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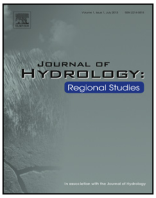

Short Communication

Evaluation of sixteen reference evapotranspiration methods under sahelian conditions in the Senegal River Valley

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ABSTRACT

Study region: Reference evapotranspiration (ETo) plays a key role in irrigation systems design, water management under irrigated and rainfed production. Under the sahelian conditions in the Senegal River Valley that receives less than 300 mm annual rainfall, rice crop water use should be estimated for the sustainability of the resource.

Study focus: However the Penman–Monteith (PM) equation is revealed the most accurate one; it necessitates several climatic parameters that are not always available mostly in the developing countries. The objective of this study was to evaluate the performance of 16 ETo equations against the ASCE-PM equation under the sahelian conditions at Ndiaye and Fanaye (Senegal) for alternate equation for ETo estimation with less climatic parameters. The results showed that the Hargreaves, modified Hargreaves, Ravazzani and Tralkovic equations systematically overestimated ETo with the highest percentage error of estimate (PE). In contrast, Makkink–Hansen, Oudin and Turc equations systematically underestimated ETo. Temperature based equations of Romenenko and Schendel performed relatively better at Fanaye with 5.5% and 9.6% PE, fitting slopes of 0.92 and 1.05, and mean ratio (MR) of 1.00 and 1.14, respectively. Mass transfer equations of Trabert and Mahringer also had good performance compared to the Penman–Monteith equation.

New hydrological insights for the region: Overall, Valiantzas, Trabert, Romanenko, Schendel and Mahringer equations were the promising equations that could be used for reference evapotranspiration estimation in the Senegal River Valley.

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1. Introduction

Under the sahelian climate conditions, water resources scarcity is the most limiting factor for food and fiber production, with low and erratic rainfall which limits rainfed agricultural productivity and exposes the extensive agricultural production systems to high risk. Irrigation water is becoming increasingly scarce (Rijsberman, 2006) and costly in the Sahel environment similar to the Senegal River Valley (SRV) where the rice potential yields could be as high as 12 tons ha^{-1} under effective irrigation management (de Vries et al., 2010). Annual average precipitation along the Senegal River watershed ranges from 270 to 1475 mm (FAO, 1997) whereas the areas with small precipitation (sahelian conditions) are considerably larger than the one with a high precipitation. Development of irrigation systems with efficient use of water is essential for the sustainability of the crop production system and accurate estimation of crop water use (evapotranspiration) is also a critical component of achieving effective and sustainable irrigation vs. crop production stability.

Evapotranspiration is an important parameter for climatological and hydrological studies, as well as for agricultural water resources management. Crop water use is generally 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). Different reference evapotranspiration methods exist 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 models (Thornthwaite, 1948; Doorenbos and Pruitt, 1977), (b) radiation models (Doorenbos and Pruitt, 1977; Hargreaves and Samani, 1985), and (c) combination models (FAO-56 PM) (Allen et al., 1998). The standardized Penman–Monteith equation had been adopted and recommended for reference evapotranspiration estimation (ASCE-EWRI, 2005). Crop actual evapotranspiration (ETa) can be directly measured with lysimeters (Jia et al., 2006; Benli et al., 2006; Miranda et al., 2006; Williams and Ayars, 2005), by Bowen Ratio Energy Balance System (Bowen, 1926; Irmak and Irmak, 2008; Irmak et al., 2008, 2010, 2013; Kabenge et al., 2013), and eddy covariance technique (Aubinet et al., 2000; Wilson et al., 2001; Baldocchi, 2003; Amayreh and Al-Abed, 2004; 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 gages) (Chen and Robinson, 2009; Irmak et al., 2005; Broner and Law, 1991).

Numerous studies worldwide have shown that the FAO-56 PM model to be the most accurate method under various climatic conditions (Jensen et al., 1990; Allen et al., 1998; Irmak et al., 2003, 2008; Hargreaves and Allen, 2003; ASCE-EWRI, 2005; Jabloun and Sahli, 2008; Trajkovic and Kolakovic, 2009; Martinez and Thepadia, 2010; Xystrakis and Matzarakis, 2011; Azhar and Perera, 2011; Tabari et al., 2011). However, all the weather data needed to solve the PM model are often incomplete and/or not available in many of the developing countries like Senegal. The application of ETo equations that require fewer meteorological parameters is recommended under certain situations where complete weather data are lacking. Trajkovic and Kolakovic, 2009 reported that the pan-based equation can be successful alternative to the FAO-56 Penman–Monteith equation at Novi Sad (Serbia). Martinez and Thepadia (2010) demonstrated that in the absence of regionally-calibrated Turc equation is recommended for estimating reference evapotranspiration using measured maximum and minimum air temperature and estimated radiation in Florida. Irmak et al. (2003) and Yoder et al. (2005) noted that the Turc radiation-based method showed promise in the southeastern United States under data-limited conditions. Jensen et al. (1990) reported that among twenty models, the Turc method is ranked second after the Penman–Monteith equation for monthly ETo estimation. From a cross comparison of 31 reference evapotranspiration methods, Tabari et al. (2011) showed that the five best methods, as compared to the PM model, were the two radiation-based which they had developed, the temperature-based Blaney–Criddle, the Hargreaves-M4, and the Snyder pan evaporation based equations. Previously from an evaluation of four reference evapotranspiration models with the least weather parameters (Makkink, Turc, Priestley–Taylor and Hargreaves) under four climates, Tabari (2010) reported that the Turc method was the best suited model in cold humid and arid climate; and the Hargreaves equation was the most accurate model under humid and semi-arid condition. Xystrakis and Matzarakis (2011) reported that Hansen and Turc equations were the most useful with the least average monthly error during an evaluation of 13 empirical reference evapotranspiration equations in Greece. Hargreaves equation was the best model to estimate ETo in eastern arid and semiarid regions of Iran (Sabziparvar and Tabari, 2010; Tabari, 2010), but it was shown to overestimate ETo under the humid conditions of northeast Louisiana's climate (Rojas and Sheffield, 2013).

In the Senegal River Valley, rainfed agriculture is unfeasible because of high evaporation demand in the rainy season and a low and irregular rainfall (around 300 mm/year). Therefore, agricultural activities are mainly developed under irrigated conditions as the amount of annual rainfall is not adequate to meet seasonal crop water requirements. Significant efforts have been made to increase food production in the SRV since rice crisis in 2008, by increasing total cultivated area under irrigated cropping systems and the development of rice-double cropping system (SAED, 2011). However, for a long time, water management was not considered as a critical management practice and irrigation schemes have been abandoned after few years of cultivation due to buildup of soil salinity in Senegal River Delta and Valley (Raes et al., 1995). In general, under ideal conditions, water supply should follow the demand; but, in the small-scale irrigation schemes, unbalance between supply and demand can result in yield reduction due to water stress (Raes et al., 1994) and increased salinity (OMVS-SOGREAH, 1998). To our knowledge, there are no reports of studies that have evaluated the performance of reference evapotranspiration equations under the Senegal River Valley where irrigated rice production is the major activity of the riverine populations. The objectives of this study were to: (i) compare the performance of ETo estimated by different methods with the ASCE-PM method, and (ii) assess the reliability of ETo models that use the least weather variables under sahelian conditions.

2. Materials and methods

Weather variables were collected between February 2013 and May 2014 at the Africa Rice Center (Sahelian Regional Station, Senegal) research stations at Ndiaye (16° 11′ N, 16° 15′ W), and Fanaye (16° 32′ N, 15° 11′ W). Ndiaye is located in the Senegal River Delta, 35 km inland; and Fanaye is located in the Senegal River valley, 150 km inland. The experimental sites are characterized by a typical Sahelian climate with a short rainy season from July to early October. Daily weather data, including wind speed, maximum and minimum air temperature, maximum and minimum relative humidity, incoming solar radiation and precipitation were measured over a well-watered grass surface using automated weather stations (the automatic agro-weather station CimAGRO) that were installed in both experimental fields at Ndiaye and Fanaye. The automatic agro-weather station CimAGRO is a compact system designed with Institut National de la Recherche Agronomique (INRA) partnership to complete a weather database and to provide tools to help making the individual or collective decision (i.e., crops, diseases, irrigation management models, etc.). Due to Cimel's exclusive MicroAmps® technology, CimAGRO ensures an exceptional reliable metrology as well as an easy use and a very flexible implementation. It is autonomous station powered by solar generator (Tamper-resistant built-in miniature solar panel) and is compliant with WMO recommendations for measurement quality. Equipped with extremely reliable and stable sensors that are interchangeable without programming (plug and play connections) and resistant to all types of difficult weather conditions. The incorporated sensors are: automatic rain gauge, air temperature and humidity under cover sensor, thermopile pyranometer, and wind sensors. All variables were sampled every 60 s and recorded on an hourly basis.

2.1. *Reference evapotranspiration estimation equations*

The selection of the 16 reference evapotranspiration equations was based on their performance tests and evaluations under arid climate and their simplicity in terms of number of climate parameters necessary to solve them.

2.1.1. *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 (Allen et al., 2005). The daily form of the

Penman–Monteith reference evapotranspiration equation with fixed stomatal resistance values for grass surface is:

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma Cn\,u2/(Tmean + 273))(es - ea)}{\Delta + \gamma(1 + Cd\,u2)} \tag{1}$$

where, ETo is reference evapotranspiration (mm/day), Δ is the slope of saturation vapor pressure vs. 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}), $Tmean$ = 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 = actual vapor pressure (kPa), $es - ea$ = saturation vapor pressure deficit (kPa), γ = psychrometric constant (kPa °C^{-1}), Cn = 900 °C mm s^3 Mg^{-1} d^{-1} for grass-reference surface and 1600 °C mm s^3 Mg^{-1} d^{-1} for alfalfa-reference surface, Cd = 0.34 s m^{-1} for grass and 0.38 s m^{-1} for alfalfa. All parameters necessary for computing ETo were computed according the procedure developed in FAO-56 by Allen et al. (1998).

2.1.2. Hargreaves and Samani model

The Hargreaves and Samani (1985) equation is an empirical radiation-based method, which is extensively used in the conditions of limited weather data. It is expressed as:

$$ETo = 0.0023Ra(Tmean + 17.8)(T\max - T\min)^{0.5} \tag{2}$$

where, Ra = water equivalent of extraterrestrial radiation (mm day^{-1}); $Tmean$ = mean air temperature; $Tmax$ = daily maximum air temperature (°C); $Tmin$ = daily minimum air temperature (°C).

2.1.3. Trajkovic (2007) method

$$ETo = 0.0023\,Ra(Tmean + 17.8)(T\max - T\min)^{0.424} \tag{3}$$

2.1.4. Ravazzani et al. (2012) method

$$ETo = (0.817 + 0.00022Z)0.0023\,Ra(Tmean + 17.8)(T\max - T\min)^{0.5} \tag{4}$$

2.1.5. Berti et al. (2014): Modified Hargreaves

$$ETo = 0.00193\,Ra(Tmean + 17.8)(T\max - T\min)^{0.517} \tag{5}$$

2.1.6. Schendel (1967) method

$$ETo = 16\frac{Tmean}{RH} \tag{6}$$

2.1.7. Trabert (1896) method

$$ETo = 0.4080.3075\sqrt{u}(es - ea) \tag{7}$$

2.1.8. Penman (1948) combination method

$$\lambda E = \frac{\Delta(Rn - G) + (\gamma\lambda Ea)}{\Delta + \gamma} \tag{8}$$

where, E is defined as open water evaporation, λ is the latent heat of vaporization in MJ kg^{-1} (λ = 2.45 MJ kg^{-1} at a temperature of 20 °C), Ea is the vapor transport flux in mm d^{-1}.

2.1.9. Penman (1963) combination method

$$ET_0 = \left[\frac{\Delta}{\Delta + \gamma}(Rn - G) + \frac{\gamma}{\Delta + \gamma}6.43(1.0 + 0.53\,u2(es - ea))\right]/\lambda \tag{9}$$

2.1.10. Romanenko (1961) method

$$ETo = 0.0018(Tmean + 25)^2(100 - RH) \tag{10}$$

2.1.11. Romanenko's equation (modified by Oudin et al., 2005)

$$ETo = 4.5\left[1 + \left(\frac{Tmean}{25}\right)\right]^2 \left(1 - \frac{ea}{es}\right) \tag{11}$$

2.1.12. Mahringer (1970) method

$$ETo = 0.15072\sqrt{3.6u}(es - ea) \tag{12}$$

2.1.13. Turc (1961) method

$$ETo = 0.013\frac{Tmean}{Tmean + 15}\frac{23.88 * Rs + 50}{\lambda} \quad \text{for RH} \geq 50\% \tag{13}$$

$$ETo = \left(1 + \frac{50 - RH}{70}\right)0.013\frac{Tmean}{Tmean + 15}\frac{23.88 * Rs + 50}{\lambda} \quad \text{for RH} < 50\% \tag{14}$$

2.1.14. Makkink (1967) modified Hansen (1984) equation

$$ETo = 0.7\frac{\Delta}{\Delta + \gamma}\frac{Rs}{\lambda} \tag{15}$$

2.1.15. Makkink (1957) method described by Allen (2003)

$$ETo = 0.61\frac{\Delta}{\Delta + \gamma}\frac{Rs}{\lambda} - 0.12 \tag{16}$$

2.1.16. Valiantzas 1 method (Valiantzas, 2013)

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

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

$$Tdew = \frac{116.91 + 237.3\ln(ea)}{16.78 - \ln(ea)} \tag{18}$$

2.1.17. Valiantzas 2 method (Valiantzas, 2013)

$$\begin{aligned} ETo = {} & 0.051(1 - \alpha)Rs(Tmean + 9.5)^{0.5} - 2.4\left(\frac{Rs}{Ra}\right)^2 \\ & + 0.048(Tmean + 20)(1 - RH/100)(0.5 + 0.536u2) + 0.00012z \end{aligned} \tag{19}$$

In Eq. (19) $\alpha = 0.25$ was used.

2.2. Evaluation criteria

The PM model was assumed to represent the actual reference equation and the performance of all other methods was compared to the PM model estimates on a daily time step. The pair-wise comparisons were made using linear regression. For further comparison, root mean squared error (RMSE), mean absolute error (MAE), percentage error of estimate (PE) and mean ratio (MR) were used to evaluate the simplified reference evapotranspiration models:

$$RMSE = \sqrt{\sum_{k=0}^{n}\frac{(Pi - Oi)^2}{n}} \tag{20}$$

$$MAE = n^{-1}\sum_{1}^{n}(Pi = Oi) \tag{21}$$

$$PE = \left|\frac{Pav - Oav}{Oav}\right| 100\% \tag{22}$$

$$MR = n^{-1}\sum_{1}^{n}\frac{Pi}{Oi} \tag{23}$$

where, n = number of observations, Pi = estimated ETo by other equations, Oi = PM-estimated ETo (actual), pav = mean of the estimated ETo, oav = mean of the Oi.

3. Results and discussion

3.1. Weather conditions during the study period

Trends and magnitudes of measured climate variables, including air temperature, relative humidity, precipitation and wind speed for both sites during the study period are presented in Figs. 1 and 2 . At Ndiaye, *Tmax* ranged from 23 °C to 43 °C and *Tmin* varied from 11 °C to 29 °C with low thermic amplitude from June to October that corresponded to the rainy season at the site. At Fanaye, *Tmax* varied from 23 °C (early January) to 46 °C (late May); *Tmin* varied from 8 °C to 33 °C. Average (February through May) temperature and relative humidity were 27 °C and 70% at Ndiaye and 28 °C and 45% at Fanaye, respectively. Wind was much stronger at Fanaye than at Ndiaye. It varied from 1.0 to 14 m/s at Fanaye and from 1.0 to 10 m/s at Ndiaye. Average wind speed was 5 and 6 m/s at Ndiaye and Fanaye, respectively. Total precipitation recorded during from February 2013 to May 2014 was 414 and 216 mm at Ndiaye and Fanaye, respectively. Solar radiation was similar at both sites averaging 21 and 21 MJ/m^2/day at Ndiaye and Fanaye, respectively. On average, May was the hottest month while the period of November–December had the lower solar radiation. Wind speed, air temperature and relative humidity are the driving forces of evapotranspiration through their implicit effect on vapor pressure deficit. Obviously, vapor pressure deficit was much higher at Fanaye than at Ndiaye, ranging between 1 and 5 kPa and 0.2 and 4 kPa at Ndiaye and Fanaye respectively, and averaged 1.1 kPa and 2.4 kPa, respectively, from February through May. As a consequence, reference evapotranspiration was much higher at Fanaye than at Ndiaye (Fig. 3). Reference evapotranspiration varied from 1 to 14 mm/day with an average of 6 mm/day at Ndiaye and from 3 to 18 mm/day with an average of 10 mm/day at Fanaye (Fig. 3). From February through May, ET ranged from 4 to 12 mm/day, stayed in the range of approximately 2–7 mm/day from May through end of January; and gradually increased again up to 14 mm/day at Ndiaye (Fig. 3a). At Fanaye (Fig. 3b), ETo gradually increased from about 4 mm/day to over 18 mm/day in late May and gradually decreased below 4 mm/day in late August; stayed in the range of 8–12 mm until early January and gradually increased again (up to 16 mm/day) until early May.

At Fanaye, *Tmax* reached 45 °C and *Tmin* was as high as 33 °C and the warm temperatures coupled with lower relative humidity resulted in high reference evapotranspiration values. A very limited number of studies are reported on the evapotranspiration estimation in Senegal and other sahelian countries. Reference evapotranspiration as high as 15 mm/day was reported at Mbidi (Senegal) by Cornet (1977). Bouya Ahmed (2012) reported monthly average ETo as high as 14 mm/day in the month of March in Mauritania. El-Nesr et al. (2010) reported that the average ETo varied from 5 mm/day in January to more than 15 mm/day in July with extreme average values ranging from 4 mm/day in January to 18.5 mm/day in July in the Arabian Peninsula.

3.2. Comparison of the reference evapotranspiration equations to the ASCE-PM equation

Daily evapotranspiration estimates produced using 16 simplified methods were compared against the PM evapotranspiration data. The performance of ETo equations compared to ASCE-PM ETo is

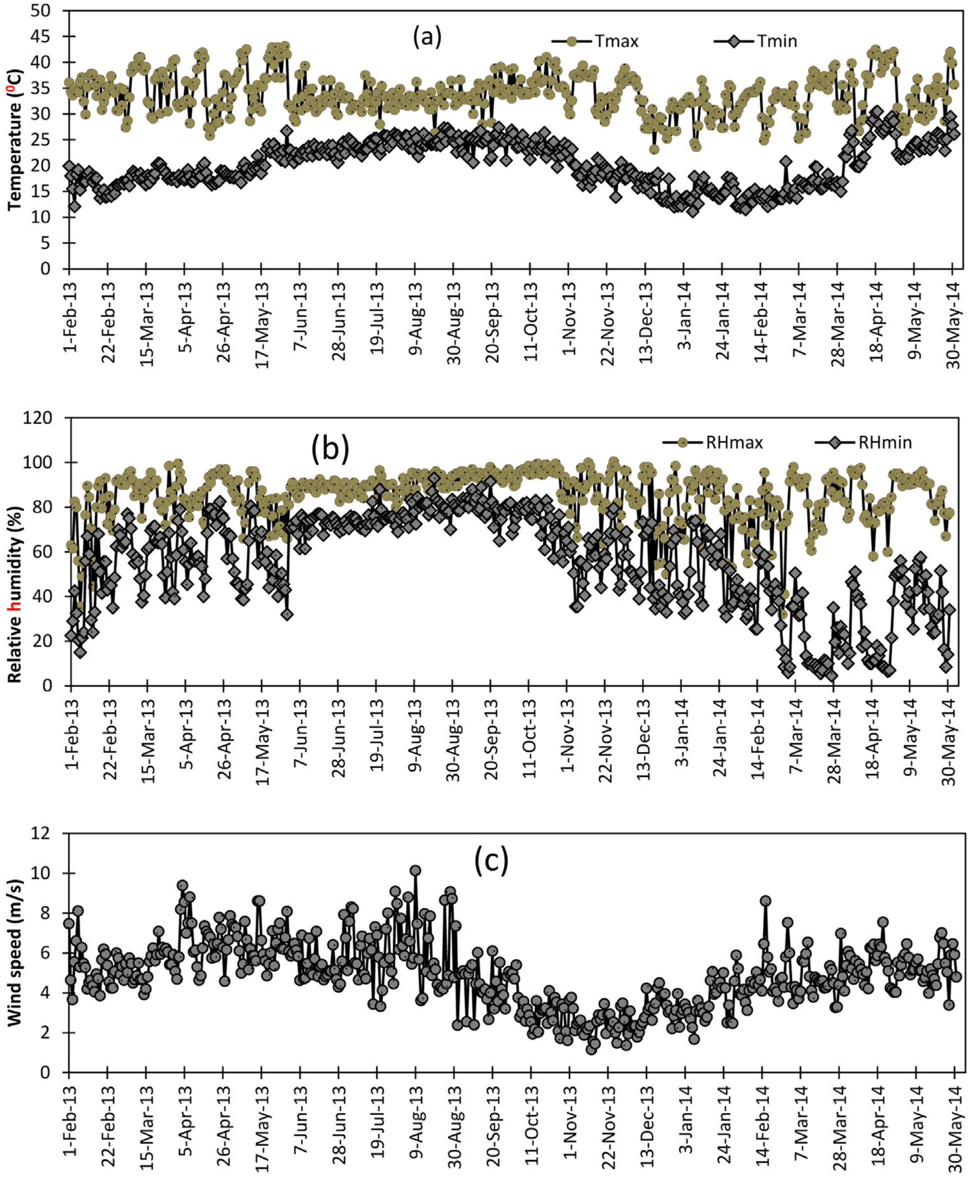

Fig. 1. Climate variables during the study period at Ndiaye: (a) daily air temperature; (b) relative humidity; (c) wind speed; (d) vapor pressure deficit; (e) precipitation, and (f) solar radiation.

shown in Figs. 4 and 5 and Table 1 for both sites. The radiative methods such as Hargreaves and Samani (1985), Modified Hargreaves et al. (1985), Ravazzani et al. (2012) and Trajkovic (2007) equations systematically overestimated reference evapotranspiration under the sahelian conditions in the Senegal River Valley with the regression slope of 1.9, 1.7, 1.6 and 1.6 at Ndiaye and 1.5, 1.3, 1.2 and 1.2 at Fanaye, respectively. The large difference among fitting slopes between both sites could require site calibration of these radiation ETo equations which showed the poorer performance at Ndiaye (35 km from the coast) than at Fanaye (150 km inland) (Valiantzas, 2013; Berti et al., 2014). The Hargreaves model was shown to be the poorest method among all with the highest RMSE that reached

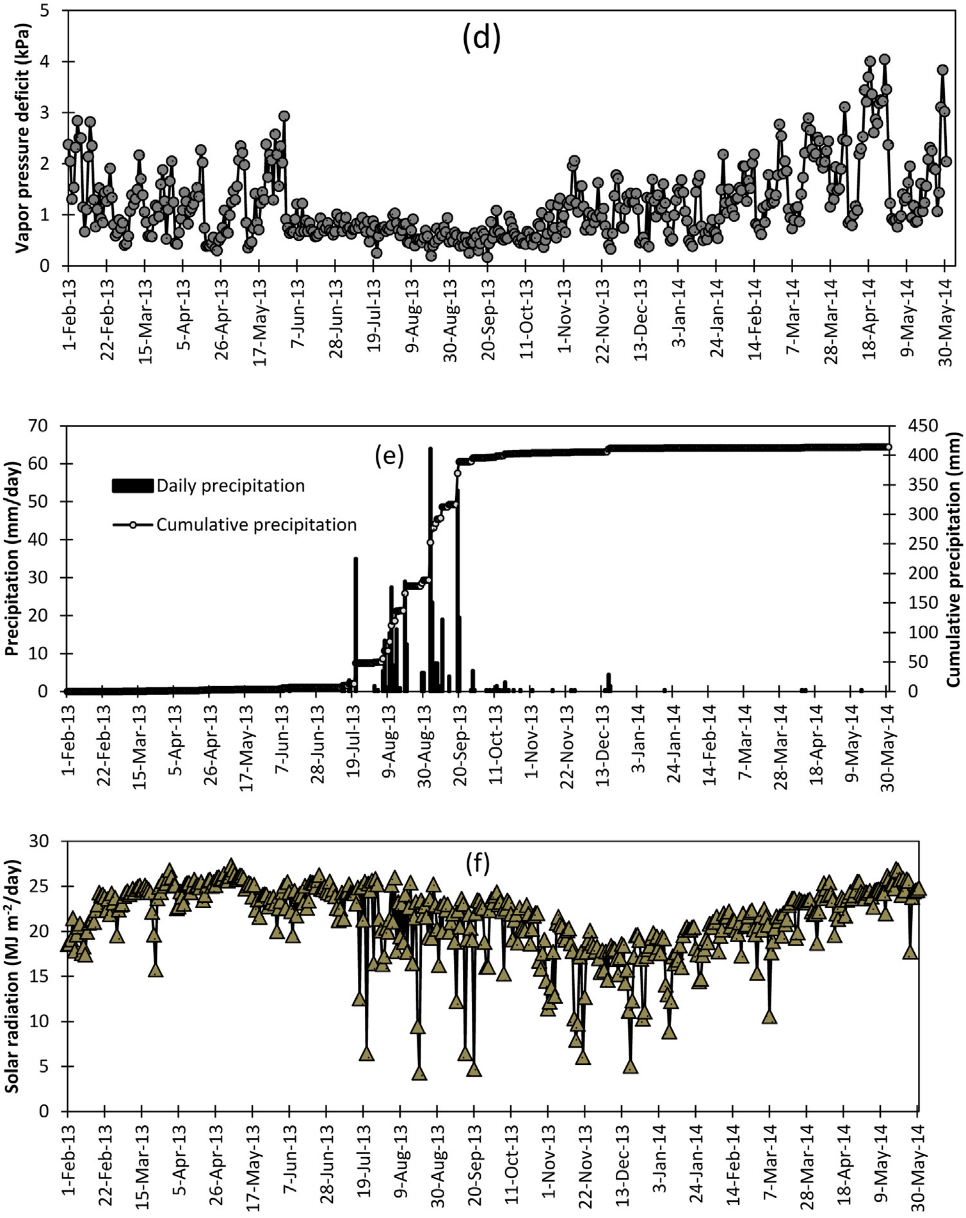

Fig. 1. (*Continued*).

6.9 mm/day and 6.0 mm/day at Ndiaye and Fanaye, respectively, and the highest PE of 107 and 55% at the same site, respectively. These high RMSE values are approximately over 40% of the maximum ETo values that were observed in both sites, thus are considered to be very large RMSE values. Very high ETo difference with ASCE-PM ETo is questionable relate to the non-adaptability of the model although Hargreaves equation is recommended to calculate ETo if air temperature measured at the station is the only available data (Allen et al., 1998). However, Irmak et al. (2008) reported as root mean square difference (RMSD) as high as 4.5 mm/day at Bushland, Texas, and 2.36 mm/day at Davis,

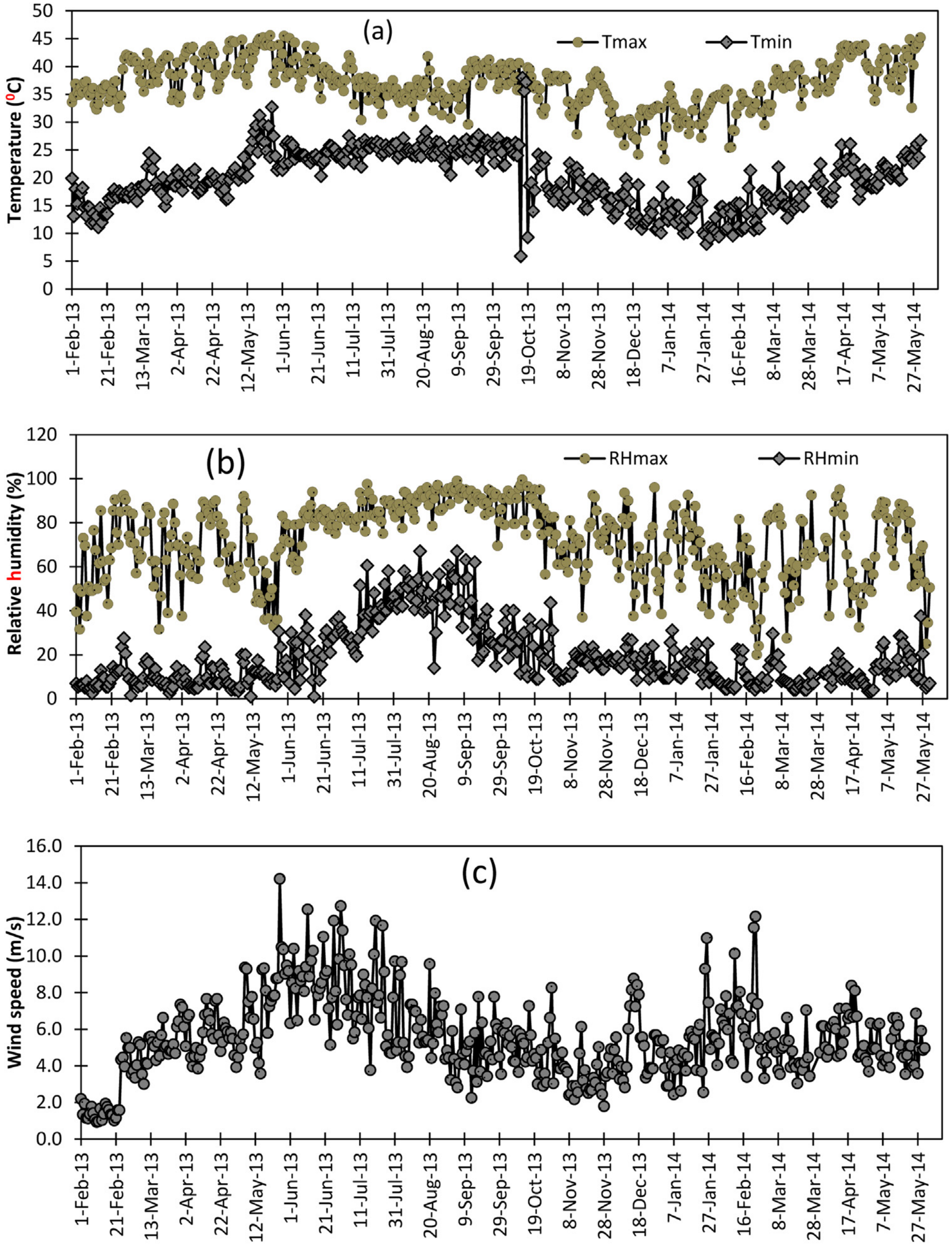

Fig. 2. Climate variables during the study period at Fanaye: (a) daily air temperature; (b) relative humidity; (c) wind speed; (d) vapor pressure deficit; (e) precipitation, and (f) solar radiation.

California using Jensen–Haise model with comparison to ASCE-PM model. Contrary to our finding, Sabziparvar and Tabari (2010) reported that Hargreaves equation was the best to estimate ETo in eastern arid and semiarid regions of Iran. Also, Mohawesh (2011) reported that Hargreaves modified models were the best in light of MBE, RMSE, MAE values that ranged from −1.47 to 0.81, 3.87–1.14 and

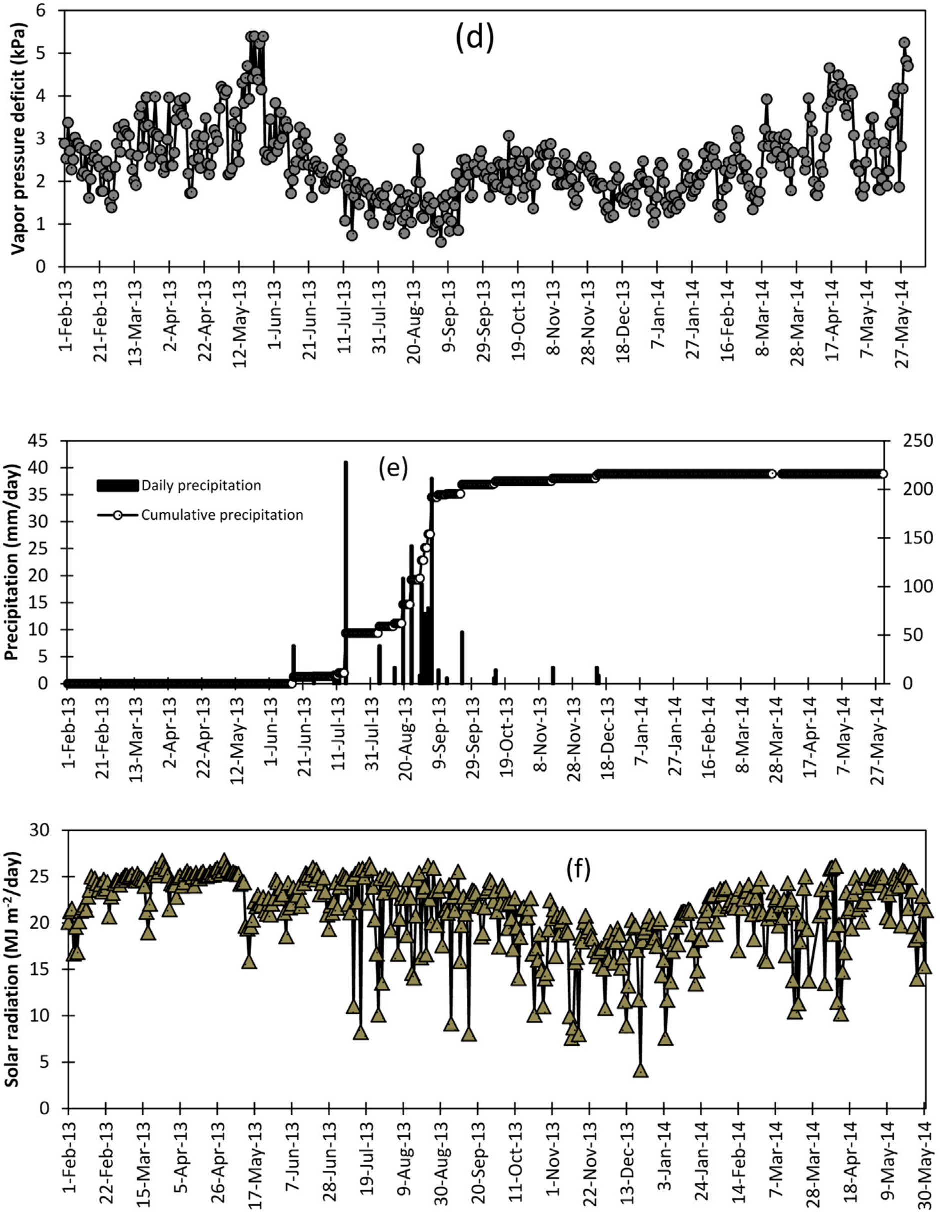

Fig. 2. (*Continued*).

0.87–3.15 mm/day for HarM1, and from −1.45 to 0.89, 1.08–3.91, and 0.85–3.16 mm/day for HarM2, respectively, which would make them the best models while the MBE, RMSE and MAE for other models ranged from −6.18 to 2.79, 6.90–1.08 and 4.74–0.85 mm/day, respectively. Automated weather station maintenance and replacement are costly and data can largely deviate from the real values without appropriate caution and maintenance. Therefore the estimated ETo can differ from the ASCE-PM ETo. Allen et al. (1998) proposed the use of physically based equations of meteorological parameter estimation, such as air temperature-based estimation of radiation to overcome such difficulties. These

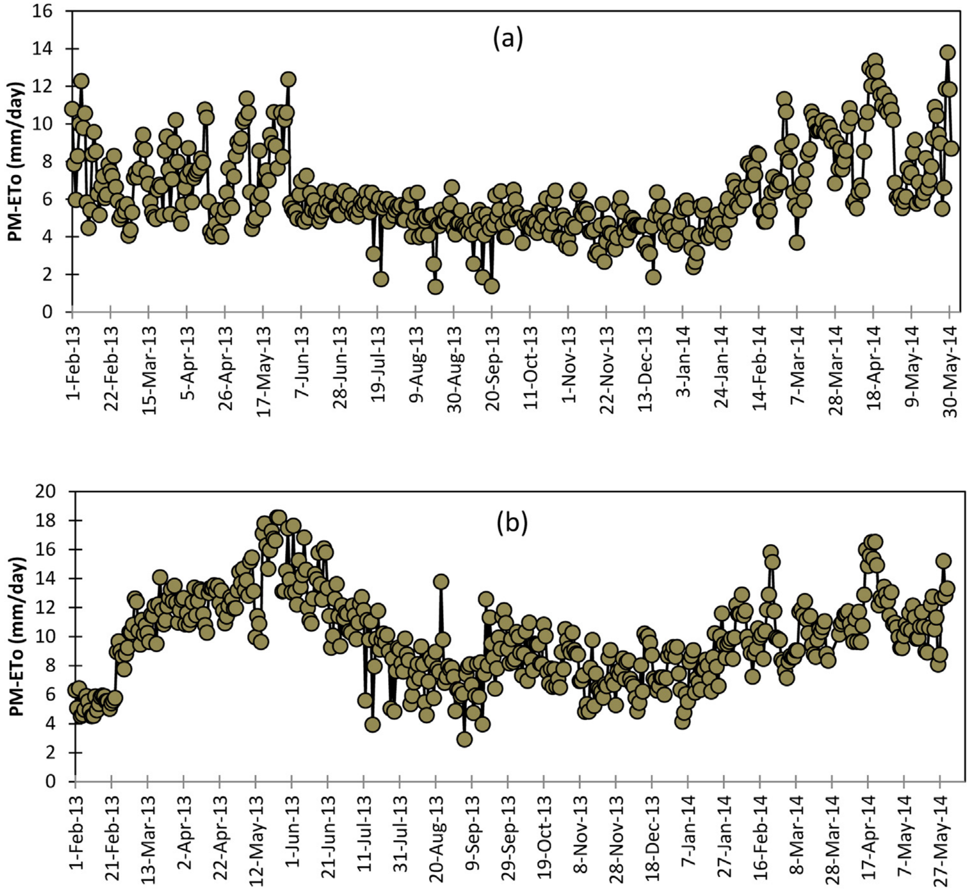

Fig. 3. Daily Penman–Monteith grass-reference evapotranspiration (PM-ETo) during the study period at (a) Ndiaye and (b) Fanaye, Senegal.

Table 1

Performance evaluation of the 16 ETo models at Ndiaye and Fanaye (Senegal River Basin).

ETo model	Ndiaye					Fanaye				
	PE (%)	RMSE (mm/day)	MAE (mm/day)	MR	Slope	PE (%)	RMSE (mm/day)	MAE (mm/day)	MR	Slope
Trabert	25	2.0	1.8	0.69	0.72	5.47	1.62	1.14	1.03	1.08
Penman (1963)	14.74	1.02	0.93	1.16	1.14	5.98	1.88	1.35	1.09	1.05
Romanenko	23.47	2.00	1.75	0.74	0.8	5.46	2.57	2.05	1.00	0.92
Oudin et al. (2005)	44.28	2.97	2.78	0.54	0.58	29.59	3.67	3.19	0.74	0.68
Penman (1948)	41.03	2.78	2.58	0.56	0.63	21.18	3.08	2.56	0.82	0.78
Mahringer	42.71	2.76	2.68	0.53	0.62	19.31	2.59	2.16	0.80	0.81
Makkink–Hansen	26.11	2.48	1.72	0.79	0.68	52.27	5.79	5.18	0.51	0.45
Turc	25.51	2.46	1.69	0.80	0.76	50.79	5.60	5.05	0.52	0.47
Allen–Makkink	14.43	2.03	1.72	1.21	1.06	25.05	3.58	2.95	0.80	0.72
Hargreaves HG	107.17	6.97	6.70	2.19	1.94	55.16	6.00	5.51	1.62	1.49
Mod. Hargreaves	81.69	5.41	5.13	1.92	1.7	36.53	4.33	3.82	1.43	1.32
Schendel	38.81	2.65	2.50	0.56	1.02	9.63	4.33	2.91	1.14	1.05
Trajkovic	70.18	4.67	4.42	1.82	1.58	24.95	3.34	2.82	1.31	1.20
Ravazzani	69.58	4.66	4.38	1.80	1.58	27.36	3.57	3.04	1.33	1.22
Valiantza 1	18.64	1.509	1.24	0.8	0.79	25.73	3.146	2.71	0.77	0.72
Valiantza 2	2.47	0.79	0.63	1	0.95	25.77	3.146	2.7	0.77	0.85

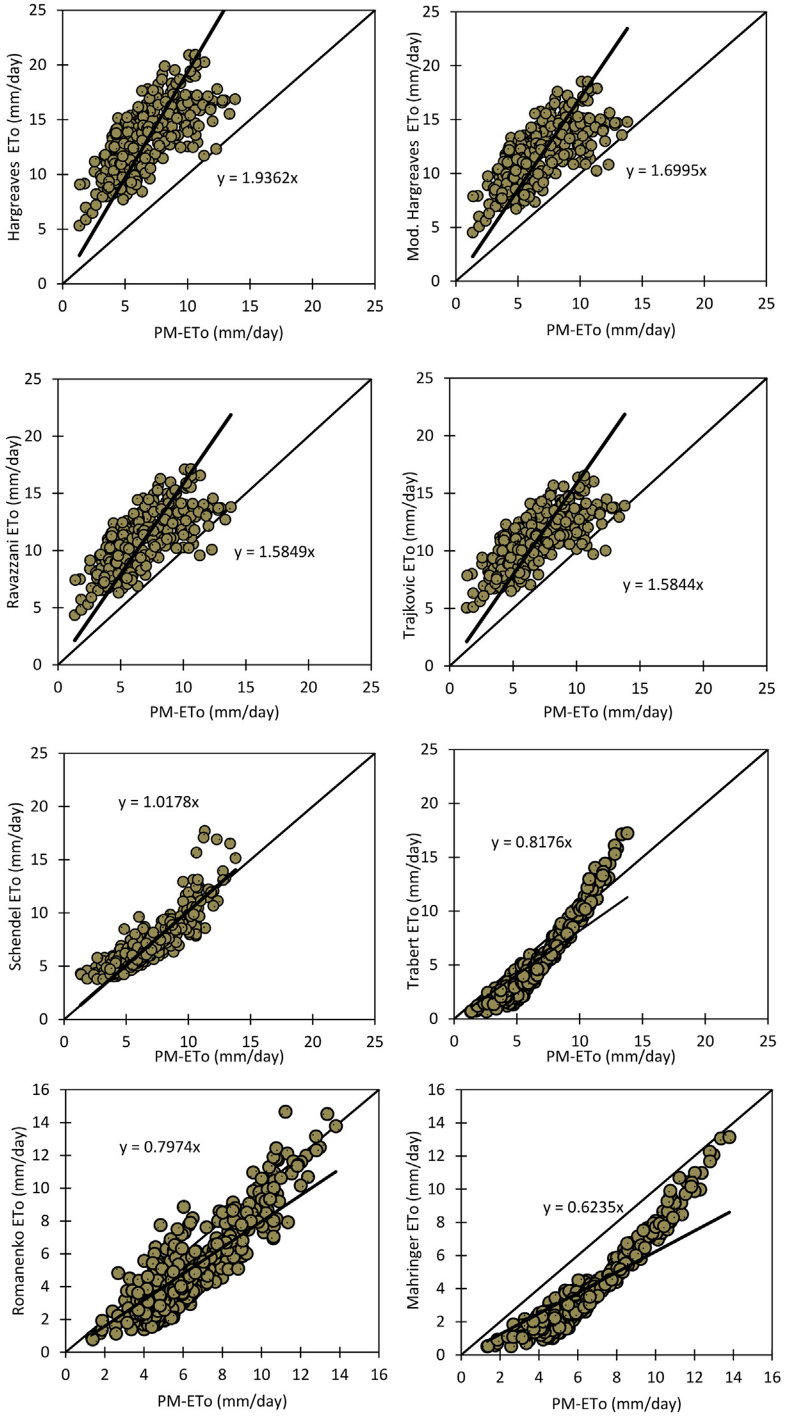

Fig. 4. Relationship between the daily reference evapotranspiration (ETo) estimates of each method versus the Penman–Monteith grass-reference evapotranspiration (PM-ETo) for Ndiaye.

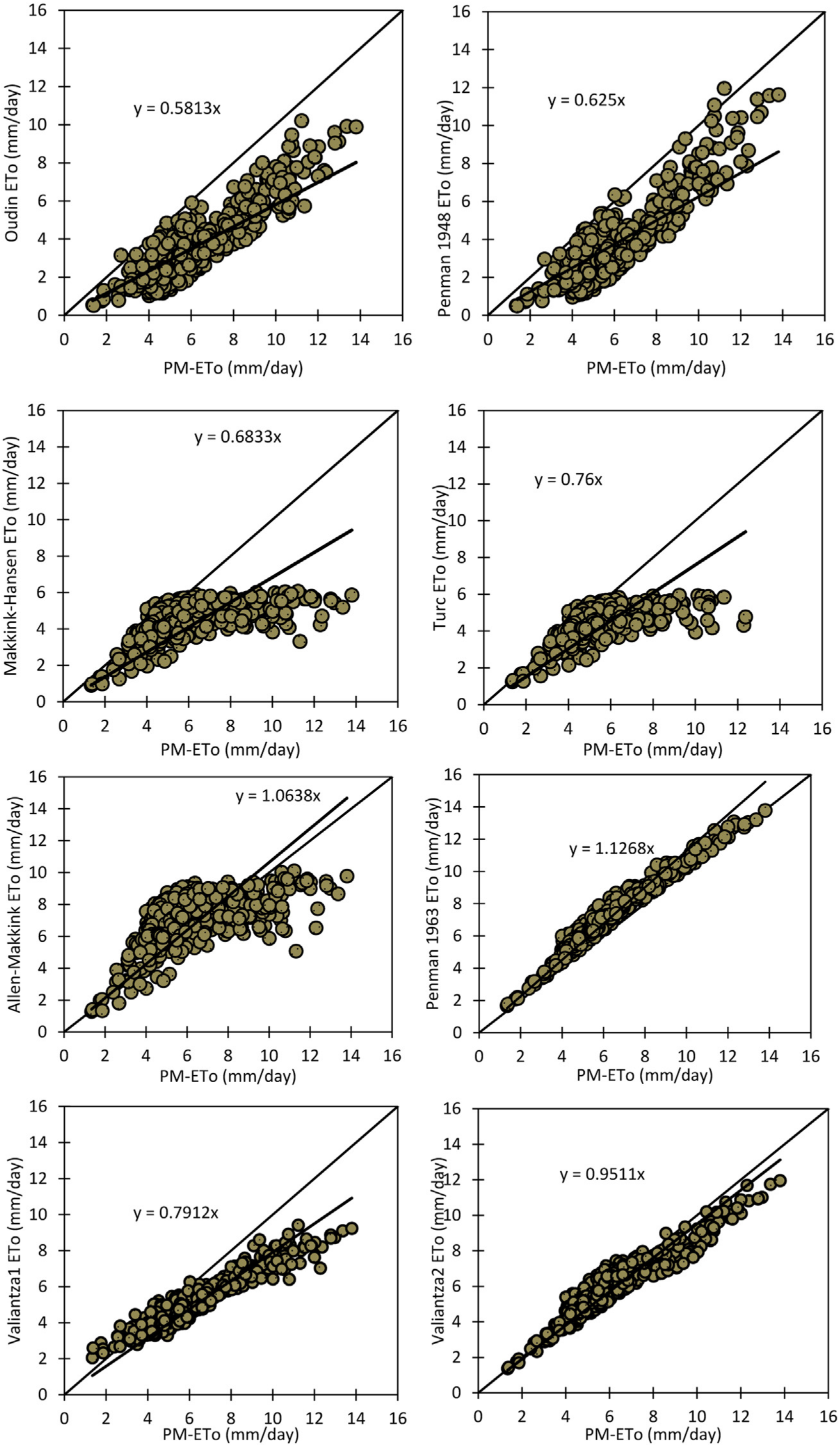

Fig. 4. (*Continued*).

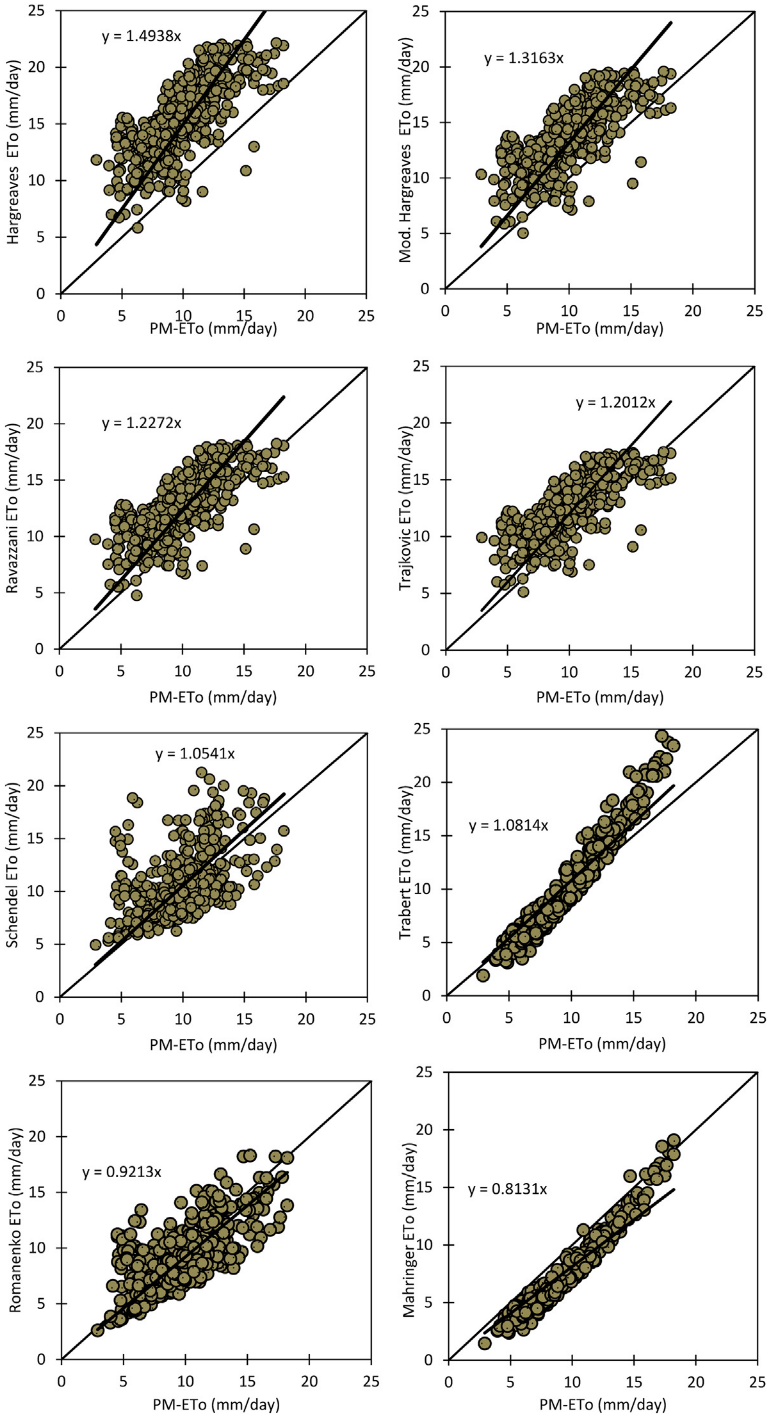

Fig. 5. Relationship between the daily reference evapotranspiration (ETo) estimates of each method versus the Penman–Monteith grass-reference evapotranspiration (PM-ETo) ETo for Fanaye, Senegal.

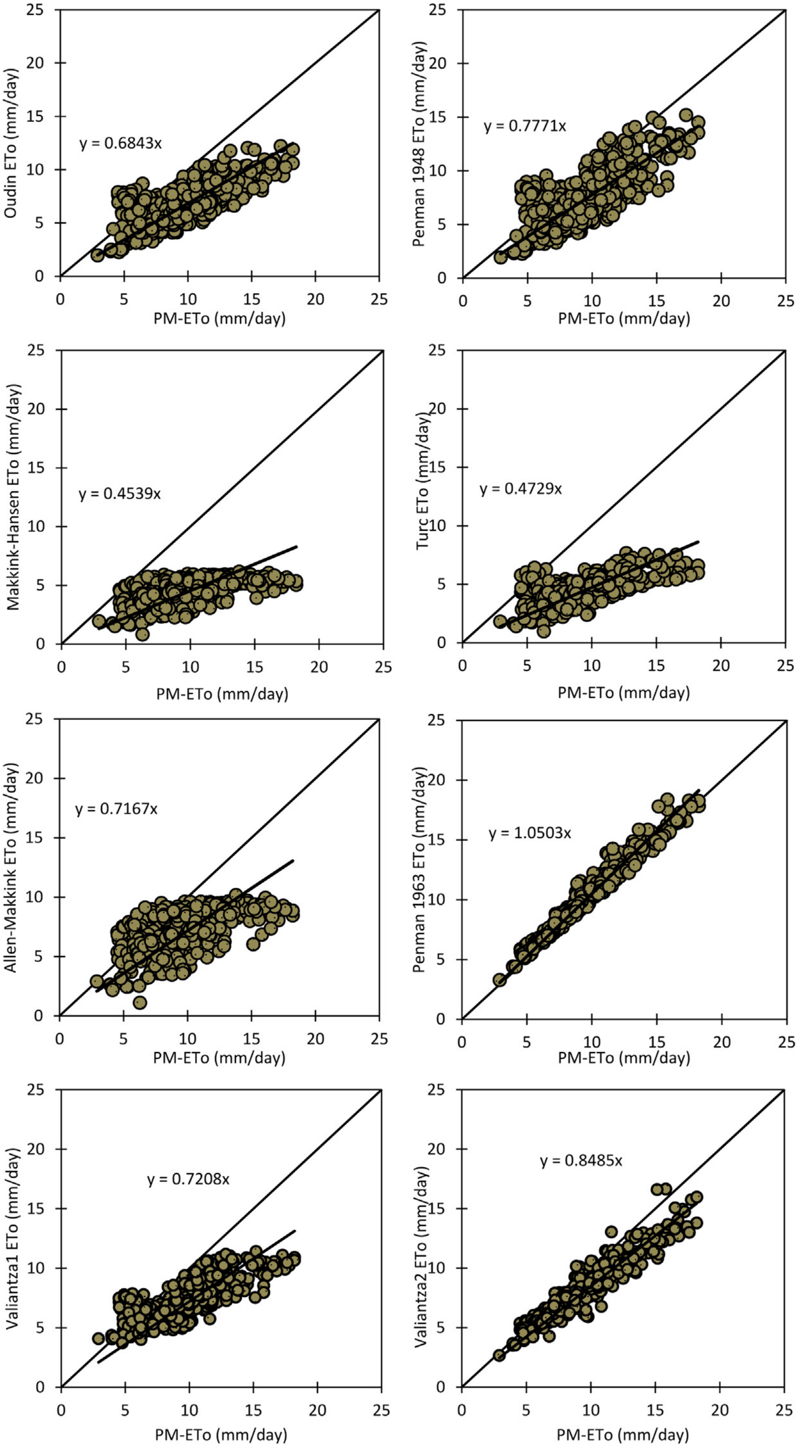

Fig. 5. (*Continued*).

differences in the performance of the same model in different locations emphasizes the importance and the necessity of developing calibration parameters for non-combination based equations (temperature and radiation-based) for local climatic conditions, which is one of the objectives of this study.

Mass transfer equations of Trabert and Mahringer performed relatively well under the sahelian climatic conditions. Trabert equation overestimated ETo at Fanaye with only 6% RMSE, MAE, MR and fitting slope of 1.62 mm/day, 1.14, 1.03 and 1.08 respectively, while the corresponding parameters at Ndiaye were 24.67% overestimation, 1.95, 1.76, 0.69 and 0.72, respectively. The equation slightly overestimated at ETo values greater than approximately 12 mm/day. The Mahringer equation also had better performance at Fanaye, registering MR of 0.80 and PE of 19%. The underestimation of this equation was smaller for ETo values greater than about 10 mm/day. The performance of Trabert and Mahringer equations with underestimations of 25 and 43% at Ndiaye and only 6 and 19% at Fanaye, respectively, is similar to the results reported by Tabari et al. (2011) who indicated that Trabert and Mahringer equations underestimated ETo with an average of 26 and 31%, respectively. However, Trabert equation resulted in a very good MR performance of 1.03 and simple linear fitting slope of 1.08 at Fanaye. Trabert equation registered the lowest RMSE and the lowest MAE of all equations evaluated at Fanaye. Although Trabert equation had good statistics and good fitting at lower ETo mostly at Fanaye, it consistently overestimated the ASCE-PM ETo values greater than 12 mm/day. Based on these results, this equation presents a good alternative estimating reference evapotranspiration under the sahelian environment in the Senegal River Valley with site calibration parameters developed in this study. Our results contradict those reported by Jakimavičius et al. (2013) who reported that Trabert equation had only 0.49 correlation with the measured values in Lithuania and, Bogawski and Bednorz (2014) who noticed poor performance of the Mahringer method in Poland.

The Schendel equation showed very good fitting slopes of 1.02 and 1.05 at Ndiaye and Fanaye, respectively; however, it overestimated ETo by 39 and 10% with MR of 0.56 and 1.14 at the respective locations, especially for ETo values greater than about 10 mm/day. The Schendel equation performed better at Fanaye, which is a much less humid location (RHmean = 45%) than Ndiaye (RHmean = 70%). This confirms the results of Tabari et al. (2011) who indicating that Schendel equation was not a suitable method for estimation of ETo at humid locations. In fact, the average RH was 70% at Ndiaye against 45% at Fanaye during the study period. RH is therefore 64.4% higher at Ndiaye as compared to Fanaye. The Schendel equation performed well elsewhere (Lithuania), analysis revealed that in the studied period of 1974–1983, the smallest difference was observed between the measured values and the values calculated by Schendel equation (−0.6%) (Jakimavičius et al., 2013).

Romanenko equation exhibited interesting results at Fanaye with underestimated ETo of 6%, MR of 1.0 and a simple linear fitting slope of 0.92. At Ndiaye, it underestimated ETo for about 24% with MR of 0.74 and fitting slope of 0.80. Romanenko equation represents one of the humidity methods and resulted in poor results, but it performed similarly as the Schendel equation. Both equations performed better under dry and semiarid condition than the humid semiarid conditions in the Senegal River Valley. In Iran, the Romanenko equation was the best model in estimating ETo among the mass transfer-based methods as reported by Tabari et al. (2011) and adversely it was found comparatively less reliable at the Junagadh meteorological station located in the Gujarat state of India (Gundalia and Dholakia, 2013).

Makkink–Hansen and Turc equations showed very good estimation at ETo range of about 6–8 mm/day. Allen–Makkink method exhibited a very strong and good correlation with the ASCE-PM ETo values less than 8 mm/day, however, it did not produce accurate results for ETo values greater than 10 mm/day at both sites in the high evaporative demand environment of sahelian region. Overall, these three equations had the lowest fitting slopes of 0.45, 0.47 and 0.72, respectively, and high MAE and high PE up to 52% relative to ASCE-PM ETo values. The results of this study infirmed the conclusion of Irmak et al. (2008) and Yoder et al. (2005) and Martinez and Thepadia (2010) that Turc equation showed promise in the southeastern United States under limited-data conditions. Makkink method followed the same trend as that of Penman–Monteith method and was classified second after Priestly–Taylor method before Hargreaves and Blaney–Criddle (temperature-based) and Rohwer (Mass-transfer) (Xu and Singh, 2002). Tabari (2010) reported the inaccuracy of the Allen–Makkink equation under all climates in Iran. Furthermore, Sabziparvar et al. (2010) showed that the annual ETo rate in the warm arid sites was overestimated by 66% relative to the corresponding ETo under the cold semiarid site in Iran.

The choice of ETo equation to be used should consider the origin and the environmental conditions of its development. These methods have the advantage of requiring few meteorological data; however, they were developed for use in specific studies and are most appropriately applied to climates similar to that where they were developed (Chattopadhyay and Hulme, 1997; Xu and Chen, 2005). The large deviation of ETo estimated by these equations can be expected when these methods are extrapolated to other climatic areas without recalibrating the constants involved in the formulae (Hounam, 1971). However, García et al. (2007) and Xu and Singh (2002) reported that the recalibrated models produced acceptable monthly values in cold and temperate humid climates, but failed to produce the monthly variation pattern for the semiarid climate and the tropical humid climate (Gavilán et al., 2006; Borges and Mendiondo, 2007).

The Penman (1948) equation also underestimated ETo by about 41% at Ndiaye and 21% at Fanaye. The Penman 1963 produced good estimates of ETo with fitting slope of 1.14 and 1.05 and MR of 1.14 and 1.09 at Ndiaye and Fanaye respectively. It can accurately be used in place of the Penman–Monteith equation and also its performance is significantly improved when it is used with saturation vapor pressure deficits calculated using both maximum and minimum air temperatures (Ahmed and Hussein, 1999).

The Valinantzas 1 underestimated ETo while the Valinantzas 1 showed perfect fit at lower ETo (ETo < 8 mm/day) and underestimated ETo at higher values. Valinantzas 2 presented the best fit to the ASCE-PM with MR and a regression slope of 1.0 and 0.95 at Ndiaye and 0.77 and 0.85 at Fanaye, respectively. The Valiantzas 2 can be an alternative method to the ASCE-PM for estimating reference evapotranspiration under these study conditions. The site-specific calibration in the sahelian climatic conditions will be required to improve its performance as reported by Valinantzas (2013). However, these two equations by Valinantzas (2013) performed better than the Hargreaves and modified Hargreaves equations (Valinantzas, 2013). Valinantzas 2 had the lowest PE (2.47%) and the lowest RMSE (0.79 mm/day) of all the sixteen equations evaluated. The Valinantzas equations showed consistency at Fanaye site with smaller PE, RMSE, MAE, MR and MBE. Valiantzas' equations were observed to perform better than the two-input ANFIS models in Turkey (Kisi and Zounemat-Kermani, 2014). Valipour (2014) found that Valiantzas equations were suitable for provinces of Iran (coefficient of determination (R^2) was greater than 0.99); however, the Valiantzas 1 was more suitable for the central and south of Iran (9 provinces), and the Valiantzas 2 (T, R_s, RH, u) was the most accurate and suitable for western, eastern, and northern Iran (22 provinces). From the results of this study and others, the Valiantzas' equations are promising one and could therefore be used an alternative and accurate method for estimating ETo under the SRV climatic conditions.

The non-adaptability of many of the reference evapotranspiration models might have resulted from development of these models for a specific climatic region, or specific period of the year. Maidment (1992) and DVWK (1996) reported that Turc method is valid for temperatures above 0 °C and for humid climates only. Also, Sabziparvar et al. (2010) showed overestimation of annual ETo by 66% in the warm arid locations relative to cold semiarid site in Iran. Therefore, documentation on the origin and development conditions should follow models description with operational conditions for applicability to other environments. The application of simple equations requires calibration to regional conditions, because large biases can result from applying partially empirical formulae that have been calibrated for different regions, which in turn, can result in erroneous estimates ETo and crop water requirements and can also result in inaccurate water balance estimates.

4. Conclusions

This study evaluated the performance of 16 reference evapotranspiration equations against the ASCE-PM ETo equation under the sahelian conditions in the Senegal River Valley. The Hargreaves, the modified Hargreaves, Ravazzani and Tralkovic equation systematically overestimated ETo with the highest PE. In contrast to the four equations, Makkink–Hansen, Oudin and Turc equations systematically underestimated ETo. Temperature-based equations of Romenenko and Schendel performed relatively better at Fanaye with 6% and 10% PE, regression slopes (between the method ETo estimates vs. the ASCE-PM ETo) of 0.92 and 1.05, and MR of 1.00 and 1.14, respectively. Mass transfer equations of Trabert and Mahringer also had better performance at Fanaye than at Ndiaye, and represent simple ETo estimation methods that could be used under conditions of limited climate data in the Senegal River Valley. On average, the best five equations (after the ASCE-PM and the Penman 1963 equations) that could be used as an alternative to the ASCE-PM equation are ranked as follow: Valiantzas, Trabert, Romanenko, Schendel and Mahringer equations. However, these equations have to be calibrated for the local conditions and tested using broad number of weather stations data covering several years to account for changes in climate variables. The results of this study should provide invaluable data and information to the water management agencies, irrigators, Extension personnel, and university researchers in terms of which method to select for more accurate ETo estimations in the SRV for irrigation and water management and for water analyses that can aid in more efficient and sustainable use of water resources.

Conflict of interest

There is no conflict of interest within the authorship of this manuscript.

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