-1</sup> )	Average ratio of Eq. (12)- $R_n$ /measured $R_n$ <sup>b</sup>	$r^2$	Slope <sup>c</sup>	Intercept <sup>c</sup>	SEP of daily prediction <sup>a</sup> (MJ m <sup>-2</sup> d <sup>-1</sup> )	Average ratio of FAO56- $R_n$ /measured $R_n$ <sup>b</sup>	$r^2$	Slope <sup>c</sup>	Intercept <sup>c</sup>
Gainesville, Fla., 1998	1.42	0.98	0.91	0.781	0.925	1.29	1.00	0.93	0.803	0.789
Gainesville, Fla., 1999	1.37	0.96	0.90	0.771	1.274	1.37	0.96	0.91	0.805	0.919
Watkinsville, Ga., 1999	1.34	1.25	0.91	1.010	-0.484	1.43	1.01	0.90	0.992	-0.002
Watkinsville, Ga., 2000	1.00	1.22	0.96	1.050	-0.616	1.29	1.50	0.93	1.051	-0.323
Watkinsville, Ga., 2001	1.18	1.20	0.92	0.912	-0.218	1.33	1.20	0.90	0.877	0.555
Logan, Utah, 1988	0.84	1.04	0.97	0.845	1.902	0.95	1.02	0.96	0.973	0.406
Bushland, Tex., 1998	0.96	1.15	0.97	0.897	1.292	1.02	1.18	0.96	0.957	0.697
Bushland, Tex., 1999	1.34	1.17	0.95	0.772	3.021	1.26	1.19	0.95	0.849	2.107

<sup>a</sup>Standard error of prediction (SEP) was calculated using daily  $R_n$  values for each equation ( $n = 365$ ).

<sup>b</sup>Average ratio is an average of daily ratio of Eq. (12)  $R_n$  or FAO56- $R_n$  to measured  $R_n$  ( $n = 365$  for all locations for individual years with the exception of Logan, Utah, where  $n = 141$ ).

<sup>c</sup>Regression coefficients (slope and intercept) were calculated as predicted  $R_n$  [Eq. (12) or FAO56- $R_n$ ] = slope  $\times$  measured  $R_n$  + intercept.

The  $r^2$  values of FAO56- $R_n$  varied from as low as 0.68 for Gainesville in 1999 and for Watkinsville in 2001 to 0.86 for Bushland in 1988. Thus, Eq. (13) was able to explain at least 79% of the variability in  $R_n$  predictions from only measured  $T_{max}$ ,  $T_{min}$ , and  $RH_{mean}$  data for the humid and arid locations studied. It is important to note that the SEP values of Eq. (13) and FAO56- $R_n$  procedures (Table 3) resulted in slightly higher values when predicted  $R_s$  values were used as compared with the SEP values in Table 2 where measured  $R_s$  values are used. This is expected since the precision of both Eq. (13) and the FAO56- $R_n$  procedure are dependent largely on the accurate predictions of daily  $R_s$ . However, based on the results in Table 3, it appears that Eq. (13) provides reasonable and consistent  $R_n$  predictions when only measured  $T_{max}$  and  $T_{min}$  values and the Hargreaves and Samani (1982)  $R_s$  equation are used as inputs. Its predictions were as good or better than FAO56- $R_n$  predictions in most cases. This is a significant advantage of Eq. (13) over FAO56- $R_n$  procedures when the required input parameters and simplifications in computations are considered.

### Weekly Comparisons of $R_{s,p}$ Equation [Eq. (13)] Predictions with Measured $R_n$ Values

Comparisons of Eq. (13) and FAO56- $R_n$  are shown in 1:1 plots in Figs. 10(A and B) and 11(A and B) for Gainesville, Watkinsville, Logan, and Bushland, respectively. The figures of the FAO56 weekly  $R_n$  versus measured  $R_n$  are not shown. The performance indicators of weekly  $R_n$  predictions of Eq. (13) as well as FAO56 method are summarized in Table 4 for comparison. Note that all  $R_n$  values, including the measured values, in Figs. 10(A and B) and 11(A and B) and in Table 4 were calculated on a daily basis using Eq. (13) and then averaged over a one-week period.

The  $R_{s,p}$  equations' weekly average  $R_n$  predictions resulted in remarkably good agreement with the measured  $R_n$  values for all locations with data points scattering very close to the 1:1 line in most cases. Results in Table 4 and Figs. 10(A and B) and 11(A and B) clearly showed that the performance of Eq. (13) for predicting  $R_n$  significantly improved when it is used to predict weekly average  $R_n$  from daily predictions. The SEP values of Eq. (13) were considerably lower than the FAO56 method for Gaines-

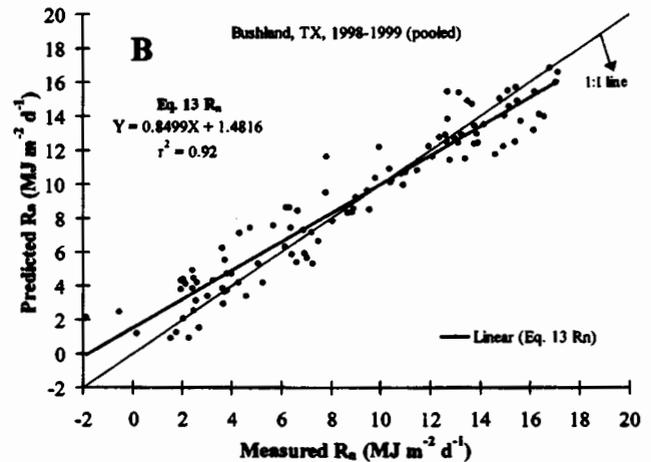
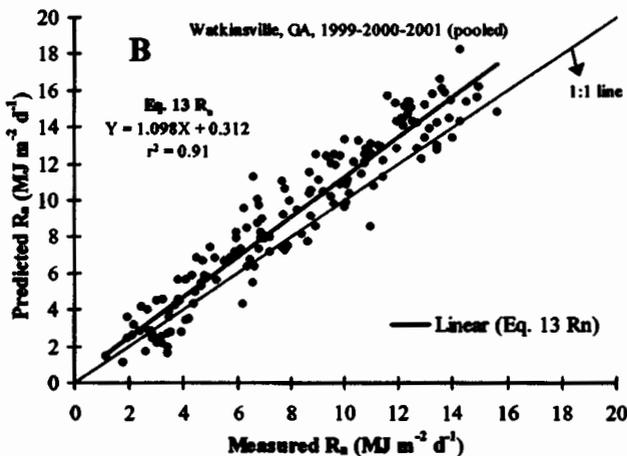
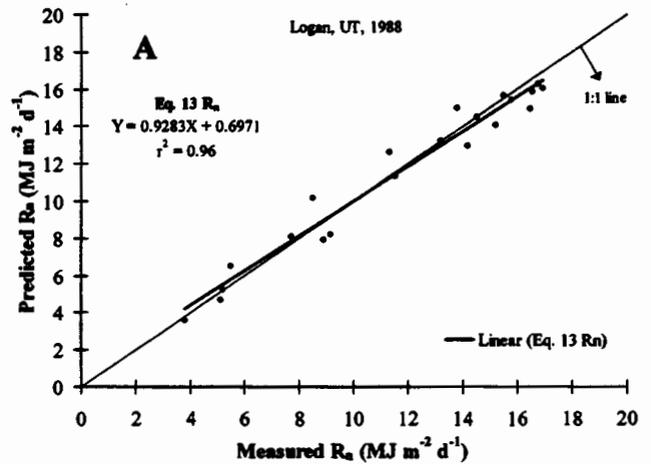
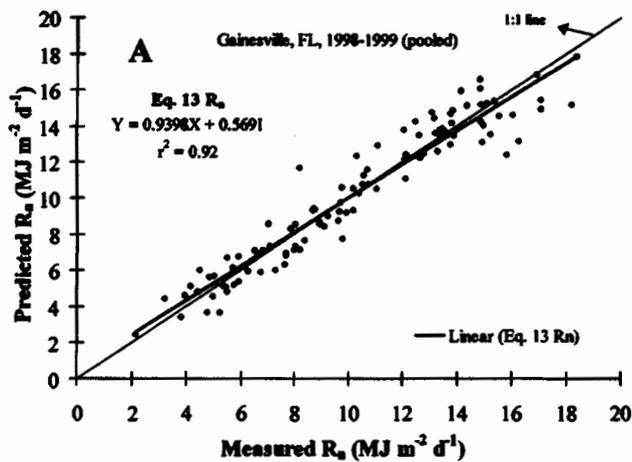
**Table 3.** Daily Comparison of Predicted- $R_s$ -Based Equations' [Eq. (13)] Predictions with Measured  $R_n$  Values: Standard Error of Daily  $R_n$  Prediction (SEP), Average Ratio of Eq. (13) to Measured  $R_n$ , and Regression Coefficients between Measured and Predicted  $R_n$  Values for Four Locations in the United States

Location, year	Predicted- $R_s$ -based [Eq. (13)] $R_n$					FAO56 $R_n$				
	SEP of daily prediction <sup>a</sup> (MJ m <sup>-2</sup> d <sup>-1</sup> )	Average ratio of Eq. (13)- $R_n$ /measured $R_n$ <sup>b</sup>	$r^2$	Slope <sup>c</sup>	Intercept <sup>c</sup>	SEP of daily prediction <sup>a</sup> (MJ m <sup>-2</sup> d <sup>-1</sup> )	Average ratio of FAO56- $R_n$ /measured $R_n$ <sup>b</sup>	$r^2$	Slope <sup>c</sup>	Intercept <sup>c</sup>
Gainesville, Fla., 1998	2.00	1.12	0.82	0.809	1.808	2.50	1.34	0.73	0.741	2.937
Gainesville, Fla., 1999	1.90	1.06	0.81	0.825	1.871	2.50	1.14	0.68	0.771	2.627
Watkinsville, Ga., 1999	1.95	1.21	0.81	0.971	1.568	2.39	1.22	0.72	0.833	2.429
Watkinsville, Ga., 2000	1.85	0.97	0.85	1.013	0.897	2.38	1.88	0.75	0.832	2.262
Watkinsville, Ga., 2001	1.86	1.26	0.80	0.904	1.772	2.34	1.41	0.68	0.826	2.361
Logan, Utah, 1988	1.75	1.02	0.85	0.822	2.007	1.77	1.03	0.85	0.826	2.156
Bushland, Tex., 1998	2.00	1.04	0.86	0.931	0.622	1.97	1.25	0.86	0.821	1.645
Bushland, Tex., 1999	2.64	1.23	0.79	0.697	2.888	2.21	1.29	0.85	0.680	2.989

<sup>a</sup>Standard error of prediction (SEP) was calculated using daily  $R_n$  values for each equation ( $n = 365$ ).

<sup>b</sup>Average ratio is an average of daily ratio of Eq. (13)- $R_n$  or FAO 56- $R_n$  to measured  $R_n$  ( $n = 365$  for all locations for individual years with the exception of Logan, Utah, where  $n = 141$ ).

<sup>c</sup>Regression coefficients (slope and intercept) were calculated as predicted  $R_n$  [Eq. (13)- $R_n$  or FAO 56- $R_n$ ] = slope  $\times$  measured  $R_n$  + intercept.



**Fig. 10.** Comparison of weekly average  $R_n$  values of predicted- $R_s$ -based equation [Eq. (13)] with measured weekly average  $R_n$  for (A) Gainesville, Fla. and (B) Watkinsville, Ga.

**Fig. 11.** Comparison of weekly average  $R_n$  values of predicted- $R_s$ -based equation [Eq. (13)] with measured weekly average  $R_n$  for (A) Logan, Utah and (B) Bushland, Tex.

ville and Watkinsville ranging from  $0.98 \text{ MJ m}^{-2} \text{ d}^{-1}$  for Watkinsville in 2000 to  $1.20 \text{ MJ m}^{-2} \text{ d}^{-1}$  in 1999 (Table 4). The FAO56 predictions were slightly better for Logan and Bushland. The SEP of the weekly  $R_n$  predictions from FAO56 for these two locations ranged from  $0.86$  to  $1.29 \text{ MJ m}^{-2} \text{ d}^{-1}$ . Both Eq. (13) and the FAO56 method overpredicted for Watkinsville (all three years) and Bushland (1999) locations. The average ratios of Eq. (13) to measured  $R_n$  for Watkinsville were 1.17, 1.11, and 1.14 in 1999, 2000, and 2001, respectively, and the ratio was 1.13 for Bushland in 1999. The ratios of FAO56 to measured  $R_n$  for Watkinsville were 1.14, 1.15, and 1.12 in the same years and it was 1.33 for Bushland in 1999 (Table 4). Note that if the winter  $R_n$  values (from December to February) had been excluded for Bushland, the performance of the  $R_{s-p}$  equation would have been much better. The  $r^2$  values between the Eq. (13) predictions and the measured  $R_n$  values were usually higher than the FAO56 method, varying from 0.89 for Watkinsville in 2001 to 0.96 in Logan and Bushland in 1998 (Table 4). The  $r^2$  values of the FAO56 method were higher than the Eq. (13) values for Bushland location in both years (0.97 versus 0.96 in 1998 and 0.94 versus 0.92 in 1999). Thus, Eq. (13) was able to explain at least 89% of the variability in weekly average  $R_n$  when Hargreaves and Samani (1982) equation was used to predict daily  $R_s$ .

## Summary and Conclusions

The procedure outlined in the Food and Agriculture Organization Irrigation and Drainage Paper No. 56 (FAO56- $R_n$ ) for predicting daily net radiation ( $R_n$ ) has been widely used. However, when the availability of detailed climatological data in the United States and around the world is considered, it appears that there is a need for methods that can predict daily  $R_n$  with fewer inputs and computation. Two equations were developed to reduce the input requirements as well as computation intensity for predicting daily net radiation ( $R_n$ ). The first equation [measured- $R_s$ -based ( $R_{s-M}$ )] requires maximum and minimum air temperatures ( $T_{\max}$  and  $T_{\min}$ ), measured solar radiation ( $R_s$ ), and inverse relative distance from Earth to sun ( $d_r$ ), and the second equation [predicted- $R_s$ -based ( $R_{s-p}$ )] requires  $T_{\max}$ ,  $T_{\min}$ , mean relative humidity ( $\text{RH}_{\text{mean}}$ ), and predicted  $R_s$ . The  $R_{s-M}$  equation was calibrated using 17 years of measured and carefully screened daily weather data for Gainesville, Florida. Daily values of  $R_n$  obtained from the FAO56- $R_n$  procedure were used as an index for the calibration. The  $R_{s-p}$  equation was developed using two years of measured daily  $R_n$  data for Gainesville. The Hargreaves and Samani (1982),  $R_s$  equation, which requires only  $T_{\max}$  and  $T_{\min}$  to predict  $R_s$ , was substituted into the  $R_{s-p}$  equation. The performance of both equations was evaluated in different locations including humid and arid, and coastal and inland regions (Gaines-

**Table 4.** Weekly Comparison of Proposed Equations' [Predicted- $R_s$ -Based, Eq. (13)] Predictions (using Predicted  $R_s$ ) with Measured  $R_n$  Values: Standard Error of Weekly  $R_n$  Prediction (SEP), Average Ratio of Eq. (13) to Measured  $R_n$ , and Regression Coefficients between Measured and Predicted  $R_n$  Values for Four Locations in the United States

Location, year	Predicted- $R_s$ -based [Eq. (13)] $R_n$					FAO56 $R_n$				
	SEP of weekly prediction <sup>a</sup> (MJ m <sup>-2</sup> d <sup>-1</sup> )	Average ratio of Eq. (13)- $R_n$ /measured $R_n$ <sup>b</sup>	$r^2$	Slope <sup>c</sup>	Intercept <sup>c</sup>	SEP of weekly prediction <sup>b</sup> (MJ m <sup>-2</sup> d <sup>-1</sup> )	Average ratio of FAO56- $R_n$ /measured $R_n$ <sup>b</sup>	$r^2$	Slope <sup>c</sup>	Intercept <sup>c</sup>
Gainesville, Fla., 1998	1.15	0.99	0.92	0.934	0.508	1.33	1.03	0.90	0.949	0.773
Gainesville, Fla., 1999	1.08	1.02	0.92	0.946	0.628	1.59	1.04	0.83	0.978	0.507
Watkinsville, Ga., 1999	1.20	1.17	0.90	1.113	0.422	1.29	1.14	0.89	1.091	0.376
Watkinsville, Ga., 2000	0.98	1.11	0.94	1.149	0.214	1.17	1.15	0.92	1.064	0.344
Watkinsville, Ga., 2001	1.17	1.14	0.89	1.016	0.855	1.30	1.12	0.86	1.090	0.195
Logan, Utah, 1988	0.89	1.00	0.96	0.928	0.697	0.86	1.01	0.96	0.950	0.653
Bushland, Tex., 1998	0.97	1.01	0.96	0.999	0.000	0.91	1.06	0.97	0.932	0.636
Bushland, Tex., 1999	1.52	1.13	0.92	0.717	2.752	1.29	1.33	0.94	0.767	2.230

<sup>a</sup>Standard error of prediction (SEP) was calculated using daily  $R_n$  values for each equation ( $n=365$ ).

<sup>b</sup>Average ratio is an average of daily ratio of Eq. (13)  $R_n$  or FAO 56- $R_n$  to measured  $R_n$  ( $n=365$  for all locations for individual years with the exception of Logan, Utah, where  $n=141$ ).

<sup>c</sup>Regression coefficients (slope and intercept) were calculated as predicted  $R_n$  [Eq. (13)- $R_n$  or FAO 56- $R_n$ ] = slope  $\times$  measured  $R_n$  + intercept.

ville, Fla., Miami, Fla., Tampa, Fla., Tifton, Ga., Watkinsville, Ga., Mobile, Ala., Logan, Utah, and Bushland, Tex.) in the United States.

Daily  $R_n$  values predicted by  $R_{s-M}$  equation were in close agreement with those obtained from FAO56- $R_n$  procedures in all locations and for all evaluation years. Comparisons of  $R_{s-M}$  equation and FAO56- $R_n$  predictions with the measured  $R_n$  values showed that the  $R_{s-M}$  equations' predictions were as good or better than the FAO56- $R_n$  in most cases. The performance of the  $R_{s-P}$  equation was quite good when compared with the measured  $R_n$  in Gainesville, Watkinsville, Logan, and Bushland locations providing similar or better daily  $R_n$  predictions than the FAO56- $R_n$  procedures. The  $R_{s-P}$  equation was able to explain at least 79% of the variability in  $R_n$  predictions from only measured  $T_{max}$  and  $T_{min}$  data for the humid and arid locations studied. The performance of the  $R_{s-P}$  equation was significantly improved when its daily predictions were averaged on a weekly basis and compared with the measured  $R_n$  in all locations. One advantage of using the  $R_{s-M}$  equation is that it uses fewer input parameters and less computation than the FAO56- $R_n$  procedures. Thus, it is more suitable for use in automated dataloggers, computer programs, and spread sheet applications. The significant advantage of the  $R_{s-P}$  equation is that it predicts daily  $R_n$  from only measured  $T_{max}$  and  $T_{min}$  (because, when it is not available, RH can be predicted from air temperature data with a sufficient accuracy) with a reasonable precision when measured  $R_s$  is not available. These results can greatly improve and facilitate  $R_n$  predictions by engineers, agronomists, climatologists, and others who work routinely with National Weather Service climatological data that only record  $T_{max}$ ,  $T_{min}$ , and rainfall on a regular basis.

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