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Evaluation of Methodologies to Estimate Reference Evapotranspiration in Florida

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The Penman-Monteith equation was considered by the United Nations Food and Agriculture Organization (FAO) as the standard method to calculate reference evapotranspiration (ETo). The lack of data availability, especially in long-term historical records, was the basic obstacle for a broader use of the FAO Penman-Monteith equation. Long-term records often included daily maximum and minimum temperatures and precipitation. In these circumstances empirical methods could be used but required calibration for local conditions and were not readily transferable to other regions. The main objectives of this study were to compare reference evapotranspiration estimated by the FAO Penman-Monteith equation to reference evapotranspiration estimated by the Priestley and Taylor and the Hargreaves empirical methods. The use of the FAO Penman-Monteith equation with estimated solar radiation, relative humidity, and wind speed was also evaluated. Daily, 10-d, and monthly values of reference evapotranspiration calculated by Penman-Monteith and the other methods were compared. The Priestley and Taylor method was found to be the best method to use when available long-term historical records included only daily temperature and precipitation. This methodology can be used in climatological studies for irrigation planning and to better understand the effects of seasonal climate variability on crop water requirements in Florida.

Evapotranspiration (ET) is the soil-plant system water requirement, which is the combination of two separate processes, soil surface evaporation and plant transpiration. ET is an important agrometeorological parameter for climatological studies, water resources planning, and irrigation scheduling (Bautista et al., 2009; Sentelhas et al., 2010; Wu, 1997). ET is influenced by several factors such as the environment, crop characteristics, and management practices. The concept of reference evapotranspiration (ETo) presented by Allen et al. (1998) is the evapotranspiration from a reference surface, which is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 $s \cdot m^{-1}$ and an albedo of 0.23. It closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The ETo concept was introduced to evapotranspiration studies to eliminate the influence of soil type, crop characteristics and management in ET measurements. Therefore, ETo is calculated using only weather parameters.

The Food and Agriculture Organization of the United Nations (FAO) consider the FAO Penman-Monteith method (FAO-56) as the standard method to calculate ETo. This method is physically based and incorporates physiological and aerodynamic factors (Bautista et al., 2009; Sentelhas et al., 2010). However, FAO Penman-Monteith requires meteorological parameters which may not be available everywhere. The lack of data availability, especially in long-term historical records, is the basic obstacle for a broader use of the FAO Penman-Monteith equation. Long-term records often include only daily minimum and maximum temperatures, and precipitation. In these circumstances empirical methods can be used to estimate ETo.

Numerous equations have been created to estimate ETo. The standard method to estimate ETo, FAO Penman-Monteith, was also used to evaluate alternative methods (Allen et al., 1994 a, b). These alternative methods have the advantage of requiring few meteorological data. However, they were generally calibrated for local conditions and not readily transferable to other regions (Grismer, 2002). Priestley and Taylor is a radiation-based method and is a simplification of the original Penman equation (Priestley and Taylor, 1972). Under humid conditions, it has shown good results and acceptable estimates of ETo on an annual basis (Trajkovic and Kolakovic, 2009). Lu et al. (2005) studying six methods to estimate ETo in the southeastern USA using radiation and temperature-based equations, found good correlation between the methods, mainly between Priestley and Taylor and other empirical methods. In a study conducted in Georgia, Priestley and Taylor underestimated monthly average ETo during the winter in most locations across the state and overestimated during warm season months (Suleiman and Hoogenboom, 2007). Nevertheless the Priestley and Taylor equation was found to be a good method to estimate ETo after proper calibration in southern Ontario, Canada (Sentelhas et al., 2010).

The Hargreaves equation, presented by Hargreaves and Samani (1985), is temperature based and can be used when only temperature is available. This method generally provides more accurate ETo estimates for periods of 5 d or longer (Jensen et al., 1997). Under humid conditions Hargreaves generally overestimates ETo. However, after local calibration Trajkovic (2007) reported overestimation of about 1% when compared to ETo estimated by FAO Penman-Monteith.

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Allen et al. (1998) suggested an approach that estimates missing data to calculate ETo using the Penman-Monteith equation. The authors suggested the estimation of solar radiation using minimum and maximum temperature, relative humidity assuming that minimum temperature was equal to dewpoint temperature and the use of wind speed data from a nearby location within the same homogenous region. For southern Ontario, Canada, Sentelhas et al. (2010) found poor relationship between ETo calculated by FAO Penman-Monteith using observed and estimated solar radiation, relative humidity, and wind speed.

The main objective of this study was to select a methodology to estimate ETo under Florida conditions when only temperature and precipitation data were available. Specific objectives were to compare ETo calculated by the FAO Penman-Monteith method to ETo estimated by empirical methods (Priestley and Taylor and Hargreaves) and to ETo calculated by the same FAO Penman-Monteith method but using estimated solar radiation, relative humidity, and wind speed.

Material and Methods

Florida climate regions and weather data collection

For the purpose of this study the state of Florida was divided into three regions (South, Central, and North–Panhandle) based on climatological characteristics (Fig. 1) (Crisman, 2008). The southernmost region of the state was characterized as having a humid tropical climate; the central transitional region as subtropical subhumid mesothermal; and the northern region as subtropical humid mesothermal.

Minimum and maximum temperatures, solar radiation, relative humidity and wind speed data were obtained from Florida Automated Weather Network (FAWN; http://fawn.ifas.ufl.edu/) stations located in each climate region between the years of 2003 and 2009. The number of weather stations available in each region ranged from 18 in the northern region to 9 and 2 in the central and southern regions, respectively. Weather data quality checking were performed to eliminate records with potential problems such as days with solar radiation equal to zero or higher than extraterrestrial solar radiation (radiation at the top of the atmosphere). Additionally, daily wind speed records were checked and eliminated if equal to zero for two or more consecutive days.

Methods for estimating reference evapotranspiration

Penman-Monteith. According to Allen et al. (1998), FAO Penman-Monteith (FAO-56) should be used as a standard method for estimating ETo. This method was expressed by the following equation:

$$ETo_{PM} = \frac{0.408\Delta(Rn-G)+\gamma\left(\frac{900}{T+273}\right)U_2(e_s-e_a)}{\Delta+\gamma\,(1+0.34U_2)} \qquad [1]$$

where: ETo was the reference evapotranspiration (mm·day^{-1}); Δ was the slope of the saturation vapor pressure vs. air temperature curve (kPa·°C^{-1}); Rn was the daily net radiation (MJ·m^{-2}·day^{-1}); G was the soil heat flux density (MJ·m^{-2}·day^{-1}), considered as null for daily estimates; γ was the psychrometric constant (0.0677 kPa·°C^{-1}); T was the daily mean air temperature (°C) at 2 m (6 ft and 7 inches), based on the average of maximum and minimum temperatures; U_2 was the wind speed (m·s^{-1}) at 2 m (6 ft and 7 inches) height; e_s and e_a represented the saturation and actual vapor pressures (kPa), respectively. Rn was estimated by the following equations:

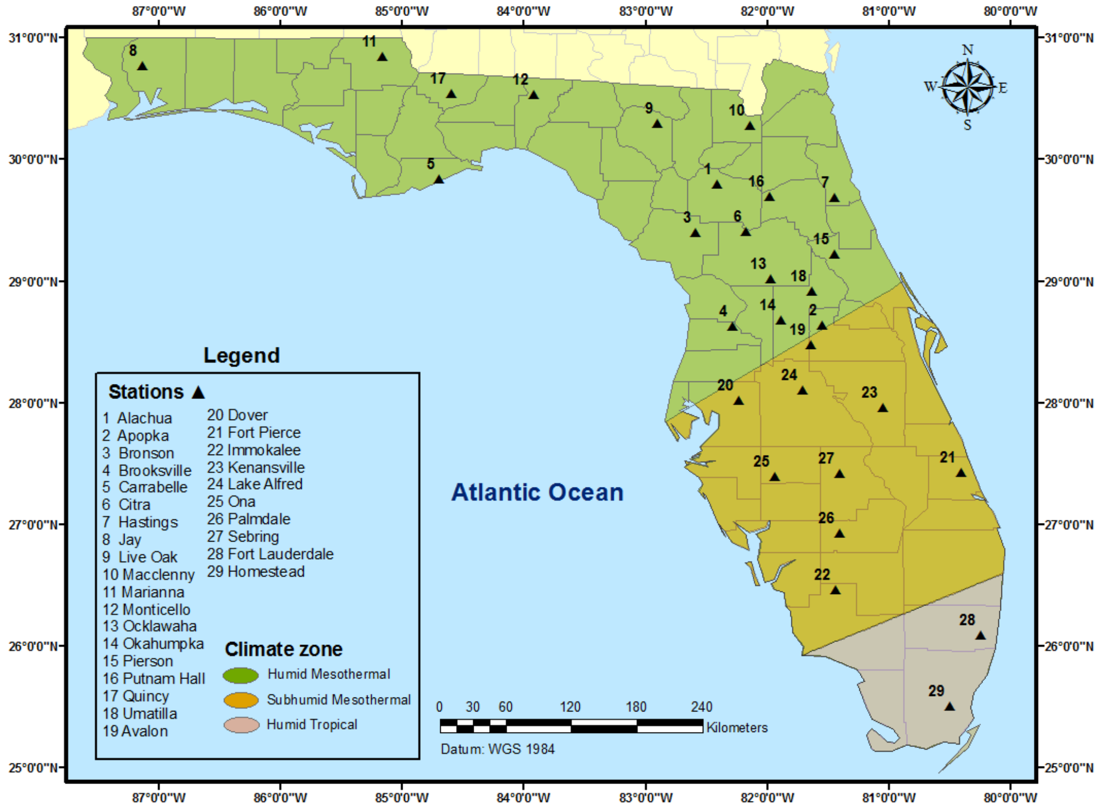

Fig. 1. Climate zones and geographical location of the Florida Automated Weather Network (FAWN) stations used in the study, Florida.

$$Rn = Rns - Rnl \tag*{[2]}$$

$$Rns = 0.77SR \tag*{[3]}$$

$$Rnl = \left[\sigma\left(\frac{Tmax_K^4 + Tmin_K^4}{2}\right)\left(0.34 - 0{,}14\sqrt{e_a}\right)\left(1.35\frac{SR}{SRo} - 0.35\right)\right] \tag*{[4]}$$

$$Rso = 0.75Ra \tag*{[5]}$$

where: Rns was the net shortwave radiation ($MJ \cdot m^{-2} \cdot day^{-1}$); Rnl was the net outgoing longwave radiation ($MJ \cdot m^{-2} \cdot day^{-1}$); SR was the incoming solar radiation ($MJ \cdot m^{-2} \cdot day^{-1}$); σ was the Stefan-Boltzmann constant ($4.903\ 10^{-9}\ MJ \cdot K^{-4}\ m^{-2} \cdot day^{-1}$) (Allen et al., 1998); $Tmax_K$ and $Tmin_K$ were respectively maximum and minimum absolute temperature during 24-h period (K); Rso was the clear sky solar radiation ($MJ \cdot m^{-2} \cdot day^{-1}$); and Ra was the extraterrestrial solar radiation ($MJ \cdot m^{-2} \cdot day^{-1}$).

PRIESTLEY AND TAYLOR. The Priestley and Taylor equation (1972) is radiation-based and a simplification of the original Penman equation. This method was expressed by the following equation:

$$ETo = 1.26\ \frac{\Delta}{\Delta + \gamma}\left(\frac{Rn - G}{\lambda}\right) \tag*{[6]}$$

where: λ was the latent heat of vaporization ($2.45\ MJ \cdot kg^{-1}$). 1.26 was the Priestley and Taylor coefficient, an empiric coefficient that may vary for different regions, being influenced by soil moisture and vegetation types (Priestley and Taylor, 1972; Sentelhas et al., 2010; Suleiman and Hoogenboom, 2007). In this study the coefficient was calibrated for each region and also for colder and warmer months of the year. Solar radiation and actual vapor pressure were estimated based on minimum and maximum temperatures and assuming that dewpoint temperature was equal to the minimum temperature.

HARGREAVES. The Hargreaves method (Hargreaves and Samani, 1985) is temperature-based and was expressed by the following equation:

$$ETo = CH\ Ra'(Tmax - Tmin)^{0.5}(T + 17.8) \tag*{[7]}$$

where: Ra′ was the extraterrestrial radiation ($mm \cdot day^{-1}$); CH was the Hargreaves empiric coefficient; and Tmax and Tmin were, respectively, maximum and minimum temperature during the 24-h period (°C). For this study CH was calibrated for each region and was found to be different for colder (October–March) and warmer (April–September) months of the year.

FAO PENMAN-MONTEITH (FAO-56) WITH ESTIMATED PARAMETERS. The FAO Penman-Monteith equation requires a large range of climatological parameters, often not available in most locations and long-term historical records. To use this equation for estimating ETo, Allen et al. (1998) suggested the estimation of missing data such as solar radiation, actual vapor pressure, and wind speed. Estimated solar radiation (eSR) replaces SR in equations (3) and (5) and was calculated as follows:

$$eSR = K_{SR} Ra\sqrt{Tmax - Tmin} \tag*{[8]}$$

where: K_{SR} was an adjustment factor. K_{SR} value was 0.19 or 0.16 for coastal and continental conditions, respectively (Allen et al., 1998). In this study different K_{SR} values were adjusted for wet days (days with precipitation greater than zero) and dry days (days with precipitation equal to zero), as proposed by Garcia y Garcia and Hoogenboom (2005).

Estimation of actual vapor pressure (e_a) requires making the assumption that dewpoint temperature is near the daily minimum temperature. It usually happens in the first hours of the morning (Allen et al., 1998). Based on this assumption e_a can be estimated using the following equation:

$$e_a = 0.6108\ exp\left(\frac{17.27\ Tmin}{Tmin + 237.3}\right) \tag*{[9]}$$

When wind speed data were not available, Allen et al. (1998) proposed to use average wind speed data from a nearby station within the same homogenous region. In this study we used climatological monthly wind speed data provided by the Center for Ocean and Atmospheric Prediction Studies (COAPS; http://www.coaps.fsu.edu/) at Florida State University.

STATISTICAL ANALYSIS. ETo calculated using the FAO Penman-Monteith equation were compared to ETo values obtained using the Priestley and Taylor and Hargreaves empirical methods and the FAO Penman-Monteith equation but with estimated instead of observed weather variables to select the best methodology for each region. Estimated ETo was evaluated using root mean square error (RMSE), mean error (ME), and coefficient of determination (R^2), as suggested by Douglas et al. (2009) and Sentelhas et al. (2010).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ETo_{est} - ETo_{PM})^2} \tag*{[10]}$$

$$ME = \frac{1}{n}\sum_{i=1}^{n}(ETo_{est} - ETo_{PM}) \tag*{[11]}$$

Results and Discussion

Climate conditions during the period of study (2003–09)

Monthly air temperature and precipitation observed from 2003 to 2009 and the climatological normal for the state of Florida are shown in Fig. 2. Average observed rainfall in the southern region of the state was of 1,308 mm (51.5 inches) per year, slightly lower than the climatological normal of 1,485 mm (58.5 inches) per year. Air temperature averaged 24.0 °C (75.1 °F), similar to the normal of 24.2 °C (75.6 °F). In the central region annual rainfall averaged 1,191 mm (46.9 inches), also below the normal rainfall (1,332 mm) (52.4 inches). Average temperature in this region was 22.5 °C (72.5 °F), similar to the normal of 22.6 °C (72.7 °F). In the north–panhandle region, the average observed rainfall was of 1,273 mm (50.1 inches) yearly, slightly lower than the normal of 1,391 mm (54.8 inches) and the observed average temperature was similar to the normal temperature.

Overall the observed annual rainfall between the years of 2003 and 2009 in all regions was slightly lower than normal while the average observed temperature was similar to the normal. These results indicate that the meteorological conditions during the study period were in general similar to the climatological normal. Climate variability during the study period was also characterized by the occurrence of two El Niño Southern Oscillation (ENSO) warm (El Niño) events (2002–03 and 2006–07) and one cold (La Niña) event (2008–09).

Monthly temperature averages did not vary much during the years of the study, especially during summer months (Fig. 3). The lowest and highest monthly average temperatures were observed in Jan. 2003 and Aug. 2005, respectively. Monthly rainfall was generally lower than normal between 2006 and 2008 while 2005 was the wettest year during the period of study. In general, rain-

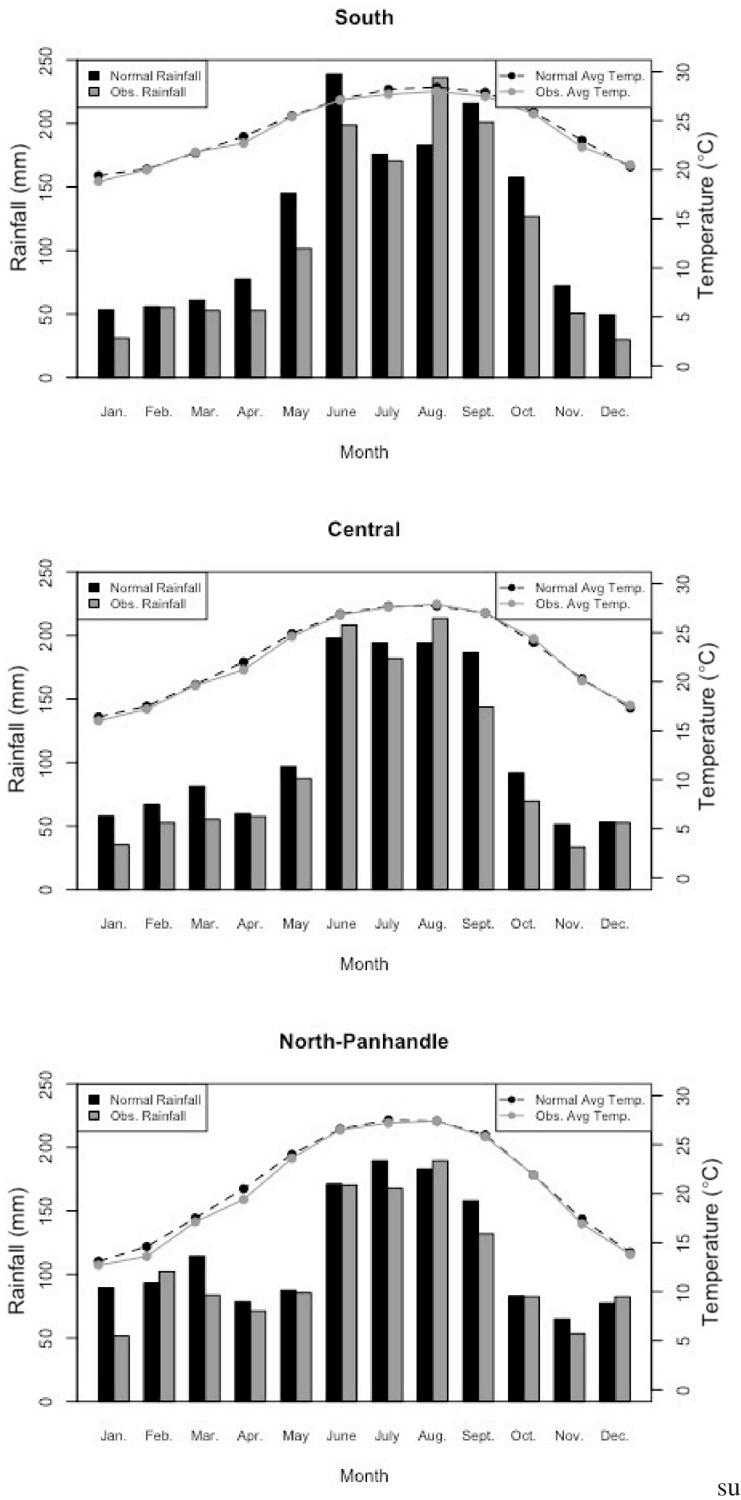

Fig. 2. Normal and observed monthly rainfall (mm) and average air temperature (°C) for the regions: (**a**) South; (**b**) Central; and (**c**) North-Panhandle, Florida.

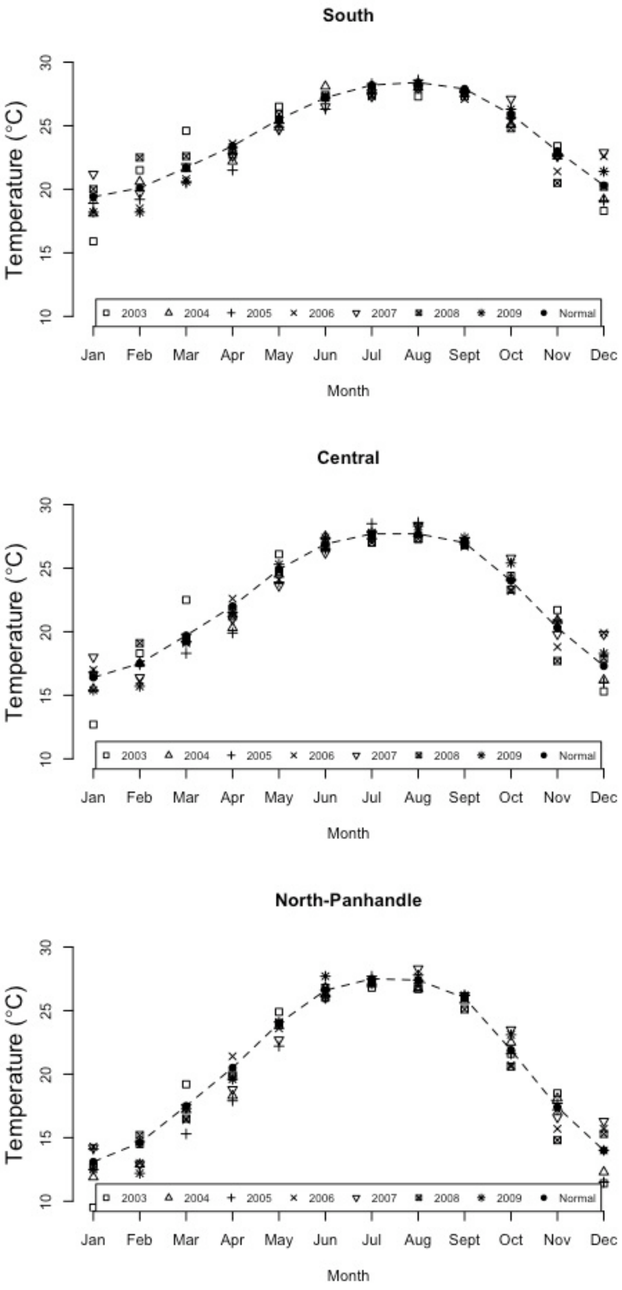

Fig. 3. Normal, average for all years of the study (2003–09), and yearly observed average air temperature (°C) for the regions: (**a**) South; (**b**) Central; and (**c**) North-Panhandle, Florida.

fall was lower than the climatological normal during the period of study (Fig. 4). In the South and Central regions 60% of the annual rainfall was concentrated between June and September.

Estimated ETo was higher during the month of May (Fig. 5). The month of May does not present the highest values for temperature and Ra. However, it is dryer when compared to the summer months. It can be observed that estimated monthly ETo did not vary much during the years of the study but 2006 and 2007, dry years in the Central and North–Panhandle regions, presented higher values of ETo. During those years cloudiness was lower, allowing for a higher incidence of solar radiation at the surface. In 2003 and 2005, wet years, estimated ETo were lower than for the other years.

Estimation of reference evapotranspiration by empirical methods

The estimation of solar radiation using the coefficient K_{SR} with the value originally proposed by Allen et al. (1998) generally

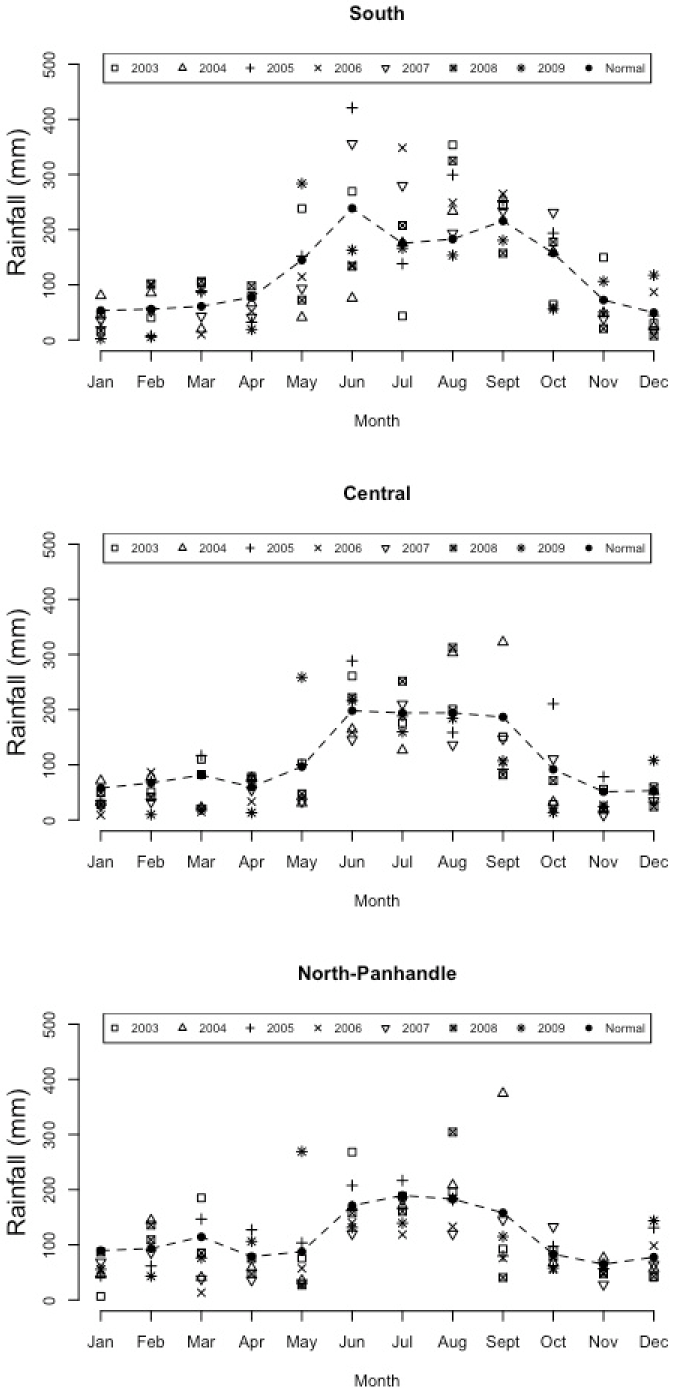

Fig. 4. Normal, average for all years of the study (2003–09), and yearly observed rainfall (mm) for the regions: (**a**) South; (**b**) Central; and (**c**) North-Panhandle, Florida.

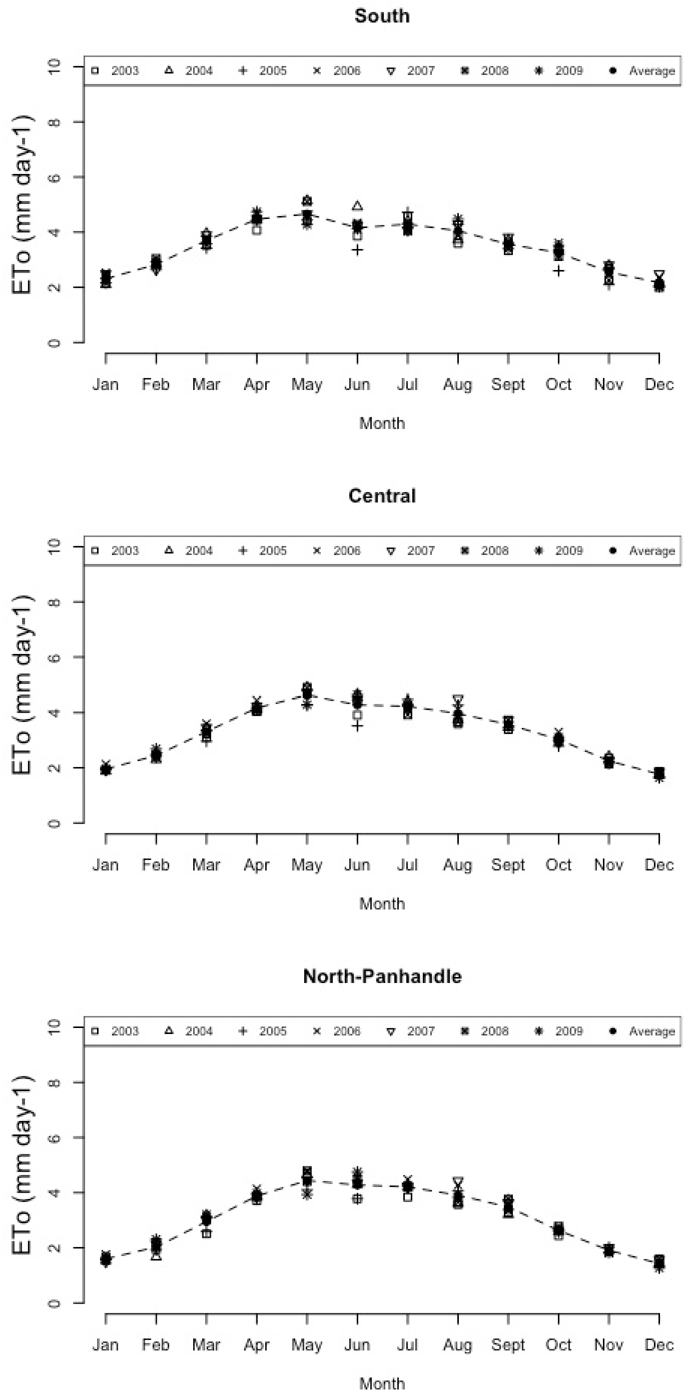

Fig. 5. Estimated monthly ETo (mm·day^{-1}) for the regions: (**a**) South; (**b**) Central; and (**c**) North-Panhandle, Florida.

resulted in overestimation of solar radiation. K_{SR} was adjusted to better represent the climate conditions found in the southeastern USA (Table 1). Also, as proposed by Garcia y Garcia and Hoogenboom (2005), different K_{SR} values were defined for rainy and dry days.

The calculation of ETo using the FAO Penman-Monteith method with estimated solar radiation, relative humidity, and wind speed generally overestimated ETo in the Central and North–Panhandle regions of Florida. Empirical coefficients for the cold (October to March) and warm (April to September) season months (Table 2) were used to improve ETo estimation. However, this method presented the highest values for mean error (ME) (Table 3) and root mean square error (RMSE) (Table 4) and lowest values of R^2. Results for the southern region were particularly worse than for other regions with R^2 values consistently lower for daily, 10-d, and monthly time periods. The low correlation between the results obtained using FAO Penman-Monteith and empirical methods in the southern region could be attributed to

Table 1. Solar radiation coefficients for rainy (rainfall >0.0 mm) and dry (rainfall = 0.0 mm) days.

	Solar radiation coefficient	
Region	Rain >0	Rain = 0
South	0.12	0.17
Central	0.13	0.16
North–Panhandle	0.13	0.16

Table 2. Locally calibrated empirical coefficients for the FAO Penman-Monteith with estimated weather variables (ePM), Priestley and Taylor (PT), and Hargreaves (HA) methods.

Equation	Season	South	Central	North–Panhandle
ePM	Winter	0.8	0.65	0.67
	Summer	1.0	0.83	0.87
PT	Winter	1.43	1.25	1.25
	Summer	1.33	1.14	1.14
HA	Winter–summer	0.0022	0.0018	0.0018

Table 3. Mean error of ETo estimated by FAO Penman-Monteith with estimated weather variables (ePM), Priestley and Taylor (PT), and Hargreaves (HA) as compared to FAO Penman-Monteith.

Region	ePM	PT	HA
South	–0.016	0.011	0.103
Central	–0.032	–0.079	–0.066
Panhandle–North	0.123	–0.012	0.030

Table 4. Root mean square error (RMSE) and coefficient of determination (R^2) for different time periods (daily, 10-d, and monthly), regions (South, Central and North–Panhandle), and methods [FAO Penman-Monteith with estimated weather variables (ePM), Priestley and Taylor (PT), and Hargreaves (HA)].

Region	Period	Equation	RMSE	R^2
South	Daily	ePM	1.057	0.360
		PT	0.890	0.495
		HA	0.983	0.376
	10-day	ePM	0.552	0.687
		PT	0.402	0.819
		HA	0.530	0.702
	Monthly	ePM	0.398	0.807
		PT	0.278	0.896
		HA	0.399	0.810
Central	Daily	ePM	0.730	0.675
		PT	0.648	0.740
		HA	0.706	0.689
	10-d	ePM	0.280	0.926
		PT	0.221	0.960
		HA	0.253	0.944
	Monthly	ePM	0.232	0.946
		PT	0.171	0.977
		HA	0.195	0.966
Panhandle	Daily	ePM	0.704	0.7553
		PT	0.631	0.791
		HA	0.671	0.765
	10-d	ePM	0.272	0.955
		PT	0.211	0.968
		HA	0.216	0.967
	Monthly	ePM	0.238	0.967
		PT	0.169	0.980
		HA	0.171	0.979

the proximity of weather stations to the ocean, resulting in different patterns of air temperature, relative humidity and wind speed. In the North–Panhandle region, estimated values of R^2 for daily, 10-d, and monthly time periods were of 0.75, 0.95, and 0.97, respectively. It demonstrates the increased accuracy of ETo estimations for longer time periods. Sentelhas et al. (2010), studying the best method to estimate ETo in southern Ontario, Canada, found R^2 ranging from 0.20 to 0.47 and an average RMSE of 1.21 $mm\cdot day^{-1}$ (0.047 inches/day).

Results for the Priestley and Taylor method demonstrated that the calibration for cold season months resulted in better ETo estimations than during warm season months, when it generally overestimated ETo. In general this method presented good correlation with FAO Penman-Monteith (Table 2). For all regions of Florida and time-periods, estimated RMSE and ME using the Priestley and Taylor equation were the lowest and R^2 was the highest among the methodologies studied (Tables 3 and 4). In the Central and North–Panhandle regions, estimated R^2 was higher than 0.95 for 10-d and monthly time periods. In the Southern region, R^2 was equal to 0.82 and 0.90 and RMSE equal to 0.40 mm (0.016 inches) and 0.28 mm (0.011 inches) for 10-d and monthly time periods, respectively. Lu et al. (2005), studying six methods to estimate ETo in the Southeast, found a good relationship between the empirical methods evaluated in their study with Priestley and Taylor showing the best correlation with other methods. Suleiman and Hoogenboon (2007) reported that Priestley and Taylor underestimated ETo during winter months and overestimated during the summer months in the coastal and mountainous areas of the state of Georgia.

The Hargreaves method overestimated ETo, especially in the southern region, where the overestimation was more pronounced than in the Central and North–Panhandle regions. The Hargreaves equation was developed for semi-arid conditions in California and tends to overestimate ETo in humid climates (Sentelhas et al., 2010; Trajkovic and Kolakovic, 2009). Results obtained using the Hargreaves equation presented poor correlation and high values of ME and RMSE for the southern region (Tables 3 and 4). Its performance improved for longer time periods, showing good correlation with ETo estimated by FAO Penman-Monteith in the case of monthly time periods ($R^2 = 0.810$). In the Central and North–Panhandle regions this method presented improved correlation with FAO Penman-Monteith, only slightly below correlations obtained by using the Priestley and Taylor equation for daily time periods.

The results of this study were comparable to the ones obtained by Turco et al. (2005) comparing empiric methods to FAO Penman-Monteith. They concluded that the Hargreaves equation overestimated FAO Penman-Monteith but presented good correlation to the standard. Trajkovic (2007) with a similar study under humid conditions found R^2 of 0.97 between FAO Penman-Monteith and Hargreaves and high RMSE. Lu et al. (2005) found good correlation between different methods to estimate ETo in the southeastern USA although Hargreaves tended to overestimate ETo. Bautista et al. (2009) found high correlation between ETo estimated by the FAO Penman-Monteith and the Hargreaves equation in semi-arid and tropical sub-humid conditions. Under tropical sub-humid conditions Hargreaves tended to underestimate ETo during cold months (December to May) and overestimate during warm months (June to November).

Overall ETo estimated by the Priestley and Taylor equation had the highest correlation and lower RMSE when compared to ETo estimated by the FAO Penman-Monteith equation. However, in the case of 10-d and monthly time periods, results obtained using the Hargreaves equation were similar to the ones obtained using the Priestley and Taylor equation. Additionally, the fact that the calibration of the Hargreaves methodology requires only one empirical coefficient as opposed to Priestley and Taylor that requires four empirical coefficients provides an additional incentive to its use for estimating long-term 10-d and monthly ETo time series when only temperature and rainfall records were available.

In general it can be concluded that empirical equations can be successfully used to estimate ETo when only temperature data were available. This methodology can be used in climatological studies for irrigation planning and to better understand the effects of seasonal climate variability on crop water requirements in the state of Florida.

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