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Evaluation of FAO-56 Penman–Monteith and alternative methods for estimating reference evapotranspiration using limited climatic data at Pusa

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ABSTRACT

The FAO-56 Penman–Monteith method (FAO-56 PM) is standard method recognized by the Food and Agriculture Organization of the United Nations for estimating reference evapotranspiration (ET_O). Unfortunately, some of climatic variables, especially relative humidity, solar radiation and wind speed are often missing which could impede the estimation of ET_O with the FAO-56 PM method. To overcome the problem of availability of climatic variables, procedures to estimate ET_O with missing climate data are proposed as part of the FAO methodology. Therefore, assessing the accuracy of these procedures for Pusa Observatory is important.

The comparison of ET_O estimates using limited data to those computed with full data set revealed that the difference between ET_O obtained from full and limited data set is small. Both the Mean Bias Error (MBE) and the Root Mean Square Error (RMSE) of the comparison were less than 0.35 and 1.00 with a minimum of “0.11 and 0.29 mm day^{-1}, respectively, leading to small errors in the ET_O estimates. R^2, ÷^{2}-test and index of agreement values confirmed strong relationships among data for the year 1998 to 2006.

***Keywords**:* Reference evapotranspiration; FAO-56 Penman-Monteith model; Limited data.

The need for an accurate and standard method to estimate reference evapotranspiration (ET_O), to predict crop water requirements, has been stated by several authors (Allen, 1996; Chiew et al., 1995; and Martinez-Cob and Tejero-Juste, 2004). A great number of equations for estimating ET_O are reported in literature (Alexandris et al., 2005; DehghaniSanij et al., 2004; Gavilán et al., 2006; and Pereira and Pruitt, 2004), but the international scientific community has accepted the FAO-56 Penman–Monteith (FAO-56 PM) equation as the most precise one for its good results when compared with other equations in various regions of the entire world (Chiew et al., 1995; Garcia et al., 2004; and Gavilán et al., 2006). Subsequent papers have demonstrated the superiority of the FAO-56 PM equation over other methods (Allen et al., 1998) when comparing it with lysimetric measurements especially for daily computations (Cai et al., 2007; Chiew et al., 1995; Garcia et al., 2004; and López-Urrea et al., 2006).

The FAO-56 PM method requires daily data on maximum and minimum air temperature (T_{max} and T_{min}), relative humidity (RH), solar radiation (R_s) and wind speed (u) for daily ET_O calculation. Unfortunately, for many locations in India, such meteorological variables are often incomplete and/or not available. But estimation methods for limited weather data are outlined by Allen et al. (1998) and found appropriate for Bulgaria (Popova et al., 2006) making their use applicable under various conditions. It is therefore important to assess the accuracy of the procedures to estimate ET_O from missing data. Thus, the present study has been carried out to assess the validity of the estimates of ET_O obtained using limited data against ET_O computed with a complete data set under the environmental conditions of Pusa (India).

MATERIALS AND METHODS

Climate data

To evaluate the performance of ET_O estimated from limited climatic data using the FAO-56 PM method, daily data recorded at Pusa meteorological station (latitude 25.98^0 N; longitude 85.67^0 E; 52.0 meters above the mean sea level) were used. The weather stations have good quality of daily data from 1998 to 2006 for estimating ET_O with the FAO-56 PM method including sunshine duration, relative humidity, wind speed and daily maximum and minimum temperatures. FAO-56 PM method was applied

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with the observed data sets to assess the accuracy of using limited data on the estimation of ET_O.

The FAO-56 Penman–Monteith equation and its computational procedures

The Penman–Monteith equation for computation of daily reference evapotranspiration assumes the reference crop evapotranspiration as that from a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered. It is expressed as (Allen *et al.*, 1998):

$$ET_o = \frac{0.408\Delta\left(R_n - G\right)+\gamma\left(\frac{900}{T+273}\right)u_2\left(e_s-e_a\right)}{\Delta+\gamma\left(1+0.34u_2\right)} \qquad \ldots (1)$$

where ET_O is the grass reference evapotranspiration (mm day$^{”1}$); Ä is the slope of the saturated vapor pressure curve (kPa °C$^{”1}$); R_n is the net radiation (MJ m$^{”2}$ day$^{”1}$); G is the soil heat flux density (MJ m$^{”2}$ day$^{”1}$); considered as null for daily estimates; T is the daily mean air temperature (°C) at 2 m height, based on the average of maximum and minimum temperatures; u_2 is the average wind speed at 2 m height (m s$^{”1}$); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); and (e_s ” e_a) is the saturation vapor pressure deficit (kPa) at temperature T; and ã is the psychrometric constant (0.0677 kPa °C$^{”1}$).

Missing climatic data

The procedures for computing reference evapotranspiration using limited climatic data stated in Allen et al., (1998) were used and these procedures are as follow:

Relative humidity

If the air humidity data is not available, the actual vapour pressure (e_a) could be obtained by assuming that the dew point temperature is close to the daily minimum air temperature (T_{min}) which is usually found at the time of sunrise in a location. The e_a is estimated by:

$$e_a = e^o\left(T_{\min}\right) = 0.6108\times e^{\left(\frac{17.27\times T_{\min}}{T_{\min}+237.3}\right)} \qquad \ldots (2)$$

T_{min} might be greater than T_{dew} in a non-reference weather station, as in a station located inside a town. Where T_{min} may require correction (Allen, 1996 and Allen et al., 1998) proposed that the estimate for e_a from T_{min} should be checked and that, when the prediction by Eq. (2) is validated for a region, it can be used for daily estimates of e_a.

Solar radiation

Allen et al. (1998) suggested a simple method to estimate R_S in the absence of solar radiation or sunshine radiation using the difference method based on the fact that differences between maximum and minimum air temperature are closely related to the existing daily solar radiation for a given location:

$$R_s = K_{rs}\left(\sqrt{T_{\max}-T_{\min}}\right)R_a \qquad \ldots (3)$$

Where, R_S is the extraterrestrial radiation (Mj m^{-2} day^{-1}) and K_{rs} is an empirical adjustment coefficient ($^oc^{-0.5}$). The value of K_{rs} ranges from 0.16 $^oc^{-0.5}$ for interior region to 0.19 $^oc^{-0.5}$ for coastal region depending upon the case (Hargreaves and Samani, 1982).

Wind speed

Where wind speed data are lacking, Allen et al. (1998) proposed to use default value of wind speed to compute reference evapotranspiration. In fact, impact of wind speed on the estimated ET_O is relatively small except for arid and windy areas (Martinez-Cob and Tejero-Juste, 2004). Thus, the authors refer the possibility to use with caution the default value of 2 m/s, which is the average value over 2000 weather stations around the globe.

Data analysis

The results from ET_O estimated by the FAO-56 PM method with missing Rs, e_a and u_2 obtained with the procedures mentioned above were compared with ET_O data computed with full data sets. The empirical calibration of the parameters of each method was performed by minimizing ET_O errors between the calibrated methods and the full-data FAO-56 PM method, approximating the slope of the regression analysis to one. The performance of the methods for each location was determined by regression analysis, always forcing the linear coefficient through the origin (a = 0). The slope (b) was used as a measure of accuracy, while coefficient of determination (R^2) was considered as a measure of precision. A perfect method should result in b = 1 and R^2 = 1. Following the suggestion of Jacovides and Kontoyiannis (1995) and

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Jabloun and Sahli (2008), the performance of the ET$_O$ estimates was also evaluated using root mean square error (RMSE) and mean bias error (MBE). The RMSE and MBE were calculated by the following equations:

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}(ET_{o-est} - ET_{o-ref})^2\right]^{1/2}, \text{ mm day}^{-1} \quad \dots (4)$$

$$\text{MBE} = \frac{1}{N}\sum_{i=1}^{N}(ET_{o-est} - ET_{o-ref}), \text{ mm day}^{-1} \quad \dots (5)$$

Other statistical parameters such as the Chi-Square ($\div^2$) -test and the correlation between ET$_O$ estimated using full data set and ET$_O$ estimated using limited data were used to evaluate the performance of the described method for the computation of ET$_O$.

$$\chi^2 = \sum_{i=1}^{N}\frac{\left(ET_{O-ref} - ET_{O-est}\right)^2}{ET_{O-est}} \quad \dots (6)$$

Where, ET$_{O\text{-ref}}$ is the reference evapotranspiration computed with full data sets and ET$_{O\text{-est}}$ is the ET$_O$ estimated from limited data and N is the number of data.

The Willmott index of agreement (d) was used as a relative measure of the difference among variables and is written as (Zhou and Zhou, 2009 and Lopez-Urera *et. al.*, 2006):

$$d = 1 - \left[\frac{\sum_{i=1}^{N}\left(ET_{O-ref} - ET_{O-est}\right)^2}{\sum_{i=1}^{N}\left(\left(ET_{O-ref} - ave\left(ET_{O-ref}\right)\right) + \left(ET_{O-est} - ave\left(ET_{O-ref}\right)\right)\right)^2}\right] \quad \dots (7)$$

where, ave(ET$_{O\text{-ref}}$) is the mean value of the observed variable. Perfect agreement would exist between observed and estimated variables if d is equal to 1.

RESULTS AND DISCUSSION

Computation of reference evapotranspiration from complete meteorological data

Reference evapotranspiration (ET$_O$) from daily meteorological data from the years 1998 to 2006 was computed using Eq. (1) for Pusa (North-Bihar). In the computational procedure complete data set including daily maximum and minimum air temperature, daily maximum and minimum relative humidity, solar radiation and wind speed were used. Results of the analysis revealed that maximum value of ET$_O$ was found during monsoon season while minimum value of ET$_O$ was observed during winter (*kharif*) season. The annual minimum values of ET$_O$ estimated by FAO-56 PM method oscillates between 0.88 to 1.17 mm day^{-1} whereas the annual maximum between 6.38 to 8.95 mm day^{-1} at Pusa Station. The normal value of ET$_O$ for the period 1998 to 2006 at Pusa Station was observed to be 3.78 mm day^{-1} while it ranged from 3.66 (2002) to 3.97 (1999 & 2006) mm day^{-1} during the period from 1998 to 2006.

Computation of reference evapotranspiration using limited meteorological data

When relative humidity data are missing

When relative humidity data are absent, Allen et al., (1998) stated that the actual vapour pressure (e$_a$) can be determined by assuming that the dew point temperature is close to the daily minimum temperature i.e. (T$_{dew}$ = T$_{min}$). ET$_{OH}$ values computed using Eq. (1) assuming e_a estimated from T_{min} using Eq. (2) shows that range of annual minimum and maximum values of ET$_{OH}$ for the region are 0.96 (1999) to 1.21 (2005) and 6.40 (2001) to 8.20 (1998) mm day^{-1}, respectively. The daily average ET$_{OH}$ values ranges from 3.61 (2002) to 3.95 (1999) mm day^{-1}.

The scatter plot Fig. 1(a) between the values of ET$_{OH}$ computed when relative humidity data were not available and the values of ET$_O$ computed from full data set shows a strong relationship between the two methods. The R^2 values were close to 1.0 (higher than 0.95) for the Pusa region. However, the scatter plot illustrates systematic underestimation for high ET$_O$ rates (ET$_O$ > 3.33 mm day$^{”1}$). The errors associated with this condition are presented in Fig. 2(a) for MBE which shows dispersion of ET$_{OH}$ when estimating ET$_O$ when relative humidity data were not available.

Table 1 summarizes the statistical indices for comparing ET$_{OH}$ computed when relative humidity data were not available with ET$_O$-ref. The RMSE and MBE values were very low as ET$_{OH}$ tends to overestimate ET$_O$ for high ET$_O$ rates (ET$_O$ > 3.33 mm day$^{”1}$). The values of RMSE and MBE between ET$_O$ and ET$_{OH}$ ranged from 0.291 (2001) to 0.380 (2005) mm day^{-1} and from 0.02 (1999) to 0.10 (2006) mm day^{-1}, respectively.

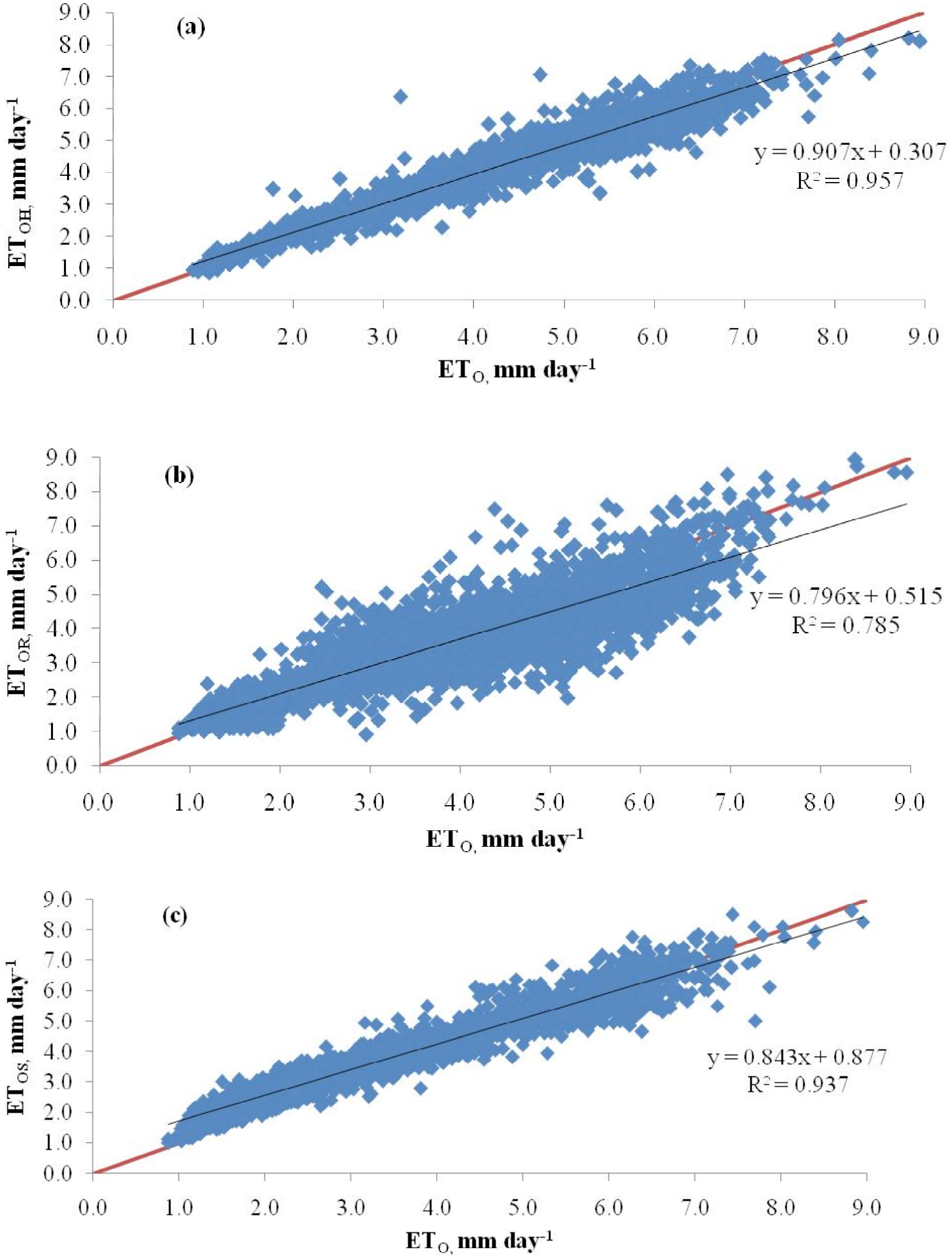

Fig. 1: Scatter plots between reference evapotranspiration (ET_O) estimated from full data set and that computed (a) when humidity is missing (ET_{OH}); (b) when solar radiation is missing (ET_{OR}); and (c) when wind speed is missing (ET_{OS}).

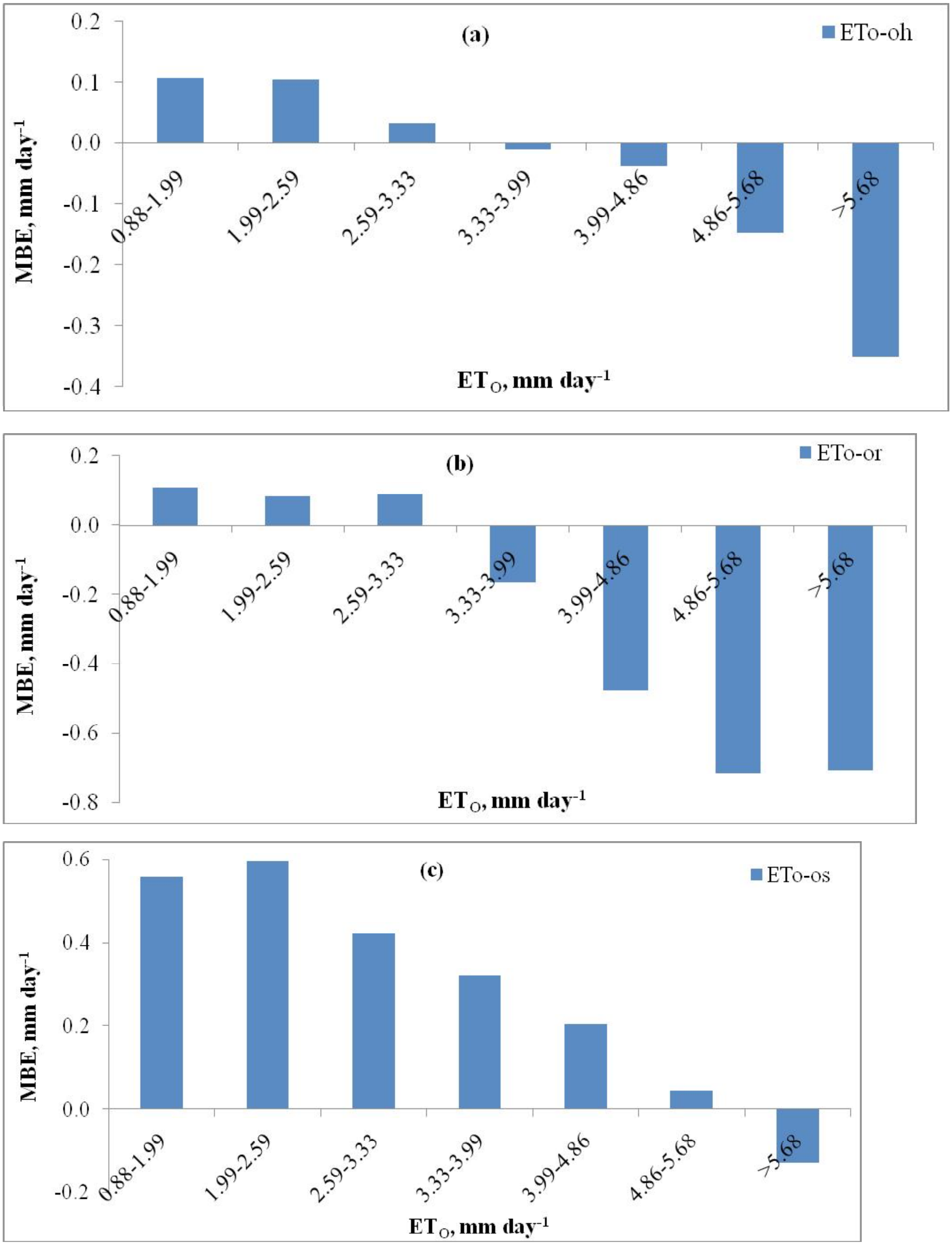

Fig. 2 : Mean Bias Error (MBE) between computed ET_O from full data set and those computed (a) when e_a is estimated from T_{min}, (b) when Rs is estimated from air temperature and (c) when default value of wind speed is used (2 m s^{-1}) for the Pusa.

Table 1: Comparison between ET_O computed from full data set and when e_a is estimated by considering $T_{dew} = T_{min}$ for different years at Pusa station.

Years	RMSE (mm day^{-1})	MBE (mm day^{-1})	Correlation	Index of agreement	χ^2- test statistics
1998	0.348	0.035	0.981	0.99	10.27
1999	0.323	0.020	0.983	0.99	8.68
2000	0.326	0.056	0.979	0.99	8.39
2001	0.291	0.038	0.979	0.99	7.46
2002	0.335	0.049	0.970	0.98	9.68
2003	0.338	0.050	0.972	0.98	9.82
2004	0.325	0.075	0.983	0.99	9.72
2005	0.380	0.083	0.975	0.98	12.37
2006	0.372	0.100	0.984	0.99	11.60

Table 2: Comparison between ET_O computed from full data set and estimated when R_S is computed from air temperature for different years at Pusa station.

Years	RMSE (mm day^{-1})	MBE (mm day^{-1})	Correlation	Index of agreement	χ^2- test statistics
1998	0.842	0.220	0.891	0.94	71.20
1999	0.949	0.326	0.858	0.91	93.70
2000	0.797	0.173	0.870	0.93	62.01
2001	0.774	0.256	0.845	0.90	68.48
2002	0.749	0.277	0.855	0.90	62.32
2003	0.770	0.305	0.867	0.91	73.97
2004	0.712	0.282	0.917	0.94	50.58
2005	0.598	0.150	0.928	0.96	32.91
2006	0.712	0.291	0.936	0.95	44.59

R^2, χ^2-test value for goodness of fit and index of agreement values show strong relationships among data which can be seen by high R^2 values around 0.95; lowest average $\div^2$- test value of 11.60 and index of agreement value around unity for all the years of observation. The values for the statistical indices are of the same order and magnitude of those referred by Cai et al., (2007) and Popova et al., (2006) in their computations of ET_O with limited data. Thus, there is a reasonably good agreement between these two methods i.e. the methods to compute ET_{OH} when relative humidity is absent and ET_O computed from full data set. These lowest values of RMSE and MBE and high values of correlation between ET_O and ET_{OH} indicate that it may be an appropriate method to compute ET_O when relative humidity is absent.

When solar radiation data are missing

The missing data Rs was computed using Eq. (3) with an assumption that difference between maximum and minimum temperatures are closely related to the existing daily solar radiation in a given location (Allen et al., 1998). The results of the analysis revealed that the range of annual minimum value of ET_{OR} was observed to be 0.90 (2004) to 1.59 (2005) mm day^{-1} while that of annual maximum was 6.71 (2002) to 9.06 (1998) mm day^{-1}. The values of daily average ET_{OR} ranges from 3.36 (2003) to 3.68 (2006) mm day^{-1}.

The weak performance of FAO-56 PM method to estimate when solar radiation is missing can be better understood by analysing the relationship between observed (ref ET_O) and estimated *SR* data (ET_{OR}) (Fig. 1(b)). The method recommended by Allen et al. (1998) to estimate *SR* proved to be fairly poor option for Pusa conditions, presenting high dispersion ($R^2 \sim 0.78$) and systematic overestimation from *SR* below 3.50 mm day^{-1} and underestimation above the ET_{OR} values of 3.50 mm day^{-1}. The errors associated with this condition are presented in Fig. 2(b) for MBE which shows an underestimation at the majority of the observations when estimating ET_O using T_{max} and T_{min} to assess R_s.

The RMSE and MBE values were larger than those when R_S is estimated using temperature difference method. The values of MBE between ET_O and ET_{OR} ranged from 0.150 (2005) to 0.326 (1999) mm day$^{"1}$. There is a reasonably good agreement between the two methods since the RMSE values were less than 0.949 mm day$^{"1}$. These values are consistent with the results presented by Popova et al., (2006). These lower values of RMSE and MBE and corresponding high $\div^2$-test values indicate that it is appropriate to compute ET_O when estimating R_s with Eq. (3). Furthermore, the values of index of agreement between the two methods for estimating ET_O using temperature difference method were relatively higher. It ranged from 0.90 (2001 & 2002) to 0.96 (2005) which are close to unity (Table 2).

When wind speed data are missing

Wind speed is not always available in agro-

Table 3 : Comparison between ET_O computed from full data set and estimated using default value of wind speed for different years at Pusa station.

Years	RMSE (mm day^{-1})	MBE (mm day^{-1})	Correlation	Index of agreement	χ^2- test statistics
1998	0.491	0.275	0.975	0.98	25.12
1999	0.533	0.328	0.971	0.97	28.56
2000	0.490	0.321	0.975	0.97	26.28
2001	0.478	0.250	0.969	0.96	25.12
2002	0.527	0.312	0.964	0.95	30.36
2003	0.504	0.245	0.966	0.96	27.59
2004	0.471	0.306	0.976	0.98	23.18
2005	0.566	0.198	0.969	0.95	32.38
2006	0.530	0.348	0.975	0.98	27.29

meteorological stations that could impede the ET_O estimation using Eq. (1). An alternatives given by Allen et al. (1998) were followed in order to estimate ET_O when default world average value of wind speed was taken 2 m s^{-1} i.e. $u_2 = 2$ m s^{-1}. The plot shows the aerodynamic effect on ET_O especially in the coldest period of the year ($ET_O < 4.5$ mm day^{-1}). The range of annual minimum and maximum values of ET_{OS} were observed to be 1.01 to 1.16 (2005) and 6.00 (2001) to 8.63 (1998) mm day^{-1}, respectively. The average value of ET_{OS} for the years 1998 to 2006 was 4.07 mm day^{-1}.

Analysis of the results indicate that there is a high correlation between ET_O-ref and ET_{OS} (R^2 exceed 0.90) (Fig. 1(c)). The actual values of the estimates are very similar (R^2 values are close to unity). However, it can be seen from Fig. 2(c) depicting the MBE values between ET_O ref and ET_{OS} that computed ET_{OS} values overestimates below 5.68 mm day^{-1} while underestimates above 5.68 mm day^{-1} (Fig. 1(c)).

Table 3 summarizes the statistical indices for comparing ET_{OS} computed when u_2 is missing as outlined above with $ET_{O\text{-ref}}$. The RMSE and MBE values were larger than those when using the default value of wind speed as ET_{OS} tends to overestimate ET_O for the different evapotranspiration rates. When using default value of wind speed, the RMSE and MBE values ranged from 0.478 (2001) to 0.566 (2005) mm day^{-1} and from 0.198 (2005) to 0.348 (2006) mm day^{-1}, respectively.

R^2, χ^2- test and index of agreement values show strong relationships among data which can be seen by high R^2 values around 0.96; average x^2- test value of 27.32 and degree of agreement values around unity for all the years of observation. Concluding, when wind speed is not available the procedure of using default value of wind speed for every years produced the best results for estimating ET_O.

SUMMARY AND CONCLUSIONS

Different methods outlined by Allen et al. (1998) to compute ET_O with limited climate data were evaluated for Pusa Observatory. The comparison over 9 years of climatic data from 1998 to 2006 revealed that the average values of reference evapotranspiration computed by the use of $T_{min} = T_{dew}$ in FAO-56 PM method (3.74 mm day^{-1}) were close to that computed by FAO-56 PM method (3.78 mm day^{-1}) for the region. However, the ET_O computed when R_S is estimated from temperature difference method was observed to be 3.53 mm day^{-1}. Hence, it was concluded that when e_a is estimated from $T_{min} = T_{dew}$ in FAO-56 PM method yielded accurate values of reference evapotranspiration. The use of R_S estimated from maximum and minimum daily temperature in FAO-56 PM method could be a good alternative to compute reference evapotranspiration. As far as the use of default value of wind speed is concerned, it led to relatively high average value of ET_O (4.07 mm day^{-1}) in the region.

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