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ORIGINAL ARTICLE

Sensitivity Analysis of FAO-56 Penman-Monteith Method for Different Agro-ecological Regions of India

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Abstract This paper analyzes the sensitivity of reference evapotranspiration (ET_o) to climatic variables for different agro-ecological regions of India: semi-arid (Kovilpatti and Parbhani), humid (Mohanpur), and sub-humid (Ludhiana and Ranichauri). The FAO-56 Penman-Monteith (FAO-56 PM) method is used to estimate ET_o, and sensitivity of ET_o has been studied in terms of change in maximum air temperature (T_{max}), minimum air temperature (T_{min}), solar radiation (R_s), average relative humidity (RH_{avg}), and wind speed (W_s). Sensitivity analysis is performed by increasing and decreasing the climate variables such as T_{max}, T_{min}, R_s, and RH_{avg} by one unit of increment and decrement, respectively, up to five units (except for W_s) while keeping the other variables and parameters constant. However, wind speed W_s (km h^{-1}) is only increased with an increment of one km h^{-1} up to five km h^{-1}. The results showed that the change in ET_o is linearly related to change in all climate variables (r^2=0.97 in most cases) at all sites. Further, ET_o is most sensitive to R_s at Kovilpatti, Mohanpur and Ranichauri, and to W_s at Ludhiana and Parbhani. However, the sensitivity of ET_o to the same variable shows considerable variation from site to site and at the same site within the year. ET_o is less sensitive to RH_{avg} followed by T_{min} at all sites.

Keywords Penman-Monteith reference evapotranspiration · Sensitivity analysis · Sensitivity coefficient · India

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1 Introduction

Of all the components of the hydrological cycle, evapotranspiration (ET) is the key component and its estimation is the prior task of researchers and practitioners working in the fields of land, crop, water, and atmosphere studies. The procedure for estimating ET rates of agricultural crops (crop ET, $ET_{c.}$) involves two steps. As a first step, computation of reference evapotranspiration (ET_o) is carried out using regularly recorded climatic data and ET_o is multiplied by the crop coefficient (K_c) in the second step. The K_c incorporates crop characteristics and averaged effects of evaporation from the soil (Doorenbos and Pruitt 1977). Accurate estimation of ET_o is the basis for solving a wide array of problems such as crop water requirement computation, irrigation scheduling, water balance computation, evaluation of land use changes etc.

There exists a multitude of methods (e.g., Jensen et al. 1990; Jennifer and Sudheer 2001; George et al. 2002; Itenfisu et al. 2003) for measurement and estimation of ET_o. Direct measurement of ET_o using the lysimeter or the water balance approach is a costly and time consuming process (Adamala et al. 2014a,b). Therefore, based on the easily available location characteristics (elevation and latitude) and meteorological parameters many indirect methods have been developed for ET_o estimation, viz. (i) temperature based (Thornthwaite 1948; Hargreaves and Samani 1985), (ii) radiation based (Priestley and Taylor 1972; Turc 1961), (iii) evaporation based (Christiansen 1968), and (iv) combination method (Penman 1948).

The reliability of ET_o estimation by the above methods largely depends on the site characteristics, quality and quantity of input climatic data, chosen method, and assumptions related to its parameterization (Adamala et al. 2015). When the required set of climate data are available for a site, ET_o is often calculated using the FAO-56 Penman-Monteith (FAO-56 PM) combination method. This method is recommended as a sole and standard method by the Food and Agriculture Organization (FAO) (Allen et al. 1998) for the estimation of ET_o if all the required data are available.

ET_o provides a measure of the integrated effect of climatic variables such as temperature (T_{avg}), humidity (RH_{avg}), wind speed (W_s), solar radiation (R_s). In humid and arid regions, ET_o provides an upper limit for ET_c and indicates the total available energy for ET_c. Among the above climatic variables, only some of the input variables exert a greater influence on ET_o, as compared to others. Thus, it is very important to understand the effect of a change in each climatic variable on estimated ET_o before performing any analysis. Generally, the above objective can be achieved by a process called sensitivity analysis. Sensitivity analysis quantifies how changes in the independent variables (input) of the equation or model affect the dependent variable (output). The results of this analysis make it possible to determine the required accuracy for measuring climatic variables to be used in estimating ET_o (Irmak et al. 2006).

In the past, a few studies (McCuen 1974; Saxton 1975; Coleman and DeCoursey 1976; Beven 1979; Piper 1989; McKenney and Rosenberg 1993; Ley et al. 1994; Rana and Katerji 1998) have been devoted to sensitivity analysis of evaporation or ET_o combination models to different input and parametric data using single or multiple climatic stations. Hupet and Vanclooster (2001) quantified the effect of the sampling frequency of commonly measured climatic variables on ET_o estimates by the FAO-56 PM equation in a moderately humid climate area in Belgium. The results showed that the R_s and W_s were the most sensitive to bias induced by the inadequate temporal sampling frequency. Goyal (2004) showed that ET_o was less sensitive to increase in R_s, followed by W_s in comparison to T_{avg} and increase in vapor pressure had a small negative effect on ET_o. Gong et al. (2006) used non-dimensional relative sensitivity coefficients to predict responses of ET_o to perturbations in four climatic variables:

T_{avg}, W_s, RH_{avg}, and sunshine duration. Results showed that RH_{avg} was the most sensitive variable, followed by short-wave radiation, T_{avg} and W_s. Irmak et al. (2006) studied the sensitivity of the standardized ASCE PM ET_o equation in different climates of the United States from semi-arid to humid conditions. The results indicated that the ET_o was most sensitive to vapor pressure deficit (*VPD*) at all sites, while the sensitivity of ET_o to the same variable showed significant variation from one site to another and at the same site within the year. Bormann (2010) compared 18 different potential evapotranspiration (PET) models with respect to their sensitivity to observed climate change. It was found that the PET models were sensitive to significant trends in climate data and all models showed different sensitivities. Kwon and Choi (2011) reported that an estimated ET_o showed different sensitivity to variations of meteorological parameters in order of vapor pressure followed by W_s and R_s. Tabari and Hosseinzadeh Talaee (2014) reported that the sensitivity of ET_o to wind speed and air temperature decreased and to sunshine hours increased from arid to the humid environment.

Most studies have focused on the sensitivity of different evaporation or ET_o combination models for a single region/climatic station. However, Irmak et al. (2006) carried out a sensitivity analysis for ASCE PM ET_o model for different regions (semi-arid, Mediterranean, coastal humid, inland humid and semi-humid, and island). The sensitivity of the FAO-56 PM combination-based equation to climatic variables for different regions (semi-arid, humid, and sub-humid) in India has not yet been studied. Thus, the objectives of this study are:

1. To perform sensitivity analysis of the FAO-56 PM method to climate variables in the following regions of India: semi-arid (Kovilpatti and Parbhani), humid (Mohanpur), and sub-humid (Ludhiana and Ranichauri).
2. To derive sensitivity coefficients for each of the climatic variables and quantify daily changes in ET_o per unit of change in each climatic variable.
3. To evaluate the seasonal trend of change in ET_o.

2 Materials and Methods

2.1 Study Area and Climate Data

For this study, five climatic stations (Fig. 1) in different agro-ecological regions of India were considered. Study regions include semi-arid (Kovilpatti and Parbhani), humid (Mohanpur), and sub-humid (Ludhiana and Ranichauri). The daily climatic data of 5-year (2001–05) period for the selected stations were collected from a project called All India Coordinated Project on Agro-meteorology (AICPAM), Central Research Institute for Dryland Agriculture (CRIDA), India. Table 1 presents information related to latitude, longitude, elevation, and meteorological characteristics of the chosen sites. The study area covers a wide range of variation in altitude (10 m at Mohanpur to 1600 m at Ranichauri above the mean sea level) and mean annual rainfall (680 mm at Ludhiana to 1500 mm at Mohanpur). The characteristics of long-term average monthly climatic variables (Table 2) shows T_{avg} ranges from 14.66 °C at Ranichauri to 28.67 °C at Kovilpatti. The maximum RH_{avg} of 79.52 % is observed at the humid site of Mohanpur and minimum RH_{avg} of 55.21 % is observed at Parbhani (semi-arid). Stronger winds with W_s of 6.72 km h^{-1} are observed at Kovilpatti (semi-arid) and weak winds of 1.53 km h^{-1} are observed at Mohanpur (humid). The R_s ranges from 16.31 MJ m^{-2} day^{-1} at Ranichauri to 25.37 MJ m^{-2} day^{-1} at Mohanpur.

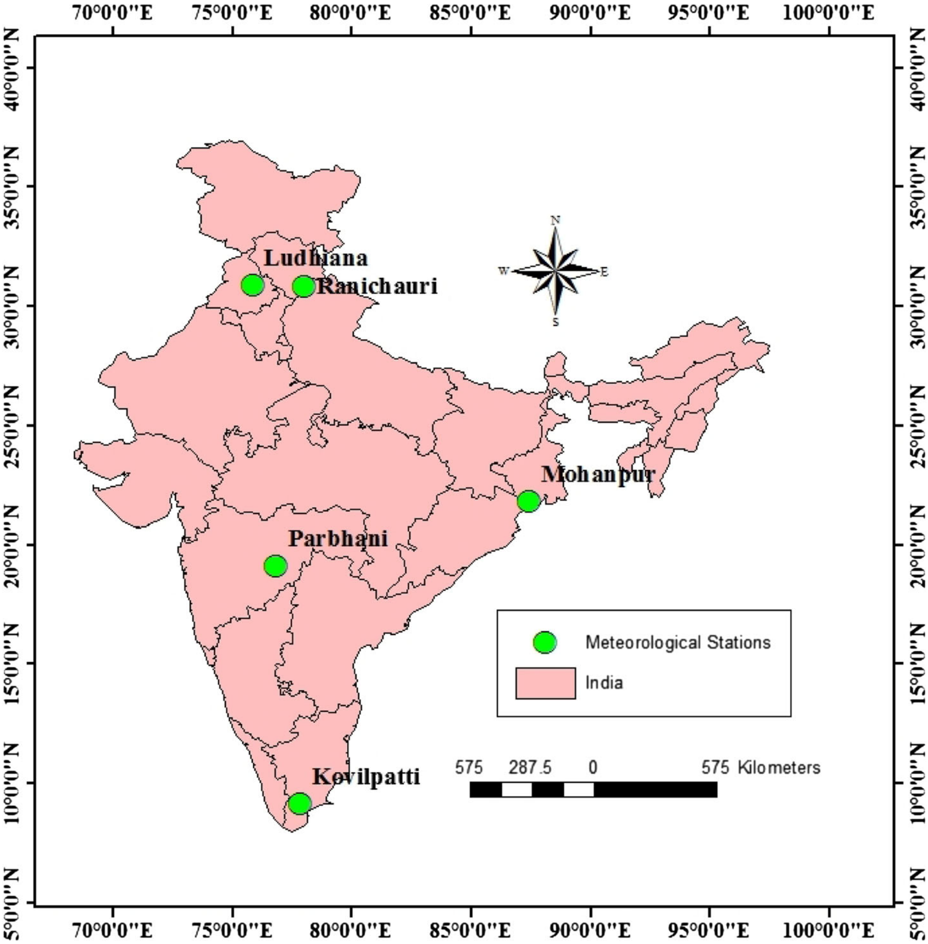

Fig. 1 The locations of selected five climatic stations as study sites in India

2.2 Evapotranspiration Computation Method

There are many indirect methods to estimate ET_o, but it is difficult to select the best ET_o estimation method for the available data and climatic conditions. To overcome this problem, a decision support system (DSS) for ET_o estimation, i.e., DSS_ET (Bandyopadhyaya et al. 2012) was developed, which supports 22 ET_o estimation methods. It can serve as a research tool with its user-friendly features like options for calculation of various intermediate parameters, generalized data input format with copy–paste option from spreadsheet applications, visualize/check input data and results, features to estimate missing data, and user-friendly graphical user interface (GUI) that enhances its applicability. In the present study, the FAO-56 PM method was considered for daily ET_o estimation and was computed using 'DSS_ET'. The equation for the estimation of daily ET_o can be written as (Allen et al. 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_{avg} + 273} W_s(e_s - e_a)}{\Delta + \gamma(1 + 0.34W_s)} \quad (1)$$

Table 1 Location specifications and climate characteristics during the period 2001–05 of the selected study sites

Station	Region	Lat. (°N)	Lon. (°E)	Ele. (m)	T_{avg} (°C)	RH_{avg} (%)	W_s (km h^{-1})	R_s (MJ m^{-2} day^{-1})	PM-ET_o (mm day^{-1})	Avg. annual rainfall (mm)
Kovilpatti	Semi-arid	9°10’	77°52’	90	28.67	62.23	6.72	19.45	5.22	840
Ludhiana	Sub-humid	30°56’	75°52’	247	23.70	66.54	4.26	18.09	3.91	680
Mohanpur	Humid	21°52’	87°26’	10	26.39	79.52	1.53	25.37	3.62	1500
Parbhani	Semi-arid	19°08’	76°50’	423	26.05	55.21	5.08	20.88	4.84	957
Ranichauri	Sub-humid	30°52’	78°02’	1600	14.66	69.81	4.98	16.31	2.87	1113

Table 2 Characteristics of long-term average monthly climatic variables for each study site

Station	Variable	Jan	Feb	Mar	Aprl	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Avg
Kovilpatti	T_{avg} (°C)	25.11	26.75	29.10	29.95	30.88	31.20	30.96	30.97	30.17	28.24	25.72	25.01	28.67
	RH_{avg} (%)	65.63	63.23	58.92	66.25	58.65	55.96	53.05	51.06	54.40	69.14	79.07	71.34	62.23
	W_S (km h^{-1})	4.16	4.92	5.42	4.96	7.59	11.48	10.58	10.78	8.59	5.94	2.91	3.29	6.72
	R_s (MJ m^{-2} day^{-1})	18.10	20.44	22.75	21.31	20.79	19.94	19.38	20.74	20.33	18.06	14.85	16.71	19.45
Ludhiana	T_{avg} (°C)	11.42	14.86	20.66	27.05	31.09	31.99	30.81	30.16	28.42	24.66	19.12	14.19	23.70
	RH_{avg} (%)	82.00	73.90	67.07	43.76	41.31	57.02	75.19	79.11	74.15	64.98	64.16	75.79	66.54
	W_S (km h^{-1})	3.65	4.12	4.11	5.10	6.23	6.48	5.42	4.49	3.61	2.47	2.65	2.77	4.26
	R_s (MJ m^{-2} day^{-1})	10.60	15.41	19.56	22.36	24.88	22.88	20.11	20.21	19.94	16.60	13.70	10.89	18.09
Mohanpur	T_{avg} (°C)	17.91	22.25	26.91	29.88	30.46	30.15	29.43	29.36	29.18	27.49	23.81	19.90	26.39
	RH_{avg} (%)	76.23	70.61	70.59	73.69	75.48	84.01	87.56	88.93	88.26	85.57	77.41	75.86	79.52
	W_S (km h^{-1})	0.92	1.32	2.18	3.41	2.87	2.55	1.68	1.17	1.03	0.51	0.29	0.46	1.53
	R_s (MJ m^{-2} day^{-1})	25.66	25.70	26.03	26.05	25.13	25.47	25.12	25.11	25.17	24.89	24.90	25.23	25.37
Parbhani	T_{avg} (°C)	20.77	23.57	27.21	30.96	33.17	30.27	27.24	25.73	26.57	25.17	22.01	19.93	26.05
	RH_{avg} (%)	53.99	49.15	37.31	33.15	35.16	57.29	71.73	78.21	73.82	61.96	55.67	55.12	55.21
	W_S (km h^{-1})	3.58	3.71	4.40	5.09	7.85	8.35	6.97	5.88	4.61	4.37	3.32	2.85	5.08
	R_s (MJ m^{-2} day^{-1})	19.07	22.15	24.53	25.63	26.22	20.97	17.46	15.66	19.49	20.46	20.07	18.83	20.88
Ranichauri	T_{avg} (°C)	6.37	8.03	12.58	16.96	19.35	20.32	19.85	19.32	17.88	15.03	11.61	8.56	14.66
	RH_{avg} (%)	70.60	69.25	58.28	48.54	54.91	71.00	86.36	89.68	85.08	71.08	66.54	66.44	69.81
	W_S (km h^{-1})	4.93	5.67	5.59	4.98	5.08	4.90	4.99	4.42	4.54	4.96	4.92	4.79	4.98
	R_s (MJ m^{-2} day^{-1})	10.48	13.58	17.50	21.17	23.96	21.06	17.49	14.92	15.74	16.17	12.85	10.79	16.31

where ET_o=reference evapotranspiration (mm day^{-1}); R_n=net radiation at the crop surface (MJ m^{-2} day^{-1}); G=soil heat flux density (MJ m^{-2} day^{-1}); T_{avg}=average daily air temperature at 2 m height (°C); W_s=wind speed at 2 m height (m s^{-1}); e_s=saturation vapor pressure (kPa); e_a=actual vapor pressure (kPa); Δ=slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1}); γ=psychometric constant (kPa °C^{-1}).

2.3 Sensitivity Analysis and Sensitivity Coefficients

There is no single, universally accepted procedure for analyzing the sensitivity and computing sensitivity coefficients. A common approach for analyzing sensitivity is to explore the effects of change in input variables, one at a time, on an output variable. The sensitivity coefficients for each climatic variable (i.e., T_{max}, T_{min}, R_s, RH_{avg}, and W_s) were derived from the ratio of change in ET_o to the unit of change (either increase or decrease) in each climatic variable on a daily basis. It is represented as follows (Smajstrla et al. 1987; Irmak et al. 2006):

$$C_s = \frac{CH_{ET_o}}{CH_{CV}} \tag{2}$$

where C_s=sensitivity coefficient, CH_{ET_o} = change in ET_o with respect to change in climate variable, and CH_{CV} = change (increase or decrease) in climate variable.

The absolute sensitivity analysis approach was used in this study. It was assumed that if any error encountered during data measurement, the quantity of error would not be any relative proportion of actual measurement. This error would be any absolute value which depends on the device used for measurement and/or operator.

2.4 Analysis of Sensitivity of ET_o with respect to Climate Variables

The sensitivity of the FAO-56 PM ET_o equation for each study site was quantified with respect to each climatic variable using the procedure reported by Irmak et al. (2006). Figure 2 shows the process flowchart of sensitivity analysis. It was assumed that maximum error could be encountered in data measurement is up to 5 units, either positive or negative. Therefore, sensitivity analysis was performed by increasing and decreasing the climate variables such as T_{max} (°C), T_{min} (°C), R_s (MJ m^{-2} day^{-1}), and RH_{avg} (%) by one unit of increment and decrement up to five units (except for W_s) while keeping the other variables and parameters constant. However, wind speed W_s (km h^{-1}) was only increased with an increment of one km h^{-1} up to five km h^{-1} because of the lower value of W_s. Here it is worth to mention that in the preliminary analysis of this study, it was found that T_{max} and T_{min} are not equally affecting ET_o in all the study sites. Therefore, T_{max} and T_{min} were considered for analysis rather than average temperature (T_{avg}). In natural condition, these climatic variables are inter-related to each other and errors in one variable may change the other variable. But if any error is encountered at the time of measuring of any variable, it does not affect the measurement of other parameters. This is because measurement data are not inter-related to each other. Therefore, for sensitivity analysis one parameter was changed at a time with other parameters remained constant during the analysis period. The most commonly used unit was considered for the unit of each climatic variable (T_{max} and T_{min} (°C), R_s (MJ m^{-2} day^{-1}), W_s (km h^{-1}), and RH_{avg} (%)).

The daily average values for each climatic variable were obtained after taking an average value for a period of 5 years (i.e., 2001–05) climate data and the base ET_o values for different

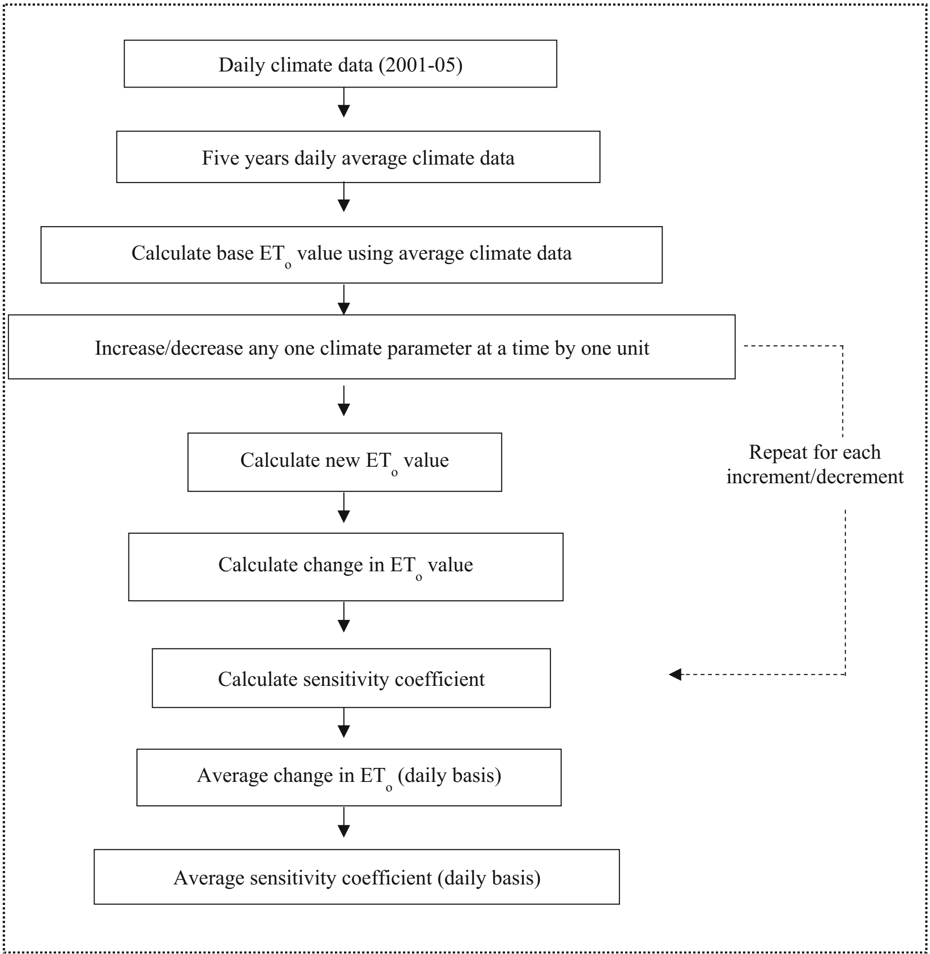

Fig. 2 Process flowchart of sensitivity analysis

stations were estimated using this data without any change (Fig. 2). Further, each climate variable was either increased and decreased or only increased (in the case of W_s) individually from one unit up to five unit with one unit interval, and a new set of ET_o values was estimated followed by the change (either increase or decrease) in ET_o on daily basis. Thus, for each study site, base ET_o, new ET_o and change in ET_o values were computed.

Quantitative and qualitative effect of climate variable on ET_o was analyzed by computing daily C_s and the slope of the linear regression line between change in ET_o with respect to change in each climate variable. For each increase or decrease in climate variable, C_s was computed. After that, average C_s was obtained on a daily basis. Similarly, the average change in ET_o was also obtained. For example, to determine daily average C_s for W_s at Ludhiana, the change in ET_o was determined as the difference between the computed base ET_o and new ET_o values for each day considering one to five unit increase in W_s. After that, the corresponding change in ET_o was divided by one, two, three, four, and five separately for each day. This value indicates C_s for one, two, three, four, and five unit increase in climate variables, respectively. This procedure was also repeated for the condition when the climate variables were decreased by one unit to up to five units (not applicable for W_s). After getting C_s with respect to each increase W_s (also include a decrease in climate variable for other cases), the average of these values indicates daily average C_s of W_s for that particular day.

3 Results and Discussion

The ET_o values were estimated by the FAO-56 PM method for three regions using mean daily climate data related to T_{max}, T_{min}, R_s, RH_{avg}, and W_s. Figure 3 shows estimated mean daily ET_o values for all selected sites. ET_o was maximum at Parbhani (1935 mm) and minimum at Ranichauri (1087 mm) among the chosen sites. In the mid-year ET_o values were higher as compared to start and end of the year for all the sites. Among the five sites, least variation in ET_o was found at Mohanpur. Further, maximum ET_o during the monsoon period (June-October) was observed at Kovilpatti. For FAO-56 PM estimated daily ET_o values, the mean and standard deviation were found to be 5.30, 3.94, 4.98, 4.85 and 2.98 mm, and 1.37, 1.84, 0.68, 1.49 and 1.13 mm for Kovilpatti, Ludhiana, Mohanpur, Parbhani, and Ranichauri, respectively.

3.1 Response between Change in ET_o to Change in Each Climatic Variable

A likely change in ET_o is expected to change in climatic variables (T_{max}, T_{min}, R_s, RH_{avg}, and W_s); however, it is important to analyze which variable has a significant effect on ET_o estimation under different regions. The amount of change in ET_o (mm day^{-1}) with respect to a unit change in each climate variable is presented in Fig. 4 for all selected sites. Five separate lines corresponding to each climatic variable (T_{max}, T_{min}, R_s, RH_{avg}, and W_s) are shown in each figure (Fig. 4). The magnitude of the effect of a change in each climate variable on the change in ET_o showed considerable variations among variables and sites (Fig. 4).

The regression coefficients (slope and intercept of the regression line) between the changes in ET_o relative to the unit change in climatic variables for each study site are given in Table 3. The slope of the regression lines (Table 3) represents the average slope for the entire year, but it does not provide information on the seasonal changes in slope. In general, the response of ET_o to all climatic variables (T_{max}, R_s, RH_{avg}, and W_s) for all sites was linear with r^2 values=0.99

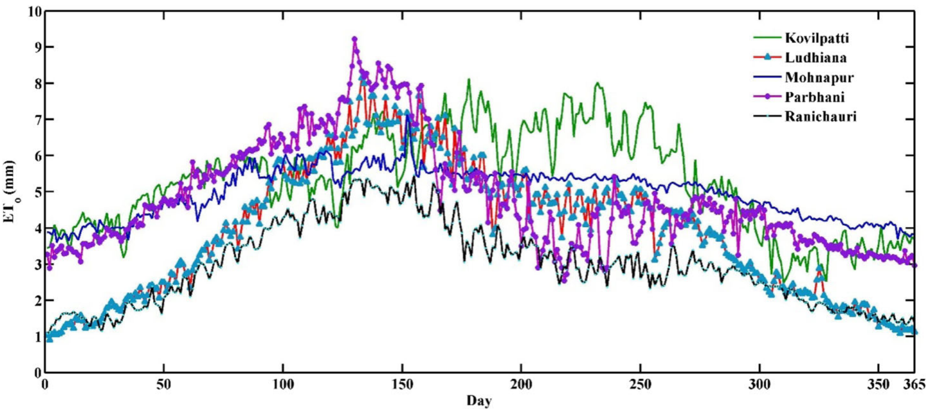

Fig. 3 Daily average FAO 56 PM estimated ET_o for each study site

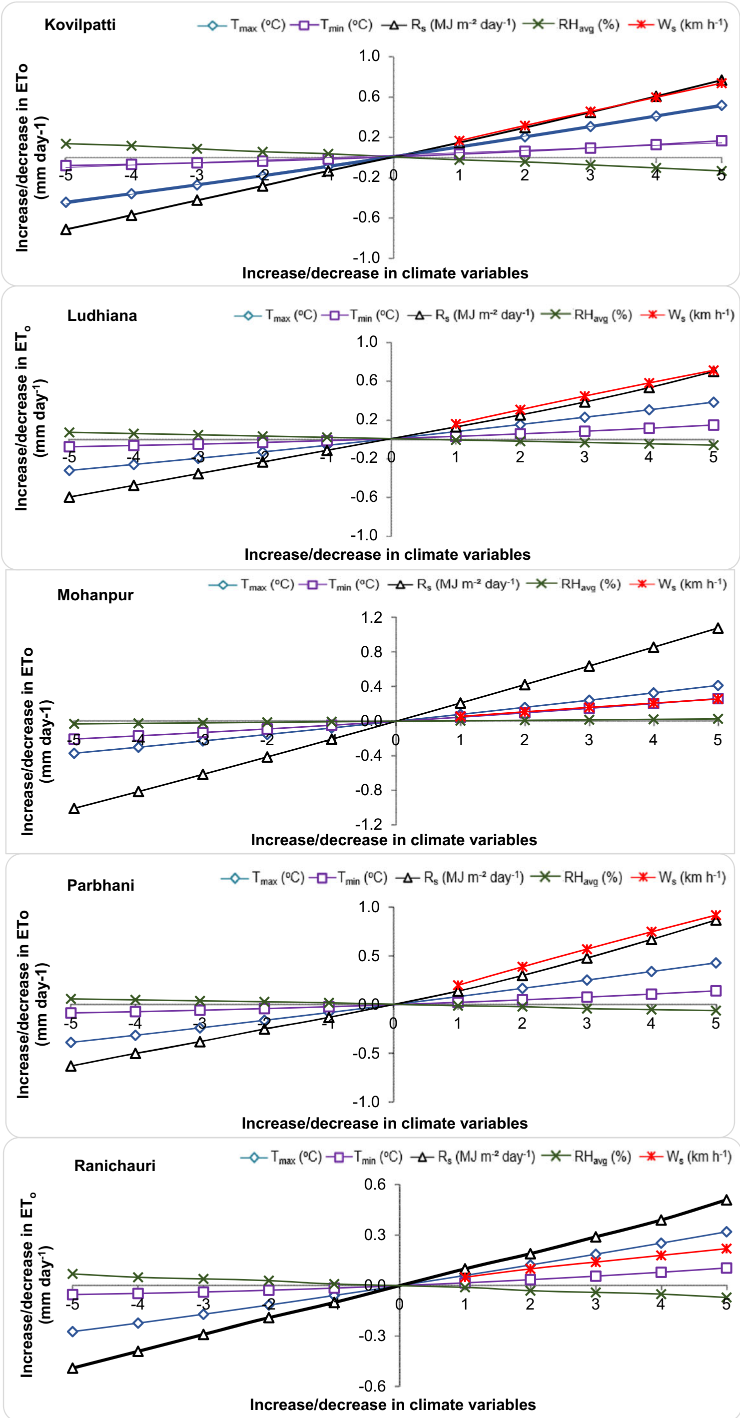

Fig. 4 Increase or decrease in ET_o (mm day^{-1}) with respect to increase or decrease in climate variables for each study site

Table 3 Regression coefficients between change in ET_o (mm day^{-1}) with respect to change in climate variables

Station	Variable	Slope	Intercept	r^2
Kovilpatti	W_S	0.142	0.022	0.99
	T_{max}	0.0963	0.0133	0.99
	T_{min}	0.0245	0.0161	0.97
	R_s	0.147	0.007	0.99
	RH_{avg}	−0.027	−0.001	0.99
Ludhiana	W_S	0.1382	0.0198	0.99
	T_{max}	0.0706	0.0103	0.99
	T_{min}	0.0223	0.0120	0.98
	R_s	0.1269	0.0148	0.99
	RH_{avg}	−0.0132	−0.0008	0.99
Mohanpur	W_S	0.0468	0.0124	0.99
	T_{max}	0.0786	0.0096	0.99
	T_{min}	0.0468	0.0124	0.99
	R_s	0.2090	0.0150	0.99
	RH_{avg}	0.0058	−0.0007	0.99
Parbhani	W_S	0.1800	0.026	0.99
	T_{max}	0.0818	0.0095	0.99
	T_{min}	0.0226	0.0130	0.98
	R_s	0.1466	0.057	0.99
	RH_{avg}	−0.0125	0.002	0.99
Ranichauri	W_S	0.0420	0.0120	0.99
	T_{max}	0.0594	0.0104	0.99
	T_{min}	0.0158	0.0114	0.97
	R_s	0.0984	0.0002	0.99
	RH_{avg}	−0.0135	0.0000	0.99

($r^2 \geq 0.97$ for T_{min}). Irmak et al. (2006) also reported the least effect of T_{min} on ET_o. Based on the slope, the change in ET_o was most sensitive (maximum slope) to R_s for Kovilpatti, Mohanpur, and Ranichauri and to W_s for Ludhiana and Parbhani.

3.2 Daily Variation in Sensitivity Coefficients

The daily variation in sensitivity coefficients (C_s) can provide important information on how ET_o responds to each climate variable throughout the year in different sites. Daily values of C_s were computed for each variable in chosen sites (Fig. 5). These C_s values represent the sensitivity of ET_o to errors in measurement of a specific climatic variable based on the assumption that other variables were accurately measured and climatic conditions were constant during the analysis period. Monthly and annual average of these coefficients for each variable are given in Table 4. All C_s values showed a large degree of daily fluctuations at all sites. The sensitivity of ET_o to the same climate variable showed variation within the site.

The sensitivity of evapotranspiration to W_s decreased from semi-arid to the humid climate. In the semi-arid region, the wind flow most probably replaces the moist air very rapidly with dry air especially in summer months, and causes an increase in ET_o compared to other regions.

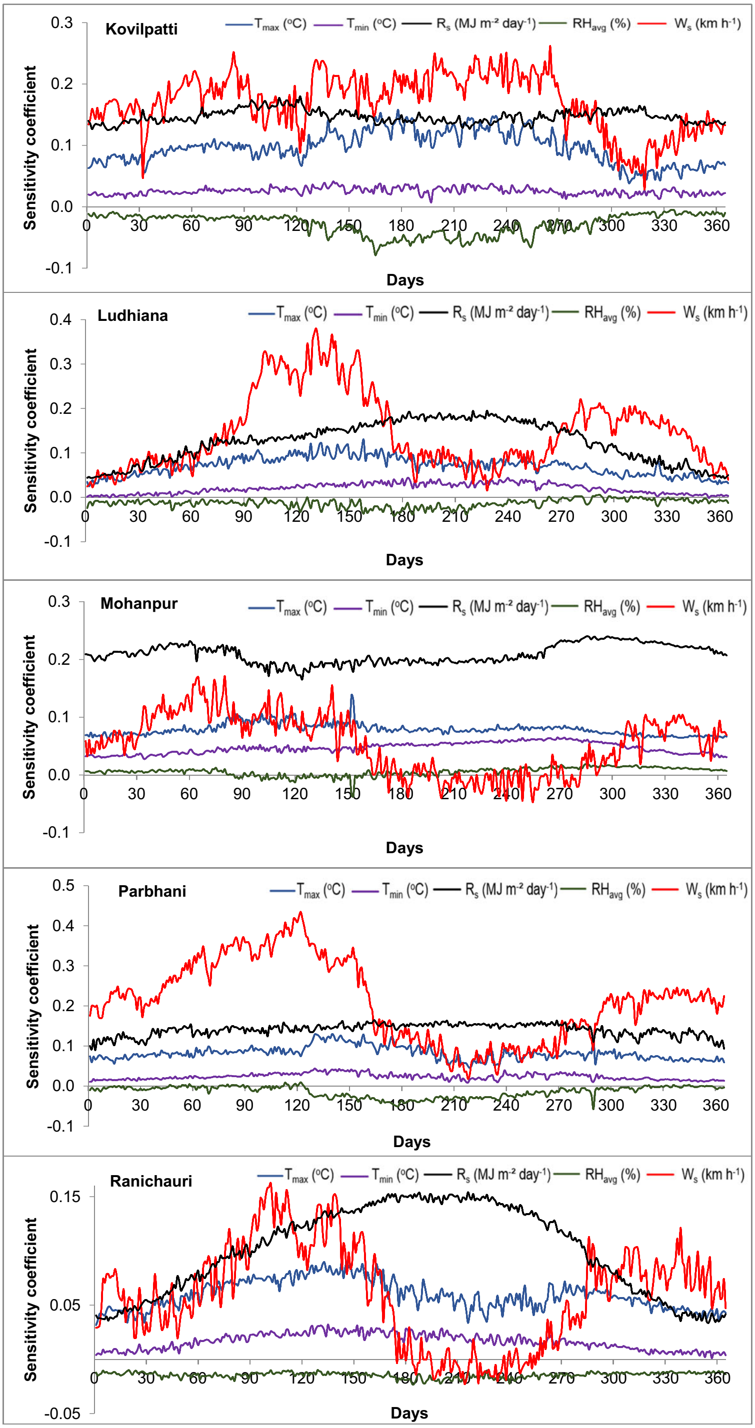

Fig. 5 Daily changes in sensitivity coefficients

Table 4 Monthly and annual average sensitivity coefficient with respect to change in each climate variable

Stations	Variables	Jan	Feb	Mar	Aprl	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Avg
Kovilpatti	W_S	0.14	0.15	0.18	0.14	0.17	0.17	0.19	0.19	0.19	0.11	0.07	0.11	0.15
	T_{max}	0.08	0.09	0.10	0.09	0.10	0.13	0.12	0.13	0.11	0.09	0.05	0.06	0.10
	T_{min}	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03
	R_s	0.13	0.14	0.31	0.16	0.15	0.14	0.14	0.14	0.14	0.15	0.15	0.14	0.16
	RH_{avg}	−0.01	−0.01	−0.01	−0.01	−0.02	−0.03	−0.03	−0.03	−0.02	−0.01	−0.01	−0.01	−0.02
Ludhiana	W_S	0.05	0.08	0.13	0.28	0.30	0.20	0.09	0.07	0.10	0.18	0.18	0.10	0.15
	T_{max}	0.04	0.06	0.08	0.09	0.10	0.10	0.08	0.07	0.07	0.06	0.05	0.04	0.07
	T_{min}	0.00	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.01	0.01	0.02
	R_s	0.05	0.08	0.12	0.13	0.15	0.17	0.18	0.18	0.16	0.12	0.08	0.06	0.12
	RH_{avg}	−0.01	−0.01	−0.01	−0.01	−0.02	−0.03	−0.02	−0.02	−0.01	0.00	0.00	−0.01	−0.01
Mohanpur	W_S	0.06	0.11	0.12	0.10	0.09	0.02	0.00	−0.01	0.00	0.02	0.08	0.07	0.05
	T_{max}	0.07	0.07	0.09	0.10	0.09	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.08
	T_{min}	0.03	0.04	0.04	0.05	0.04	0.05	0.05	0.06	0.06	0.06	0.04	0.04	0.05
	R_s	0.21	0.22	0.22	0.19	0.19	0.20	0.20	0.20	0.21	0.24	0.23	0.22	0.21
	RH_{avg}	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01
Parbhani	W_S	0.19	0.23	0.30	0.34	0.31	0.17	0.08	0.05	0.08	0.15	0.20	0.20	0.19
	T_{max}	0.07	0.08	0.09	0.09	0.11	0.10	0.08	0.07	0.08	0.08	0.07	0.07	0.08
	T_{min}	0.02	0.02	0.02	0.03	0.04	0.03	0.02	0.02	0.03	0.02	0.02	0.01	0.02
	R_s	0.12	0.14	0.28	0.15	0.15	0.15	0.15	0.15	0.15	0.14	0.14	0.12	0.15
	RH_{avg}	0.00	0.00	0.00	0.00	−0.01	−0.02	−0.02	−0.02	−0.01	−0.01	0.00	0.00	−0.01
Ranichauri	W_S	0.05	0.04	0.07	0.12	0.10	0.04	−0.01	−0.02	0.00	0.05	0.07	0.07	0.05
	T_{max}	0.04	0.05	0.07	0.07	0.08	0.07	0.06	0.05	0.06	0.06	0.05	0.04	0.06
	T_{min}	0.01	0.01	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02
	R_s	0.04	0.06	0.17	0.11	0.13	0.14	0.15	0.14	0.12	0.09	0.06	0.04	0.10
	RH_{avg}	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01	−0.01

In humid and sub-humid regions, due to the high RH_{avg} and the presence of clouds, the ET_o demand is low. Under these conditions, the wind replaces the saturated air and removes heat energy. As a result, the effect of W_s on ET_o in humid and sub-humid regions was less compared to semi-arid conditions, where small variations in W_s may result in larger variations in the ET_o rate (Estevez et al. 2009; Tabari and Hosseinzadeh Talaee 2014).

The C_s values for W_s were higher and lower during the summer and winter months, respectively in Parbhani, Ludhiana, and Kovilpatti. At Mohanpur and Ranichauri, the C_s values for W_s were very less for both the winter and summer months (except February, March and April). For Parbhani, C_s varied from 0.05 in August to 0.34 in April with an annual average value of 0.19. At Ranichauri, the C_s was almost zero in September with an annual average value of 0.05, and at Mohanpur it was zero in the months of July and September with an annual average value of 0.05.

The ET_o is primarily affected by an increase in temperature due to higher capacity of air to hold water vapor, which transfers energy to the crop and exerts as such a controlling influence on the rate of ET_o. The slopes of the regression line for T_{max} were greater in semi-arid region (Kovilpatti: 0.0963) and Parbhani: 0.0818) as compared to humid (Mohanpur: 0.0786) and sub-humid region sites (Ludhiana: 0.0706), and Ranichauri: 0.0594) (Table 3). At all sites, C_s values for T_{max} were higher during the summer months as compared to the winter months. The C_s values for T_{max} varied from 0.05 (November) to 0.13 (June) with an annual average of 0.10 at Kovilpatti. Further, the C_s values for T_{max} are the largest coefficients among all sites (Table 4). Low C_s values (annual average) of 0.07, 0.08, 0.08, and 0.06 were observed in Ludhiana, Mohanpur, Parbhani, and Ranichauri, respectively. Tabari and Hosseinzadeh Talaee (2014) also observed that ET_o was more sensitive to air temperature in semi-arid climate as compared to humid climates. The C_s values for the least sensitive variable, T_{min} showed less variation during all months for all the selected sites. The effect of T_{min} on change in ET_o was low (less slope) at Ranichauri (slope=0.0158) followed by Ludhiana (slope=0.0223), Parbhani (slope=0.0226), Kovilpatti (slope=0.0245), and Mohanpur (slope=0.0468) (Table 3). FAO-56 PM gave a positive slope for both T_{max} and T_{min}. The positive slope indicates an increase of ET_o value with an increment in climate variable.

R_s is the largest energy source and has the capability to change large quantities of liquid water into water vapor. Decreased cloudiness and increased R_s would increase ET_o and vice versa. Under humid region, ET_o was more affected by R_s in winter months than in summer months compared to other sites (Table 4). Under semi-arid and sub-humid regions, the opposite was observed, i.e., a greater sensitivity of ET_o to a unit change in R_s during the summer months compared to winter months. Similar studies were also reported by Smajstrla et al. (1987) who observed a greater sensitivity of the Penman (1948) model for a unit change in R_s during the summer months compared to the winter months in Florida. Also, Irmak et al. (2006) observed the dominance of R_s during the summer months in several semi-arid regions. Among the chosen sites, average annual C_s values for R_s was maximum (0.21) at humid region, e.g., Mohanpur, and minimum (0.10) at Ranichauri (Table 4). R_s only affects the net radiation estimations and not an aerodynamic term of the ET_o. R_s has a seasonal pattern based on the angle of incidence and the distance between Earth and Sun; this variable did not show any clear relationship between its magnitude and the C_s values in this study. Similar is the case for temperature, even though C_s values decreased when R_s was lower during winter months (Estevez et al. 2009).

The difference between the water vapor pressure at the evapotranspiring surface and the surrounding air (*VPD*) is the determining factor in the vapor removal. *VPD* of the air measures its dryness and e_s increases exponentially with increasing T_{avg} (Eq. 1). If all other factors remain unchanged, warming should cause drier air and hence increase ET_o. The change in ET_o with respect to change in RH_{avg} also showed the greater slope at Kovilpatti (slope=−0.027), whereas it was less at Mohanpur (slope=0.0058) (Table 3). Here, the most interesting point observed was that, all sites except Mohanpur showed negative slope for RH_{avg} (Table 3). The negative slope indicates decrease of ET_o value with an increment in a climate variable and vice-versa. Coefficients exhibited constant value (−0.01) for all months at Ranichauri. The C_s values at Ludhiana ranged from −0.03 to 0.00. In contrast to all other sites, the coefficients were largest during the summer months at Kovilpatti with an average annual C_s value of −0.02. At Mohanpur, C_s values for RH_{avg} varied from 0.0 to 0.01. Monthly average C_s values were zero during the period of March to July.

4 Conclusions

The FAO-56 PM method is recommended as the standard method for estimating ET_o, if all the required climatic data are available. In this study, the sensitivity of FAO-56 PM method was evaluated to change in climatic variables. The 5 years daily climatic data (T_{max}, T_{min}, R_s, RH_{avg}, and W_s) were used as an input for the estimation of ET_o by FAO-56 PM method and analyzing sensitivity at Kovilpatti, Ludhiana, Mohanpur, Parbhani, and Ranichauri sites. These stations are in semi-arid (Kovilpatti and Parbhani), humid (Mohanpur), and sub-humid (Ludhiana and Ranichauri) regions of India. The response of ET_o to changes in all climatic variables was linear with $r^2 \geq 0.97$ for all the sites. The ET_o was most sensitive to R_s at Kovilpatti, Mohanpur, and Ranichauri, and to W_s at Parbhani and Ludhiana. Thereafter, T_{max} was the most sensitive variables for most sites. ET_o was less sensitive to RH_{avg} followed by T_{min} at all sites. Results showed that the emphasis should be given to precise measurements of R_s, W_s and T_{max}. The sensitivity of ET_o to climate variables showed significant variations among the sites. The ET_o was found to be differently sensitive to the climatic variables under different sites. Daily C_s values were derived for each climatic variable and results showed that the considerable fluctuations over the seasons and the amplitude of the same coefficients showed considerable variations among the sites. This study reveals the need of accurate measurement of required climatic variables to estimate the FAO-56 PM ET_o under different agro-ecological regions in India.

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