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Koffi Djaman
Africa Rice Center, kdjaman@nmsu.edu

Hossein Tabari
KU Leuven

Alpha B. Balde
Africa Rice Center

Lamine Diop
Universite Gaston Berger

Koichi Futakuchi
Africa Rice Center

See next page for additional authors

Authors
Koffi Djaman, Hossein Tabari, Alpha B. Balde, Lamine Diop, Koichi Futakuchi, and Suat Irmak

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Analyses, calibration and validation of evapotranspiration models to predict grass-reference evapotranspiration in the Senegal river delta

Koffi Djaman[a,*], Hossein Tabari[b], Alpha B. Balde[a], Lamine Diop[c], Koichi Futakuchi[d], Suat Irmak[e]

[a] Africa Rice Center (AfricaRice) Sahel Regional Station, B.P. 96, St Louis, Senegal
[b] Hydraulics Division, Department of Civil Engineering, KU, Leuven, Belgium
[c] UFR S2ATA Sciences Agronomique, d'Aquaculture et des Technologies Alimentaires, Université Gaston Berger, Saint-Louis, Senegal
[d] Africa Rice Center (AfricaRice)-Cotonou, 01 B.P.2031, Cotonou, Benin
[e] Department of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE 68583-0726, USA

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ABSTRACT

Study region: Grass-reference evapotranspiration estimation by the Penman-Monteith method (PM-ETo) requires a number of climate variables which are not always available at all weather stations. Different alternative ETo equations have been developed and their utilization for various local climate conditions requires analyses of their accuracy as compared to the standardized Penman-Monteith method. There is a significant lack of data and information on this topic in the Senegal River Delta (SRD).

Study focus: The objective of this study was to evaluate, calibrate and validate six ETo equations ((Trabert, Mahringer, Penman1948, Albrecht, Valiantzas1 and Valiantzas2) for the SRD. Although all six equations showed good agreement with the PM-ETo ($R^2 > 0.60$) for daily ETo estimates, the Valiantzas2 equation was the best model for the Senegal River Delta and had the lowest root mean squared difference (RMSE) of 0.45 mm/day and the lowest percent error of estimate (PE) about 7.1%.

New hydrological insights for the region: In the case of data limitations, the equations calibrated in this study are recommended for ETo estimation in the Senegal River Delta. The results of this study could be used by agricultural producers, crop consultants, university researchers, policy makers for the agricultural, hydrological, and environmental studies as well as proper allocation and use and forecasting in the SRD where lowland irrigated rice is predominant.

1. Introduction

Water resources for agriculture in the context of climate change are decreasing in time and space in different parts of the world with more emphasis in the arid and semi-arid Sahelian zones. Crop water use should be accurately evaluated to improve water management and increase water use efficiency of food and fiber production. Actual crop evapotranspiration (ETa) should be accurately estimated for better irrigation scheduling to minimize negative effects of over and under-irrigation

* Corresponding author.
E-mail addresses: djamank@yahoo.fr, k.djaman@cgiar.org (K. Djaman).

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on crop productivity and environment. Crop water use is estimated from direct and indirect methods. The maximum precision of ETa could be achieved with lysimeters (Jia et al., 2006; Benli et al., 2006; Miranda et al., 2006; Williams and Ayars 2005; Payero and Irmak 2007; Valipour, 2015), by Bowen Ratio Energy Balance System (Bowen 1926; Irmak and Irmak, 2008; Irmak et al., 2008, 2010, 2013; Irmak, 2010; Kabenge et al., 2013), and eddy covariance technique (Wilson et al., 2001; Baldocchi, 2003; Schume et al., 2005; Kosugi and Katsuyama, 2007; Sun et al., 2008; Novick et al., 2009; Scott, 2010). ETa can also be indirectly estimated by the water balance method in the absence of aforementioned advanced techniques (Xu and Singh, 2002; Azizi-Zohan et al., 2008; Senay et al., 2011; Djaman et al., 2013) and atmometers (ET gauges) (Chen and Robinson 2009; Irmak et al., 2005; Broner and Law, 1991). The two-step method is also used to estimate ETa and it necessitates accurate estimates of reference evapotranspiration (ETo) and locally developed crop coefficients (Kc). Thus, crop water use is estimated by multiplying the reference evapotranspiration by pre-determined crop-specific coefficient, which is dependent on many factors, including irrigation regimes and management (Djaman and Irmak, 2013).

Number of models have been used to estimate reference evapotranspiration and range from direct measurement from a reference crop such as a perennial grass (Doorenbos and Pruitt, 1977; Watson and Burnett, 1995) or computed from weather data using: (a) temperature-based models (Thornthwaite, 1948; Doorenbos and Pruitt 1977), (b) radiation-based models (Doorenbos and Pruitt, 1977; Hargreaves and Samani, 1985), and (c) combination-based energy balance models (FAO-56 PM) (Allen et al., 1998). The ASCE Penman-Monteith method has been adopted and recommended as a standardized method for most accurate reference evapotranspiration estimation (ASCE-EWRI 2005). However, it requires several parameters to estimate reference crop evapotranspiration. In most regions globally, especially in developing countries, since weather data are limited, it is not possible to use the standardized Penman-Monteith equation, which impose challenges to the agricultural professionals, water managers, researchers, and associated personnel as to which method to use in a given local region for reference ET estimations. Several studies have evaluated a number of ETo equations in different parts of the world against the standardized Penman-Monteith method for adaptability and accuracy of ETo estimates in comparison to the standardized Penman–Monteith equation (Yoder et al., 2005; Pedro et al., 2008; Trajkovic and Kolakovic, 2009; Tabari, 2010; Xystrakis and Matzarakis, 2011; Tabari and Hosseinzadeh-Talee, 2011; Ravazzani et al., 2012; Rojas and Sheffield 2013; Jia et al., 2013; Valiantzas, 2013; Kisi, 2013; Samaras Dimitrios et al., 2014; Bogawski and Bednorz, 2014; Shiri et al., 2014; Valipour, 2015; Djaman et al., 2015, 2016). In a recent comprehensive study in the Senegal River Valley, Djaman et al. (2015) reported that the Valiantzas, Trabert, Romanenko, Schendel and Mahringer equations are the most promising equations that could be used for reference evapotranspiration estimation. They showed that the Hargreaves, modified Hargreaves, Ravazzani and Tralkovic equations systematically overestimated ETo and the Makkink–Hansen, Oudin and Turc equations systematically underestimated ETo.

In the Sahel environment like the Senegal River Valley (SRV) and Senegal River Delta (SRD) where annual precipitation is less than 300 mm (Djaman et al., 2015), irrigation water is becoming increasingly scarce (Rijsberman, 2006) and costly. Rice production is the main activity in the Senegal River Valley and Delta with potential rice yields as high as 12 tons ha^{-1} under effective irrigation management (de Vries et al., 2010). Rice production covers approximately 60,000 ha in Mauritania and Senegal and has been playing a vital role in meeting the food demand of the region's population and also has critical economic implications to the area. In the Senegal River Valley, for a long time, water management was not considered as a critical management practice and irrigation schemes have been abandoned after few years of initial cultivation due to buildup of soil salinity in Senegal River Delta and Valley (OMVS-SOGREAH, 1998; Raes et al., 1995). Irrigation requirement is a major contributor to rice production cost, because the cost of pumping irrigation water is high, accounting for about 28% of the operational cost (Comas et al., 2012). Therefore, accurate determination of irrigation water requirement is critical for economics of rice production and environmental issues in the Senegal River Delta. While different equations have been calibrated for different regions and sub-regions under different climatic conditions including in Iran (Tabari and Hosseinzadeh-Talaee 2011; Tabari et al., 2014; Heydari and Heydari, 2014; Valipour 2015), in China (Zhai et al., 2010; Gao et al., 2015), in Poland (Bogawski and Bednorz, 2014), in Sub-Humid Region of Brazil (de Sousa Lima et al., 2013), in Florida (USA) (Thepadia and Martinez, 2012), in Southeast Australia (Azhar and Perera, 2011), and in Canada (Singh and Xu, 1997) extremely limited data and information existed in terms of proper ETo estimation model to be applied in this extremely climate data-limiting agricultural area.

Therefore, as a next step of the study conducted by Djaman et al. (2015), this study aims to calibrate and validate six ETo models (Trabert, Mahringer, Penman, (1948), Albrecht, Valiantzas 1 and Valiantzas 2) using long-term climatic data for accurate and reliable estimation of reference evapotranspiration in the Senegal River Delta.

2. Materials and methods

2.1. Site description and datasets

The Senegal River Basin is located in West Africa and covers a total area of 340,000 km^2 in North Senegal, West Mali, South Mauritania and the high plateaus of the Fouta Djallon massif in Guinea (Gaye et al., 2013). The basin is drained by the 1800 km long Senegal River, the second longest river of West Africa, and its main tributaries of the Bafing, Bakoye and Faleme Rivers, all three of which have their source in the Fouta Djallon Mountains in Guinea. The basin has mostly a sub-Saharan desert climate. Geographically the basin has three distinct parts including the mountainous upper basin, the valley and the delta which is a source of biological diversity and wetlands.

Table 1
Climatic characteristics at Saint-Louis and Ndiaye during the study period.

Locations		u2(m/s)	Tmax (°C)	Tmin (°C)	Tmean ((°C)	RHmax (%)	RHmin (%)	SR (W/m^2)
Sant-Louis (1960–2012)	Min	0.0	18.8	17.3	6.6	13	1	7.0
	Max	7.3	46.5	36.2	33.4	100	94	31.8
	Mean	2.5	31.9	26.2	20.5	86	45	20.2
	St Dev	0.9	3.7	2.9	3.9	17	20	4.6
Ndiaye (2013–2015)	Min	0.7	23.1	17.5	8.5	27	4	4.3
	Max	5.2	43.2	34.1	27.8	104	89	27.3
	Mean	2.4	33.5	26.7	19.8	85	31	20.6
	St Dev	0.7	3.7	3.2	4.0	13	19	4.1

In this study, climatic variables, including maximum air temperature (Tmax), minimum air temperature (Tmin), maximum relative humidity (RHmax), minimum relative humidity (RHmin), wind speed (u_2), and solar radiation were collected from the Saint-Louis automated weather station for the 1960–2012 period and Ndiaye automated weather station for the period of February 2013 to April 2015. Saint Louis station (16° 02′ N, 16° 30′ W) is located near the mouth of the Senegal River and Ndiaye station (16° 11′ N, 16° 15′ W) in the Delta, 35 km inland from Saint-Louis. The experimental sites are located in the Senegal River Delta. Annual average, maximum and minimum weather data at the two sites are summarized in Table 1.

2.2. Reference evapotranspiration models

Six grass-reference evapotranspiration equations (Penman 1948, Albrecht, Valiantzas 1 and Valiantzas 2) in addition to the Penman–Monteith equation were selected based on their performance from the previous study by Djaman et al. (2015) in the Senegal River Valley and Delta.

Penman–Monteith (ASCE-EWRI, 2005)

Daily grass-reference ET (ETo) was computed using the standardized ASCE form of the Penman-Monteith (ASCE-EWRI PM) equation (ASCE-EWRI, 2005). The Penman-Monteith reference evapotranspiration equation with fixed stomatal resistance values for grass surface is:

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma Cnu2/(T + 273))(es - ea)}{\Delta + \gamma(1 + Cdu2)} \tag{1}$$

where: ETo is the reference evapotranspiration (mm/day), Δ is the slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1}), Rn = net radiation at the crop surface (MJ m^{-2} d^{-1}), G = soil heat flux density at the soil surface (MJ m^{-2} d^{-1}), T = mean daily air temperature at 1.5–2.5 m height (°C), u_2 = mean daily wind speed at 2 m height (m s^{-1}), es = the saturation vapor pressure (kPa), ea = the actual vapor pressure (kPa), es-ea = vapor pressure deficit (kPa), γ = psychrometric constant (kPa °C^{-1}), Cn = 900 °C mm s^3 Mg^{-1} d^{-1} for grass, Cd = 0.34 s m^{-1} for grass, γ is the psychrometric constant (kPa C^{-1}), λ is the latent heat of vaporization, 2.45 (MJ kg^{-1}). All parameters necessary for computing ETo were computed according the procedure developed in FAO-56 by Allen et al. (1998).

Trabert (1896): Tabert method

$$ETo = 0.408 * 0.3075 * \sqrt{u2} * (es - ea) \tag{2}$$

Mahringer (1970): Mahringer method

$$ETo = 0.15072 * \sqrt{3.6u2} * (es - ea) \tag{3}$$

Penman (1948): Penman, 1968 method

$$ETo = 0.35 * (1 + 0, 24 * u2) * (es - ea) \tag{4}$$

Albrecht (1950): Albrecht method

$$ETo = (0.1005 + 0.297 * u2) * (es - ea) \tag{5}$$

Valiantzas (2013) Equation 1: Valiantzas 1 method

$$\begin{aligned} ETo = {} & 0.00668 * Ra * ((Tmean + 9.5) * (Tmax - Tmin))^{0.5} - 0.0696 * \\ & (Tmax - Tmin) - 0.024 * (Tmean + 20) * (1 - RH)/100\big) - 0.00455 * Ra * \\ & (Tmax - Tdew)\hat{}(0.5) + 0.0984 * (Tmean + 17) * \\ & \big(1.03 + 0.00055 * (Tmax - Tmin)^2 - RH/100\big) \end{aligned} \tag{6}$$

where, the dew point temperature was estimated using the procedures outlined by (Allen et al., 1998):

$$Tdew = \frac{116.91 + 237.3\ln(ea)}{16.78 - \ln(ea)} \tag{7}$$

Valiantzas (2013) Equation2: valiantzas 2 method

$$ETo = 0.051 * (1 - \alpha) * Rs * (Tmean + 9.5)^{0.5} - 2.4 * \left(\frac{SR}{Ra}\right)^2$$
$$+0.048 * (Tmean + 20) * \left(1 - RH/100\right) * (0.5 + 0.536 * u2) + 0.00012 * z \quad (8)$$

with α = 0.25,

$$\mathrm{SR} = \mathrm{solarradiation}(\mathrm{MJ\,m^{-2}d^{-1}}).$$

$$\mathrm{Ra} = \mathrm{extraterrestrialradiation}(\mathrm{MJ\,m^{-2}d^{-1}}).$$

$$\mathrm{z} = \mathrm{stationelevation}(\mathrm{m})$$

$$\mathrm{Tdew} = \mathrm{dewpointtemperature}(^\circ\mathrm{C})$$

where, all other units and variables used in the above equations are the same as those used in the Penman-Monteith equation (Eq. (1)).

2.3. Calibration of the ETo equations

To calibrate the ETo equations, a linear regression relationship between daily PM-ETo and daily ETo estimates by each equation was determined and the calibration coefficients were then obtained by multiplying the slope of a regression line between ETo estimate by an ETo equation and the PM-ETo by its inverse to bring the slope of the regression line to the unity. And, the opposite value of the intercept was added to the new regression relationship to minimize the new intercept (as close to zero as possible). The dependent variable was ETo estimated by the PM-ETo and the independent variable was the ETo estimations by each of the six methods studied. Therefore, the calibration processes tend to have a new regression relationship with a slope as unity and intercept as zero. The ETo equations were calibrated and validated for the Saint-Louis weather station. The data from 1960 to 1994 were used for the equation calibration of the equations and data from 1995 to 2012 were used for the validation. This partitioning is due to the need of more data for training the equations as suggested by Xu and Sing (2000) and Valipour (2015). The data for Ndiaye station was used to evaluate (validate) the calibrated equations.

2.4. Evaluation criteria

Pair-wise comparisons were made using graphics and linear regression. For further comparison, the root mean squared error (RMSE), mean bias error (MAE), and percent error of estimate (PE) were used to evaluate the four ETo models in terms of their calibration and performance during the validation:

$$RMSE = \sqrt{\sum_{k=0}^{n} \frac{(\mathrm{Pi} - \mathrm{Oi})^2}{n}} \quad (8)$$

$$MBE = n^{-1} \sum_{1}^{n} (Pi - Oi) \quad (9)$$

$$PE = \left| \frac{Pav - Oav}{Oav} \right| * 100\% \quad (10)$$

where Pi is ETo estimated by the selected euqations, Oi is the PM-ETo, n is the number of the dataset

2.5. Sensitivity coefficients

Sensitivity coefficients of the Penman Monteith daily reference evapotranspiration (PM-ETo) to the daily climatic variables (u2, Tmax, Tmin, RHmax, RHmin, solar radiation (SR), and vapor pressure deficit (VPD), was estimated using a factor perturbation simulation approach (Irmak et al., 2006) for the period of 1960–2012. Sensitivity coefficient for each climatic variable was derived as a ratio of the amount of increase or decrease in ETo by the unit of increase or decrease in each climatic variable on a daily basis as (Irmak et al., 2006):

$$SC = \frac{\Delta ETo}{\Delta CV} \quad (11)$$

where, SC is the sensitivity coefficient, ΔETo is change in ETo with respect to change in climatic variable, and ΔCV is the change in climatic variable (1% change for u2, Tmax, Tmin, RHmax, RHmin, SR, and VPD). The average sensitivity coefficient

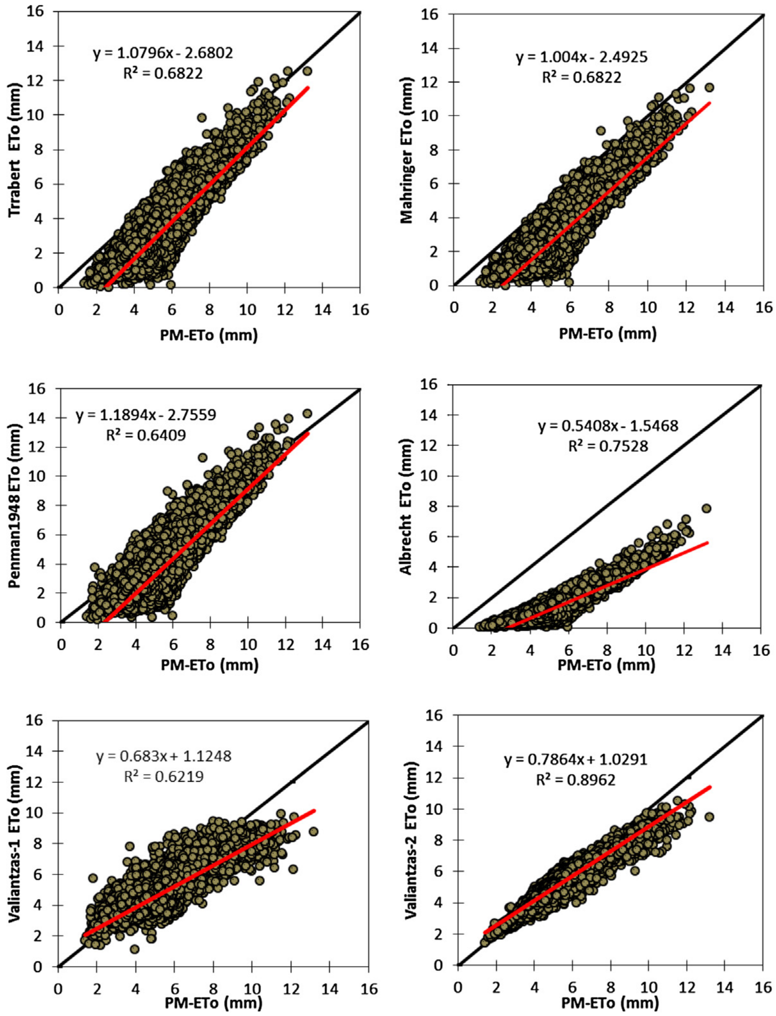

Fig. 1. Relationship between the daily ETo estimates of each method versus the PM-ETo at Saint-Louis for the 1960–2012 period.

for the study period was calculated as daily mean values for each variable. To compute the sensitivity coefficient for each climatic variable, the percent of increase or decrease in ETo was determined as the difference between the calculated base ETo and the new ETo values reported to the base ETo value computed for each day. The difference between these two values was divided by 5, 10, 15, 20 and 25% separately for each day. This method was recurrent for the state when the meteorological variables were decreased by 5, 10, 15, 20 and 25% of the actual values. A linear regression between changes in ETo with respect to changes in each variable was evaluated. Only one climatic variable was changed at the time while others remained fixed for mono-criterion sensitivity.

3. Results and discussions

3.1. Evaluation of reference evapotranspiration equations for the 1960–2012 period

The comparison of the selected reference evapotranspiration equations to the Penman-Monteith equation is presented in Fig. 1. The ETo estimates by all six equations had high correlation with the PM-ETo with high coefficient of determination R^2, ranging from 0.62 to 0.90. The best fit of a model is measured by the linear regression line slope close to unity and the intercept to zero. The slopes of the regression lines with comparison to the PM-ETo were 1.08, 1.00, 1.19, 0.55, 0.68, and 0.79 for the Trabert, Mahringer, Penman, 1948, Albrecht, Valiantzas 1 and Valiantzas 2 equations, respectively. The intercept values were −2.68, −2.49, −2.76, −1.55, 1.12, and 1.03 for the same equations, respectively. Based on the two parameters, the Valiantzas 2 equation is the most suitable ETo estimation (besides the Penman-Monteith equation) in the Senegal River Delta. The statistical analysis showed that all the selected equations underestimated ETo with RMSE ranging from 0.47 to 4.04 mm/day and the MBE ranging from −3.97 to −0.1 mm/day (Table 2). The Albrecht equation had the highest RMSE of

Table 2
Statistical performance of the evaluation of the ETo equations versus the PM-ETo model for estimating daily ETo during the study period (1960–2012) at Saint-Louis.

ETo equation	R^2	RMSE (mm/day)	MBE (mm/day)	PE (%)
Trabert	0.68	2.47	−2.26	45.6
Mahringer	0.68	2.64	−2.47	49.4
Penman 1948	0.64	2.14	−1.76	37.8
Albrecht	0.75	4.04	−3.97	76.8
Valiantzas1	0.62	1.00	−0.55	15.8
Valiantzas2	0.90	0.47	−0.10	5.9

Table 3
Statistical performance of the calibration of the ETo equations versus the PM-ETo model for estimating daily ETo during the 1960–1994 period.

ETo equation	R^2	RMSE (mm/day)	MBE(mm/day)	PE(%)
Trabert	0.69	0.92	0.00	15.7
Mahringer	0.69	0.92	0.00	15.7
Penman 1948	0.64	1.01	−0.01	17.0
Albrecht	0.77	0.77	0.05	13.0
Valiantzas1	0.64	1.06	0.07	16.7
Valiantzas2	0.90	0.45	−0.05	7.1

4.04 mm/day and the lowest MBE of −3.97 mm/day and a PE of 77%, while the Valiantzas 2 showed the lowest RMSE of 0.47 mm/day and PE of 6% (Table 2). Generally, the Valiantzas 1 and 2 were the best two equations for ETo estimation at Saint-Louis. These results are similar to the results of Djaman et al. (2015) who reported the Valiantzas equations as the most promising ones among sixteen ETo equations they evaluated in the Senegal River Valley and Delta using about only one year climate data at two weather stations at Ndiaye and Fanaye. Similar results were reported by Valipour (2015) who found that the most precise method was the Valiantzas 1 among limited data methods, and the Valiantzas 2 was the best method in Iran if recommended dataset is available.

3.2. Calibration and validation of the reference evapotranspiration equations

The model calibration markedly improved the performance of all equations. Following the calibration procedure, the regression slopes were 1.0733, 0.9982. 1.01894. 0.5408, 0.683 and 0.7865 for the Trabert, Mahringer, Penman, (1948), Albrecht, Valiantzas 1, and Valiantzas 2 equations, respectively and the opposite of the intercepts were 2.4772, 2.4771, 2.3171, 2.9191, −1.5036, and −1.3833 for the respective ETo equations. The regression lines between the ETo estimated by the calibrated equations and the PM-ETo (Fig. 2) had slopes close to unity, the intercepts were minimized (close to zero) with high R^2 values that ranged from 0.63 to 0.90 (Table 3). There was considerable reduction in RMSE for the Trabert, Mahringer, Penman, (1948), and Albrecht equations from 2.47, 2.64, 2.14 and 4.04 mm/day, respectively, to 0.92, 0.92, 0.64 and 0.77 mm/day, respectively. Model calibration reduced the RMSE of these equations by 66, 68, 55 and 83%, respectively. In contrast, there was no improvement in RMSE for both Valiantzas equations. The MBE was greatly reduced from negative 2.24, 2.47, 1.76, 3.97 0.55 and 0.1 mm/day to 0.00, 0.00, −0.01, 0.05, 0.07 and −0.05 mm/day for the Trabert, Mahringer, Penman, (1948), Albrecht, Valiantzas 1 and Valiantzas 2, respectively, representing an average of 100% reduction of the MBE for all equation except the Valiantzas 2 equation that had 52% reduction in MBE as compared to the original equation (Tables 2 and 3). Considerable reduction was observed in PE from 45.6, 49.4, 37.8 and 77.8% to 15.7, 15.7, 17 and 13% for the Trabert, Mahringer, Penman, (1948), and Albrecht equations, respectively. There was no improvement in the PE of the calibrated Valiantzas equations. Valipour (2015) reported improvement of the calibrated Trabert and Mahringer equations in Iran with MBE as low as 0.02 mm/day. He indicated that the Trabert model does not need to be calibrated for best performance in Iran (Valipour, 2015). Ahooghalandari et al. (2016) reported that whenever Valiantzas' equations were revealed suitable for ETo estimation with comparison to PM-ETo in the Pilbara region of Western Australia, their performance was improved through calibration. Best performance of the calibrated Valiantzas equation using limited data was shown in the Guizhou Province, China (Gao et al., 2015) similar to the results of the performance of the calibrated Valiantzas equation at Adana Station in Turkey (Kisi and Zounemat-Kermani, 2014). The calibrated Trabert, Albrecht, and the Mahringer equations showed different performance relative to the PM-ETo depending of the region with better performance at Ndiaye 35 km inland that Saint-Louis at the coast. The dependence of mass transfer equation on the vapor pressure deficit Djaman et al. (2015) reported better performance of the Trabert and Mahringer equations in inland area than at coastal area in the Senegal River Valley. The climate variables in coastal area like Saint-Louis located near the mouth of the Senegal River, might be influenced by water bodies as indicated by Hargreaves (1994). These results contradicted the findings of Valipour (2015) reporting better performance of the calibrated mass transfer ETo equation near the Caspian Sea and near the Persian Gulf in Iran with RH higher than 65% than other area in Iran.

The validation of the six ETo equation for the 1995–2012 period is presented in Fig. 3. The statistical analysis showed strong correlations of the calibrated equations to the PM estimates (Table 4). Similar RMSE, MBE, and PE were obtained

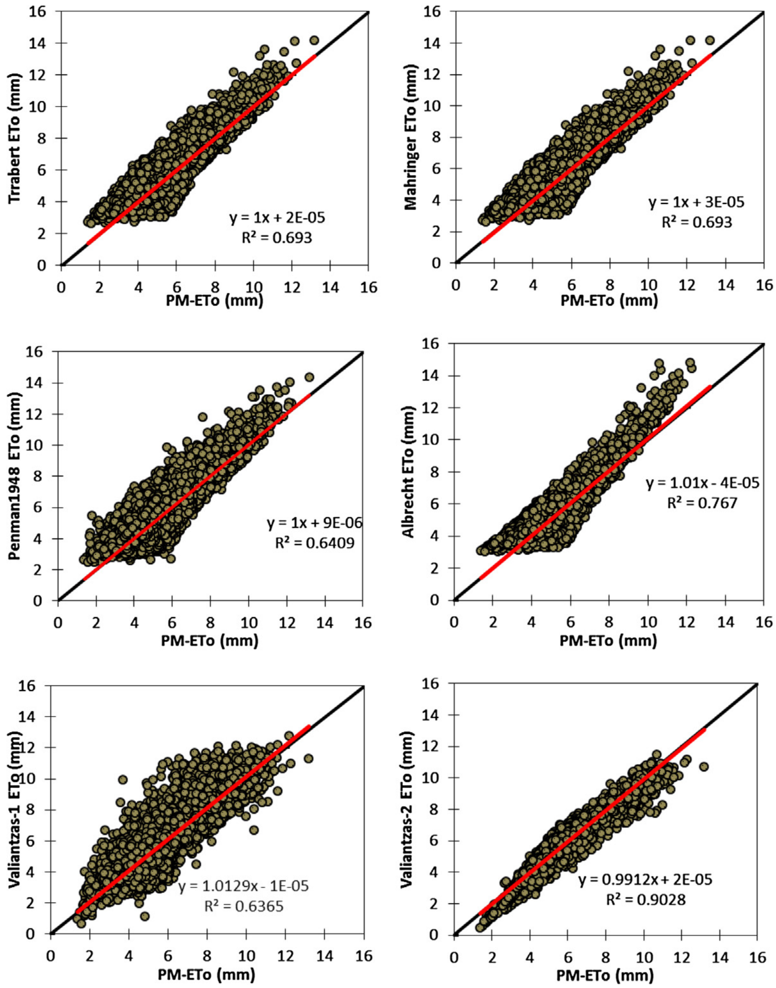

Fig. 2. Relationship between the calibrated daily ETo estimates of each method versus the PM-ETo at Saint-Louis for the 1960–1994 period.

Table 4
Statistical performance of the validation of the ETo equations versus the PM model for estimating daily ETo during the 1995–2012 period.

ETo equation	R^2	RMSE (mm/day)	MBE(mm/day)	PE(%)
Trabert	0.66	0.93	0.03	15.9
Mahringer	0.66	0.93	0.03	15.9
Penman 1948	0.62	1.01	0.02	17.1
Albrecht	0.72	0.78	0.07	13.3
Valiantzas1	0.60	1.06	0.29	16.8
Valiantzas2	0.88	0.49	−0.13	7.8

from the calibration and validation with only slight decrease in R^2. The magnitude RMSE, MBE, and PE is acceptable for ETo estimation with any of the six ETo equation at Saint-Louis. However, the calibrated Valiantzas 2 equation with the highest R^2, and the lowest RMSE (<0.5 mm/day), lowest PE (<8%) should be the first option for estimating ETo in the Senegal River Delta. Because the methods' performances can yield different results for different location, we assessed their performances for another station. The fitness of the calibrated models was confirmed using climatic data of the Ndiaye weather station located 35 km inland within the Senegal River Delta (Fig. 4, Table 5). The statistical indices used to compare the different equations relative to the PM-ETo model revealed small difference between the Ndiaye station and the calibration station at Saint-Louis. The negligible difference confirms that the calibration of the six ETo equations in the Senegal River Delta was robust and can be transferable to other locations in the study region that different equations obtained for Saint-Louis can be applied to other areas of the Senegal River Delta (Fig. 5).

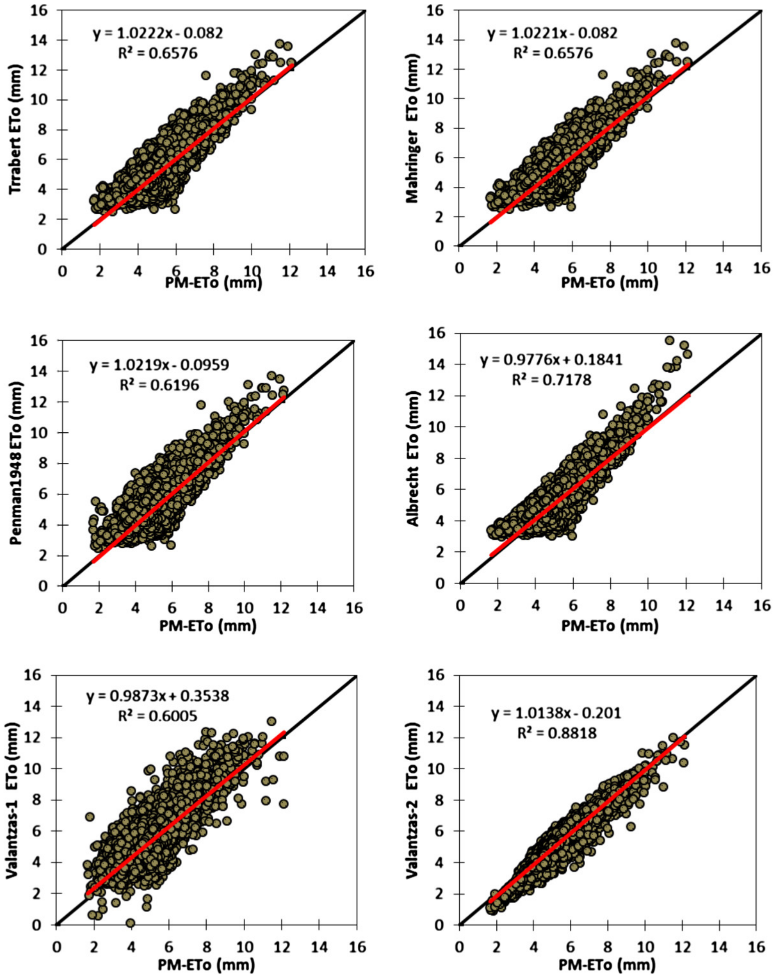

Fig. 3. Relationship between the calibrated daily ETo estimates of each method versus the PM-ETo at Saint-Louis for the 1995–2012 period.

Table 5
Statistical performance of the calibrated ETo equations versus the PM model at the Ndiaye weather station for the period of February 2013 to April 2015.

ETo equation	R^2	RMSE (mm/day)	MBE (mm/day)	PE (%)
Trabert	0.73	0.85	0.22	13.8
Mahringer	0.73	0.85	0.22	13.8
Penman 1948	0.66	0.96	0.28	15.4
Albrecht	0.80	0.69	0.08	11.2
Valiantzas1	0.70	1.08	0.56	15.0
Valiantzas2	0.93	0.52	−0.29	5.6

3.3. Sensitivity of reference evapotranspiration to climatic variables

The sensitivity analysis performed at Saint-Louis station for the period of 1969–2012, showed that maximum temperature had the most influence on daily ETo followed by solar radiation, vapor pressure deficit, maximum relative humidity, minimum relative humidity, wind speed, and minimum air temperature (Fig. 6). Daily average sensitivity coefficients are summarized in Table 6. Maximum air temperature, solar radiation Vapor pressure deficit, and relative humidity are the main variables that affected ETo. Change in daily climatic variables had strong linear relationship with the change in daily ETo with very high coefficients of determination that varied from 0.988 to 1.00 (Table 6). The results of this study are in agreement with Irmak et al. (2006) who indicated that the change in ETo was linearly related to change in climate variables (with $R^2 \geq 0.96$ in most cases), with the exception of Tmin, at all sites. There is also in agreement with Irmak et al. (2006) who reported that ETo was most sensitive to VPD at all locations under their study in the United States, while ETo was most sensitive to u2 in semiarid regions and to SR at humid locations. They indicated that ETo was not sensitive to Tmin at any of the locations. In contrast, Zhao et al. (2014) reported that the sensitivity order of climatic variables to ETo from strong

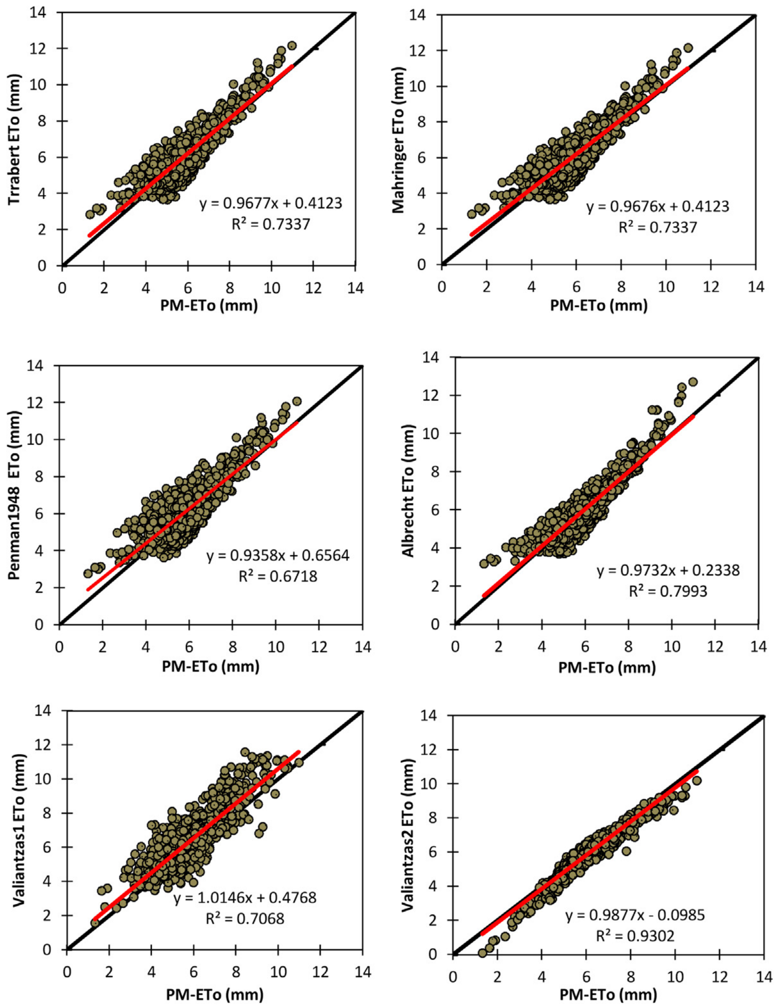

Fig. 4. Evaluation of the calibrated ETo models with comparison to the Penman–Monteith ETo at Ndiaye for the period of February 2013 to April 2015.

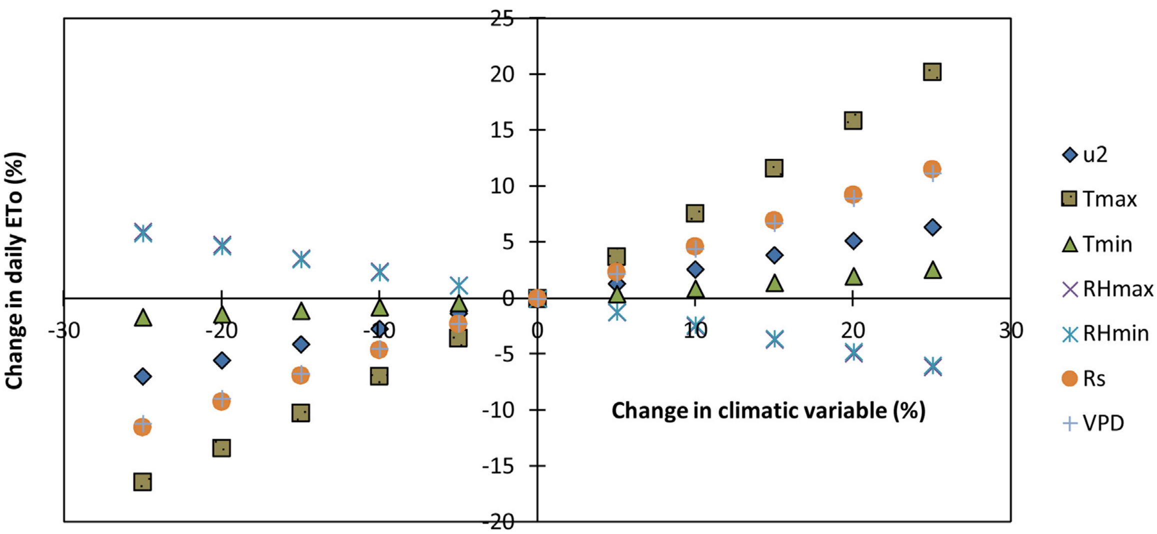

Fig. 5. Changes in daily PM-ETo values with respect to the change in climatic variables at Saint-Louis for the 1960–2012 period.

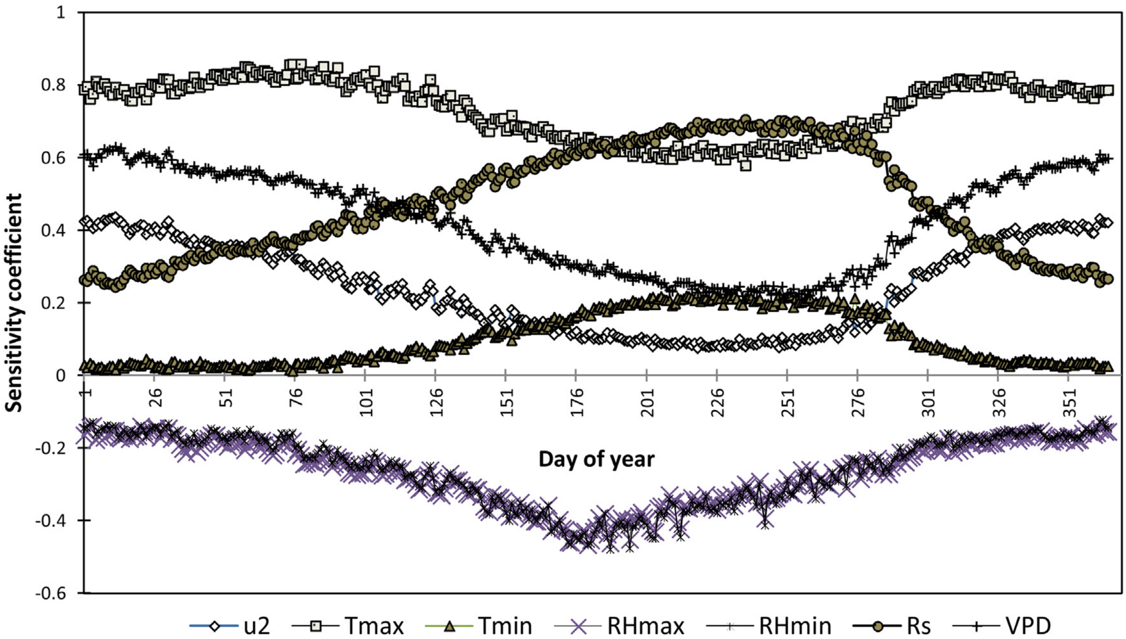

Fig. 6. Daily 1960–2012 average changes in PM-ETo sensitivity coefficient for wind speed (u2), maximum air temperature (Tmax), minimum air temperature (Tmin), maximum relative humidity (RHmax), minimum relative humidity (RHmin), and solar radiation (SR), and vapor pressure deficit (VPD) at Saint-Louis.

Table 6
Regression coefficients between changes in PM-ETo with respect to changes in different climate variables at Saint-Louis for the 1969–2012 period.

Variable	Slope	Intercept	R^2
u2	0.2665	−0.123	0.9993
Tmax	0.7315	0.7692	0.9966
Tmin	0.0846	0.1881	0.9848
RHmax	−0.2425	−0.0222	1
RHmin	−0.2356	−0.0196	1
SR	0.4613	1E-12	1
VPD	0.4475	8E-13	1

Trabert, Mahringer, Penman1948.

to weak in the Hai River Basin is located in north China is: relative humidity, air temperature, solar radiation and wind speed, respectively. In South Korea, ETo was mostly affected by the relative humidity (Aydin et al., 2015) while in Spain sensitivity analysis indicated that relative humidity, wind speed, and maximum temperature had stronger effects on ETo than sunshine duration and minimum temperature (Vicente-Serrano et al., 2014). Generally, changes in wind speed had the greatest contribution to changes in evapotranspiration in the warm semi-arid climate, while the change of air temperature and sunshine hours had less effect on evapotranspiration (Tabari and Hosseinzadeh-Talaee, 2014). Irmak et al. (2006) also found that ETo was more sensitive to wind speed than air temperature in the semi-arid climate of Texas, USA. The greater impact of wind on evapotranspiration can be explained by the lower amount of water vapor carried by the wind in drier climates as compared to the higher humidity of the wind Flow in humid climates (Irmak et al., 2003; Estevez et al., 2009; Tabari et al., 2014). Goyal (2004) reported that ETo was more sensitive to vapor pressure, wind speed, and solar radiation in arid regions of Rajasthan, India. Gong et al. (2006) found that relative humidity was the most sensitive variable, followed by solar radiation, air temperature and wind speed in Yangtze River basin in China. Irmak et al. (2006) pointed out that wind speed affects ETo rate to a far lesser extent in humid climates than under arid conditions, where small variations in wind speed may result in larger variations in ETo rate.

The trend in average daily sensitivity coefficients of ETo relative to changes in wind speed, Tmax, Tmin, RHmax, RHmin, SR and VPD are presented in Fig. 6. Change in Tmax influenced the most daily ETo and the sensitivity coefficient relative to Tmax, which varied from 0.60 to 0.82 and with an average of 0.74; decreased from January to mid-August and increased thereafter toward the end of the year (Fig. 6). Solar radiation was the second climatic variable that influenced the most the daily ETo with the sensitivity coefficient that increased from 0.27 in December to 0.71 in August and decreased up to the end of December. It was stable and high during the period of July-September (Fig. 6). The influence of change in Tmin was minimal during the period of December to April corresponding to the cold period on the site with the lowest temperature values of the year. RHmax and RHmin had similar impact of the daily ETo. Both variables negatively affect the daily ETo with the daily sensitivity coefficient decreasing from −0.14 in January to −0.48 in July, and increasing thereafter to the maximum value of −0.14 in December. The influence of variation in daily wind speed and the VPD on the variation in the daily ETo had similar trend however, the VPD has stronger effect that the wind speed (Fig. 6). Overall, the influence of the change in all climatic variables is more pronounced during the period of Mai-October. The long term (1960–2012) average daily sensitivity coefficients of u2, Tmax, Tmin, RHmax, RHmin, Rs, and VPD were 0.243, 0.735, 0.101, −0.263, −0.259, 0.481, and 0.424, respectively. These results are in agreement with Tian et al. (2014) who reported that Tmax and Rs was the variables which had the greatest influence on daily ETo over the states of Alabama, Georgia, and Florida in the United States. Irmak et al. (2006) indicated that Tmax influenced the most daily ETo at Scottsbluff and Bushland under semiarid climate during summer time. Seyyed-Hasan et al. (2013) also reported the greatest sensitivity of ETo to maximum temperature in north-western of Iran. In Northwest China, the sensitivity analysis of ETo to climatic variables showed that ETo was influenced the most by the shortwave radiation (Cao et al., 2010). Estévez et al. (2009) showed that ETo was more senility to temperature in stations along the he Guadalquivir Valley in Spain. In contrast Beijing (China) Liu et al. (2014) reported that mean air temperature is the main variable influencing change in ETo, while the maximum temperature had the least influence on the daily ETo. Results of sensitivity analyses make it possible to determine the accuracy required when measuring climatic variables used to estimate ETo (Irmak et al., 2006; Tabari et al., 2014) and can be used to predict evapotranspiration demand in response to expected change in climatic variables due to climate change.

4. Conclusions

Six grass-reference crop evapotranspiration (ETo) equations were evaluated, calibrated and validated, relative to the standardized ASCE Penman-Monteith equation, at two locations in the Senegal River Delta using long-term climatic data. The performance of all equations improved substantially after calibration. The results showed that calibration is an important tool required to enhance the performance and precision of ETo models' estimation and to adapt the best models to the climatic conditions in the Senegal River Delta. Although all the six equations showed good agreement with the PM-ETo, the Valiantzas 2 equation was the best-performing model among the models calibrated in the Senegal River Delta. Taking into account the long-term data used, the methods calibrated in this study are recommended for estimating reference evapotranspiration in the Senegal River Delta. The results of this study could be used by crop growers, crop consultants, university researchers and students, policy and decision makers for the agricultural, hydrological and environmental issues. Accurate estimation of ETo can substantially aid in encountering these issues in the region in terms of better assessment, use and projection of water resources for agricultural production. The results of this study can be used as a reference tool as to which ETo equation to choose based on the availability of the climate data at the weather stations in the Senegal River Delta.

Conflict of interest

There is no conflict of any kind.

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1. Original Submission

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2. Comments to Author

2.1. Reviewer's comments

In this manuscript, authors have compared six different equations for computing short grass reference evapotranstpration (ETo) in the Senegal River Delta and carried out sensitivity analysis of these equations to the climatic variables. The compared equations are Trabert 1896, Mahringer 1970, Penman 1948, Albrecht 1950, Valiantzas 2013_1 and Valiantzas2013_2. The ETo estimated using these six equations were compared with the standardized Penman Monteith method (PM-ETo) for suitability and accuracy of those six ETo methods. Authors found that all the six equations showed good agreement with the PM-ETo, the Valiantzas 2013_2 equation was the best-performing equation among those six equations within the Senegal River Delta. Such studies are really useful particularly in data scarce/limited regions.

Overall, the manuscript is well organized but requires some changes in the experimental design and lots of editorial revision.

The authors should consider these points to further improve the manuscript.

* It is interesting to note that the Valiantzas 2013_2 equation also requires temperature, relative humidity, wind speed, and solar radiation data for computation of ETo. If a user/modeler has all these data then why not just use PM-ETo? Authors should use only equations which are based on limited data input reuirement.
* Authors have calculated sensitivity coefficients by varying the weather parameters by 1, 2, 3, 4, and 5 units. This approach is not logical as different weather parameters are varied in different proportions. For example, if the mean wind speed is 2.5 m/s and it is varied by 5 m/s then there is 200% variation. But for a mean temperature of 30 C, variation by 5 C is only about 17% variation. Then obviously equations will be more sensitive to the wind speed.

To avoid this discrepancy, I suggest to vary all weather parameters in terms of percentage (-25%, −20%, −15%, −10%, −5%, 5%, 10%, 15%, 20%, 25%). This will help in judging the sensitivity of the models to input variable in a better way.

I suspect different authors found different sensitivity of ETo to input variables is also due to the way they varied the input variables with respect to the mean values.

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2214-5818/$ – see front matter
http://dx.doi.org/10.1016/j.ejrh.2016.12.036

* It is unclear in this manuscript what are the calibration coefficients used in the six ETo equations based on model calibration. I assume Equations 2 − 7 are based on the original equations developed by the respective authors. So, on what basis statistical performance improved from Table 2 to Table 3?
* All six equations were calibrated using data from the Saint-Louis site. But the model performance is better at Ndiaye site as compared to Saint-Louis site (Table 4 vs. Table 5). Authors should include some explanation in the manuscript on this aspect.
* Authors should give some more details about sensitivity analysis regarding (a) which equation of ETo was used for sensitivity analysis? (b) Which year/month/day data were used for sensitivity analysis? (c) How many data points were used for sensitivity analysis?
* Proper format for citing references should be used throughout the manuscript. The six selected ETo equations should be listed properly at the first mention within the text in proper format. For example, it is unclear to a reader what is Trabert or Mahringer or Albrecht (Line 103).
* Consistent symbol should be used within the manuscript to represent any short form. For example, Penman-Monteith method is shown as PM-ETo at some places and P-M-ETo at other places.
* There are different fonts/spacing used at different places throughout the manuscript including references, probably due to cut and paste. Authors are advised to make sure that uniform font and line spacing are used in the manuscript.

Specific comments:

Line 213: The intercept value for Valiantzas 2 is not −1.55 as seen in Figure 1.

Line 214: As the Valiantzas_2 equation also requires temperature, relative humidity, wind speed, and solar radiation data for computation of ETo then why not just use standardized Penman − Monteith method for estimating ETo.

Line 230: What is PMF-56 as it is not defined anywhere in the manuscript.

Line 247-250: Which citation is correct Valipour (2015) or Valipour (2014)?

Line 354: Authors should delete this part "primarily for water resources and irrigation management in the Senegal River Delta where lowland irrigated rice is the predominant production and where soil salinization is becoming recurrent threat to food production and the environmental sustainability" in the conclusion section as these aspects are not directly related to the work carried out in this study.

Table 2: Is it for Saint-Louis site or for Ndiaye site? Please make the table heading self-explanatory.

Figure 5: The figure caption is misleading as there is nothing about seasonality of ETo in this figure.

Figure 6: Please include year/years for which these sensitivity coefficients are based upon.

4. First revision

4.1. Recommendation

Minor Revision

5. Comments to the author

It is good to see that the authors have made significant changes in the manuscript based on previous reviewed comments. The revised manuscript is in much better shape as compared to the previous version. However, the manuscript still needs thorough editorial review as there are still some errors which were pointed out for previous version of the manuscript. For example, Valipour (2014) is used in main text (Line 222) but there is no citation for Valipour (2014) in the reference section. On the other hand, Valipour (2014a, b, c) are listed in the references but never referred in the main text. Similarly, PMF-56 is used in Table 2 but never defined what is PMF-56 in the whole manuscript. The Penman-Monteith grass reference ET is referred as PM-ETo in most of the main text but it is shown as P-M-ETo in Figures 1, 2, 3, 4. Authors should also check Figure 5 to make sure that sensitivity of ETo to solar radiation (RS) is same as sensitivity to VPD (or just the plotting error).

Ramesh K. Singh
USGS EROS, 47914 252nd Street, Sioux Falls, SD 57198, United States
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