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Applicability of standard FAO56-PM ET_0 model with limited meteorological dataset under humid climate of India

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ABSTRACT

Availability of meteorological data of doubtful integrity and/or non-availability of expensive equipment to record them especially in developing countries restricts use of standard FAO56-PM ET_0 model. The present study was aimed to evaluate effectiveness of alternative measures and identify minimum meteorological parameters to obtain at par FAO56-PM estimates for humid Dehradun district of Uttarakhand (India). Daily meteorological dataset for a period of 31 years (1989-2019) was used to evaluate performance of missing meteorological parameters and their different combinations (44 cases) in comparison to full dataset FAO56-PM estimates with statistical indices and their ranks based on global performance indicator (GPI) values calculated using Microsoft™ Excel as computing tool. The results confirmed that missing actual vapour pressure and saturation vapour pressure (relative humidity) values can be estimated with adequate accurateness by taking dew point temperature equal to minimum air temperature and mean air temperature, respectively, while solar radiation values with great accuracy can be obtained with minimum and maximum air temperature data only. The analysis also confirmed essential requirement of long-term wind speed data as well. Minimum and maximum air temperature along with long-term wind speed data are minimum requirement for calculating FAO56-PM ET_0 estimates in humid areas.

1. INTRODUCTION

Evapotranspiration (ET) is a process that comprises loss of water through evaporation from soil surface and transpiration from plant canopy (Aytec, 2009) which helps in cloud formation, rainfall occurrence and other water-related issues. For efficient irrigation scheduling at a place, it is essentially required to know environmental demand of water which is lost principally through ET, and its study is essential for very large number of scientific and management issues including agriculture, agricultural climatology, crop production, crop simulation models, environmental assessment, hydro-informatics, hydrology, irrigation scheduling and water resources planning (Wu, 1997; Midgley *et al.*, 2002; Irmak *et al.*, 2003; Biswas, 2004; Yoder *et al.*, 2005; Bautista *et al.*, 2009; Senay *et al.*, 2009; Sentelhas *et al.*, 2010; Kisi and Cengiz, 2013; Ababaei, 2014; Vazquez and Hampel, 2014). Any variation in climate and crop cover significantly influences availability of water resources at a place (Lopez-Moreno *et al.*, 2009). For determining the rate of loss of available soil water from specific crop (*i.e.* reference evapotranspiration, ET_0), the value of ET is to be firstly calculated with the help of meteorological data (Lopez-Urrea *et al.*, 2006; Xing *et al.*, 2008).

The FAO Penman-Monteith (FAO56-PM) method is recommended as a standard for determining ET_0 and its superior performance under different climatic conditions throughout the globe has been confirmed by various researchers (Jensen *et al.*, 1990; Smith *et al.*, 1991; Allen *et al.*, 1994; Chiew *et al.*, 1995; Allen *et al.*, 1998; Ali and Shui, 2009; Xu *et al.*, 2013). The major limitation of FAO56-PM method is that it requires a large number of meteorological parameters such as temperature, relative humidity, solar radiation and wind speed at 2 m height from ground surface which may not be available at all meteorological stations especially in developing countries. Further more, sometimes accuracy of these recorded meteorological parameters always remains questionable due to non-availability of experienced and trained data recorders /

observers. In case, if one or more of these meteorological parameters are not recorded or inaccurate data is available, Food and Agriculture Organization (FAO) in its paper No. 56 recommended their estimation using minimum available data (Allen *et al.*, 1998).

In absence of recorded sunshine hours, solar radiation can be determined with the help of minimum and maximum air temperature (Hargreaves and Samani, 1985; Allen, 1996), while actual vapour pressure can be estimated with minimum air temperature. With non-availability of wind speed data, long-term average of wind speed observed at study area or its default value (2 m s^{-1}) should be considered (Allen *et al.*, 1998; Trajkovic and Kolakovic, 2009). Due to importance of ET_0 even in data deficient places and regions, it is necessary to evaluate performance of alternative procedures to estimate ET_0 using limited meteorological data. Globally, a large number of investigators evaluated performance of FAO56-PM ET_0 model with missing meteorological parameters estimated with alternative procedures (Harmsen and Torres-Justiniano, 2001; Stockle *et al.*, 2004; Nandagiri and Kovoor, 2005; Popova *et al.*, 2006; Jabloun and Sahli, 2008; Adeboye *et al.*, 2009; Trajkovic and Kolakovic, 2009; Christopher *et al.*, 2010; Gelcer *et al.*, 2010; Sentelhas *et al.*, 2010; Kwon and Choi, 2011; Trajkovic *et al.*, 2011; Wang *et al.*, 2011; Ngongondo *et al.*, 2012; Carvalho, 2013; Fisher and Pringle, 2013; Rojas and Sheffield, 2013; Todorovic *et al.*, 2013; Córdova *et al.*, 2015; Majidi *et al.*, 2015; Burugera *et al.*, 2017; daCunha *et al.*, 2017; Djaman *et al.*, 2017; Upreti and Ojha, 2017; daSilva *et al.*, 2018; Djaman *et al.*, 2018; Ferreira *et al.*, 2018; Koudahe *et al.*, 2018; Paredes *et al.*, 2018a; Paredes *et al.*, 2018b; Jeon *et al.*, 2019; Quej *et al.*, 2019). Keeping above in view, present study was carried out to assess performance of alternative procedures to determine missing meteorological parameters and their different combinations with FAO56-PM model for Indian humid Dehradun district of Uttarakhand with specific objectives, (i) to compare performance of FAO56-PM ET_0 model using derived meteorological parameters and their different combinations with that obtained with full meteorological dataset, and (ii) to identify minimum requirement of meteorological parameters for obtaining at par FAO56-PM ET_0 estimates with full meteorological dataset.

2. MATERIALS AND METHODS

Study Area and Weather Dataset

The study was carried out for humid Dehradun district of Uttarakhand (India) which experiences an average annual rainfall of about 1600 mm. The months of May and early part of June are hottest with maximum temperature of about 42°C, while winter starts from November which lasts up to February. The daily meteorological dataset of 31 years (1989-2019) consisting of air temperature (minimum and maximum), relative humidity (minimum and maximum), sunshine hours and wind speed was collected from ICAR-Indian Institute of Soil and Water Conservation, Dehradun (78°04'E longitudes, 32°19'N latitudes and 516.5 m above mean sea level). All days with missing data were eliminated from meteorological dataset and its quality control was ensured by discarding outliers.

In late 1990s, many scientists tried to finalize an equation as "standard" or "index" among many available ET_0 equations and based on their conclusions, the FAO recommended Penman-Monteith equation in its paper No. 56 (FAO56-PM) as "standard" for computing ET_0, expressed mathematically as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T_{mean} + 273}\right)U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad ...(1)$$

Where, ET_0 = reference evapotranspiration (mm day^{-1}); Δ = slope of saturated vapour pressure curve (kPa $°C^{-1}$); R_n = net radiation at crop surface (MJ m^{-2} day^{-1}); G = soil heat flux density (MJ m^{-2} day^{-1}); γ = psychrometric constant (kPa $°C^{-1}$); T_{mean} = mean daily air temperature (°C); U_2 = wind speed at 2 m height (m sec^{-1}); e_s = saturated vapour pressure (kPa); e_a = actual vapour pressure (kPa); e_s-e_a = vapour pressure deficit (kPa).

The FAO56-PM model uses eight meteorological parameters which can be measured directly or indirectly with specific instruments at meteorological stations. Air temperature, relative humidity, sunshine hours, and wind speed are the basic meteorological parameters which are recorded/observed at these meteorological stations. Altitude is used to adjust local psychrometric constant (γ) while latitude is required to compute extra-terrestrial radiation (R_a). Solar radiation is needed to calculate net radiation (R_n) based on radiation balance model in association with R_a values. Air temperature is used to develop slope of saturated vapour pressure curve (Δ), while relative humidity is used to compute vapour pressure deficit (e_s-e_a) values.

Estimation of Missing Meteorological Parameters

Solar radiation (R_s)

The difference between maximum air temperature (T_{max}) and minimum air temperature (T_{min}) at a given location can be efficiently used as an indicator of fraction of extra-terrestrial radiation which reaches to earth's surface (Hargreaves and Samani, 1985). The mathematical expression for calculating R_s is:

$$R_s = k_{RS}\left[\sqrt{(T_{max} - T_{min})}\right] \times R_a \quad ...(2)$$

Where, R_s = solar radiation (MJ m^{-2} day^{-1}); k_{RS} = adjustment coefficient ($°C^{-0.5}$); T_{max} = maximum air temperature

(°C); T_{min} = minimum air temperature (°C); R_a = extra-terrestrial radiation (MJ m^{-2} day^{-1}).

Being the study area is located in the interior region where due to absence of large water bodies, air masses are not significantly influenced and thereby, for the present study, value of k_{RS} was taken as 0.16 (Allen *et al.*, 1998).

Relative humidity

When observed value of relative humidity is missing, actual vapour pressure (e_a) can be estimated by assuming dew point temperature (T_{dew}) at par with daily minimum temperature (T_{min}) and thereby, the equation is expressed as:

$$e_a = e^o(T_{min}) = 0.6108 \times \exp\left\{\frac{17.27 \times T_{min}}{T_{min} + 237.3}\right\} \quad ...(3)$$

Where, e_a = actual vapour pressure (kPa); T_{min} = minimum temperature (°C).

The equivalence of T_{dew} to T_{min} is valid for locations where crop cover of meteorological stations is well-watered, however, for arid and to some extent for semi-arid regions, air may not be saturated at minimum temperature and thereby, T_{min} might be more than T_{dew} which requires further calibration and, in such cases, value of T_{dew} may be obtained by considering its value 1-2° lesser than that of observed T_{min} value (Allen *et al.*, 1998). To check applicability of this specific recommendation for humid climatic condition, actual vapour pressure was calculated by taking value of T_{dew} k° less than minimum temperature for two values of k (*i.e.* 1, 2) in addition to no change in value of k (*i.e.* k = 0) as:

$$e_a = 0.6108 \times \exp\left\{\frac{[17.27 \times (T_{min} - k)]}{(T_{min} - k) + 237.3}\right\} \quad ..(4)$$

Where, e_a = actual vapour pressure (kPa); T_{min} is minimum temperature (°C).

Therefore, in this study, three cases for calculating e_a values were considered (Table 1).

Saturation vapour pressure

The values of mean saturation vapour pressure (designated as e_{sB}) were calculated by using mean air temperature in place of maximum and minimum air temperature, expressed mathematically as:

$$e_{sB} = 0.6108 \times \exp\left\{\frac{17.27 \times T_{mean}}{T_{mean} + 237.3}\right\} \quad ...(5)$$

Where, e_{sB} = mean saturation vapour pressure (kPa); T_{mean} = mean air temperature (°C).

Wind speed

When wind speed data for any location is not available, two approaches are normally considered namely, (i) long-term average (U_l) of study area (Majidi *et al.*, 2015; Koudahe *et al.*, 2018), and (ii) default value (U_d) as 2 m sec^{-1} (Allen *et al.*, 1998).

Derived Meteorological Parameters and Their Combinations

The value of solar radiation (R_s) was estimated by using maximum and minimum air temperature. Missing vapour pressure values were calculated for three cases as, $e_a(k_0)$, $e_a(k_1)$, and $e_a(k_2)$, while saturation vapour pressure (e_{sB}) was calculated by using mean air temperature and two cases of wind speed, represented by U_l and U_d. All these seven derived meteorological parameters were considered individually and in combination of two, three, and four, totalling to 44 cases.

Statistical Indices and Global Performance Indicator (GPI)

Statistical Indices

ET_0 values computed from 44 combinations of derived meteorological parameters and their different combinations were evaluated against those obtained by FAO56-PM model with complete meteorological dataset using Microsoft™ Excel as computing tool. The ET_0 values obtained from these 44 cases of derived meteorological parameters and their combinations were taken as predicted value (P_i) while those obtained with full meteorological dataset FAO56-PM model were considered as observed value (O_i). The performance of FAO56-PM model with derived meteorological parameters and their combinations against full meteorological dataset FAO56-PM model was assessed by using a number of statistical indices namely, Agreement Index (D), Mean absolute error (MAE), Maximum absolute error (MAXE), Mean bias error (MBE), Percent error of estimate (PE), Coefficient of determination (R^2), Root mean square error (RMSE), Standard error of estimate (SEE), and Weighted root mean square difference (WRMSD).

Global performance indicator (GPI)

The summative form of GPI was used to give final ranking to derived meteorological parameters and their different combinations. To remove influence of any individ-

Table: 1
Cases for calculating actual vapour pressure (e_a)

Case	Value of k	T_{dew} calculation	Designated as
(a)	0	$T_{dew} = T_{min}$	$e_a(k_0)$
(b)	1	$T_{dew} = (T_{min} - 1)$	$e_a(k_1)$
(c)	2	$T_{dew} = (T_{min} - 2)$	$e_a(k_2)$

Where, T_{dew} = dew point temperature (°C); T_{min} is minimum air temperature (°C).

ual index, all statistical indices were normalized between "0.00" (minimum value) and "1.00" (maximum value) with highest value of GPI indicating most acceptable (Despotovic *et al.*, 2015). The mathematical expression used for GPI calculation is:

$$\mathrm{GPI} = \sum_{i=0}^{n} \left(X_i - X_{ij}\right) \times a_i \quad ...(6)$$

Where, X_i and X_{ij} are median of individual statistical index "i", and value of statistical index "i" for parameter "j", respectively with value of a_i equal to (-)1 for R^2 and (+)1 for all other statistical indices.

The computational forms of different statistical indices and GPI are presented in Table 2.

Table: 2
Computational forms of considered statistical indices

Statistical index	Notation	Computational form
Agreement index	D	$1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(\lvert P_i - \bar{O}\rvert + \lvert O_i - \bar{O}\rvert)^2}$
Coefficient of determination	R²	$1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$
Mean absolute error	MAE	$\frac{1}{n}\sum_{i=1}^{n}\lvert O_i - P_i\rvert$
Maximum absolute error	MAXE	$\mathrm{MAX}(\lvert O_i - P_i\rvert)_{i=1}^{n}$
Mean bias error	MBE	$\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)$
Percent error of estimate	PE	$\left\lvert\frac{\bar{P} - \bar{O}}{\bar{O}}\right\rvert \times 100\%$
Root mean square error	RMSE	$\frac{1}{\sqrt{n}}\sqrt{\sum_{i=1}^{n}(P_i - O_i)^2}$
Standard error of estimate	SEE	$\left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n-1}\right]^{0.5}$
Weighted root mean square difference	WRMSD	0.70 × (0.67 × RMSD + 0.33 × AMRSD + 0.30 × (0.67 × pRMSD + 0.33 × pARMSD)

Where, $\bar{O}$ = mean of FAO56-PM ET_0 (mm day^{-1}) obtained with full meteorological dataset; O_i = FAO56-PM ET_0 (mm day^{-1}) obtained with full meteorological dataset; $\bar{P}$ = mean of FAO56-PM ET_0 (mm day^{-1}) obtained with derived meteorological parameters; P_i = predicted value of ET_0 (mm day^{-1}) obtained with derived meteorological parameters; n = total number of observations; WRMSD = weighted root mean square difference (mm day^{-1}); RMSD = root mean square difference; ARMSD = adjusted root mean square difference; pRMSD = root mean square difference for peak period (mm $period^{-1}$); pARMSD = adjusted root mean square difference for peak period (mm $period^{-1}$).

3. RESULTS AND DISCUSSION

Ranking of FAO56-PM ET_0 Estimates with Derived Meteorological Parameters and their Combinations Against Full Meteorological Dataset

Derived individual meteorological parameters

The comparison of FAO56-PM ET_0 estimates obtained using seven individual derived meteorological parameters against that calculated with full meteorological dataset in terms of statistical indices alongwith their individual rankings (Table 3) shows that all derived meteorological parameters produced very good and acceptable results as value of D varied in between 0.8543 (U_d) and 0.9998 [$e_a(k_0)$], MAE in between 0.03 mm day^{-1} [$e_a(k_0)$] and 0.99 mm day^{-1} (U_d), MAXE in between 0.00 mm day^{-1} (e_{sB}) and 2.00 mm day^{-1} (U_d), MBE in between -0.06 mm day^{-1} (e_{sB}) and 0.99 mm day^{-1} (U_d), PE in between 0.60% [$e_a(k_0)$] and 34.48% (U_d), R^2 in between 0.8852 (U_d) and 0.9996 [$e_a(k_0)$], RMSE in between 0.04 mm day^{-1} [$e_a(k_0)$] and 1.11 mm day^{-1}

Table: 3
Performance of FAO56-PM ET_0 estimates with derived meteorological parameters against full meteorological dataset

S.No.	Derived parameter	Statistical indices									GPI	Rank
		D	R²	MAE	MAXE	MBE	PE	RMSE	SEE	WRMSD		
1	R_s	0.9802	0.9875	0.30	0.97	0.29	10.15	0.39	0.40	0.35	-2.0273	6
2	$e_a(k_0)$	0.9998	0.9996	0.03	0.07	-0.02	0.60	0.04	0.04	0.02	0.2598	1
3	$e_a(k_1)$	0.9996	0.9992	0.04	0.15	-0.03	1.03	0.05	0.05	0.03	0.1854	2
4	$e_a(k_2)$	0.9993	0.9987	0.05	0.23	-0.04	1.50	0.07	0.07	0.04	0.0802	4
5	e_{sB}	0.9988	0.9985	0.06	0.00	-0.06	2.25	0.09	0.09	0.10	0.0814	3
6	U_l	0.9959	0.9938	0.11	0.15	-0.04	1.30	0.16	0.16	0.21	-0.3069	5
7	U_d	0.8543	0.8852	0.99	2.00	0.99	34.48	1.11	1.11	0.96	-6.6671	7

Where, R_s = solar radiation (MJ m^{-2} day^{-1}); $e_a(k_0)$ = actual vapour pressure (kPa) estimated by taking dew point temperature equal to minimum temperature; $e_a(k_1)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 1° less than minimum temperature; $e_a(k_2)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 2° less than minimum temperature; U_l = long-term average wind speed (m sec^{-1}) of study area; U_d = default wind speed (m sec^{-1}); D = agreement index; R^2 = coefficient of determination; MAE = mean absolute error; MAXE = maximum absolute error; MBE = mean bias error (mm day^{-1}); PE = percent error of estimate (%); SEE = standard error of estimate (mm day^{-1}); WRMSD = weighted root mean square difference (mm day^{-1}); GPI = global performance indicator; Rank = ranking of derived meteorological parameters.

(U_d), SEE in between 0.04 mm day^{-1} [$e_a(k_0)$] and 1.11 mm day^{-1} (U_d), and WRMSD in between 0.02 mm day^{-1} [$e_a(k_0)$] and 0.96 mm day^{-1} (U_d). The rank of derived meteorological parameters on the basis of GPI values shows that [$e_a(k_0)$] performed best with GPI as 0.2598, followed by $e_a(k_1)$ and e_{sB} with GPI values of 0.1854 and 0.0814, respectively, while U_d ranked last at seventh position with GPI value of -6.6671.

Combinations of two derived meteorological parameters

Among 17 combinations of two derived meteorological parameters against FAO56-PM model with full meteorological dataset, combination $e_a(k_0)$-e_{sB} extended highest value of D (0.9987), followed by $e_a(k_1)$-e_{sB} and $e_a(k_2)$-e_{sB} with corresponding values as 0.9983 and 0.9978, respectively (Table 4) while, combination e_{sB}-U_l produced poorest result with value of D as 0.5383. Similar trend was observed in case of R^2 as its highest value (0.9988) was obtained for combination $e_a(k_0)$-e_{sB}, followed by $e_a(k_1)$-e_{sB} and $e_a(k_2)$-e_{sB} with corresponding values as 0.9987 and 0.9984, respectively. The lowest value of MAE, MAXE, PE, RMSE, SEE and WRMSD were observed with combination, $e_a(k_0)$-e_{sB} as 0.08 mm day^{-1}, 0.00 mm day^{-1}, 2.85%, 0.09 mm day^{-1}, 0.09 mm day^{-1} and 0.09 mm day^{-1}, respectively. From Table, it is also clear that lowest value of MBE (-0.11 mm day^{-1}) was obtained with [$e_a(k_2)$-e_{sB}]. Further, combination $e_a(k_0)$-e_{sB}, followed by $e_a(k_1)$-e_{sB} and $e_a(k_2)$-e_{sB} ranked first, second and third, respectively with corresponding GPI values of 0.8677, 0.8281 and 0.8027 while, with lowest GPI (-6.1225), combination e_{sB}-U_l secured last position (*i.e.* 17th) in the tally.

Combinations of three derived meteorological parameters

The results of performance of FAO56-PM ET_0 estimates with 14 combinations of three derived meteorological parameters against full meteorological dataset FAO56-PM model (Table 5) revealed that combination $e_a(k_0)$-R_s-U_l produced highest value of D, followed by combinations $e_a(k_0)$-e_{sB}-U_d and $e_a(k_1)$-e_{sB}-U_d with corresponding values as 0.8802, 0.8649 and 0.8375. The highest value of R^2 (0.9747) was obtained with combination $e_a(k_2)$-e_{sB}-U_d, followed by $e_a(k_1)$-e_{sB}-U_d and $e_a(k_0)$-e_{sB}-U_d with corresponding values as 0.9722 and 0.9688, while its lowest value (0.7199) was obtained with combination e_{sB}-R_s-U_l. The combination $e_a(k_0)$ - R_s-U_l produced most acceptable lowest values of MAE, MBE, PE, RMSE, SEE and WRMSD as 0.67 mm day^{-1}, 0.65 mm day^{-1}, 22.54%, 0.82 mm day^{-1}, 0.82 mm day^{-1} and 0.60 mm day^{-1}, respectively, while lowest value of MAXE (1.56 mm day^{-1}) was obtained with combination, $e_a(k_0)$-e_{sB}-U_d. The combination $e_a(k_0)$-R_s-U_l topped among 14 combinations against full meteorological dataset FAO56-PM estimates with corresponding GPI value of 1.0978 while combinations $e_a(k_0)$-e_{sB}-U_d and $e_a(k_1)$-R_s-U_l ranked second and third,

Table: 4
Performance of FAO56-PM ET_0 estimates with combinations of two derived meteorological parameters against full meteorological dataset

S.No.	Combination(s) of derived parameters	Statistical indices									GPI	Rank
		D	R²	MAE	MAXE	MBE	PE	RMSE	SEE	WRMSD		
1	$e_a(k_0)$ - R_s	0.9787	0.9850	0.29	1.04	0.28	9.61	0.42	0.42	0.38	0.1029	8
2	$e_a(k_1)$ - R_s	0.9799	0.9845	0.28	1.02	0.26	8.88	0.40	0.40	0.37	0.1359	7
3	$e_a(k_2)$ - R_s	0.9810	0.9840	0.27	0.99	0.23	8.15	0.39	0.39	0.36	0.1677	6
4	e_{sB} - R_s	0.9866	0.9903	0.24	0.88	0.23	7.89	0.32	0.32	0.28	0.2853	4
5	U_l - R_s	0.9871	0.9901	0.26	0.84	0.26	8.94	0.31	0.31	0.25	0.2809	5
6	U_d - R_s	0.8070	0.8760	1.25	2.69	1.25	43.41	1.41	1.41	1.21	-2.1370	15
7	$e_a(k_0)$ - e_{sB}	0.9987	0.9988	0.08	0.00	-0.08	2.85	0.09	0.09	0.09	0.8677	1
8	$e_a(k_1)$ - e_{sB}	0.9983	0.9987	0.10	0.09	-0.09	3.29	0.11	0.11	0.10	0.8281	2
9	$e_a(k_2)$ - e_{sB}	0.9978	0.9984	0.11	0.17	-0.11	3.74	0.12	0.12	0.11	0.8027	3
10	$e_a(k_0)$ - U_l	0.9268	0.8670	0.48	1.45	0.38	13.09	0.63	0.63	0.47	-0.5771	12
11	$e_a(k_1)$ - U_l	0.8924	0.8836	0.66	1.67	0.64	22.36	0.80	0.80	0.62	-0.8880	13
12	$e_a(k_2)$ - U_l	0.8485	0.8985	0.89	1.88	0.89	31.07	0.99	1.00	0.78	-1.2111	14
13	e_{sB} - U_l	0.5383	0.7175	2.95	5.84	2.95	102.59	3.20	3.21	2.71	-6.1225	17
14	$e_a(k_0)$ - U_d	0.9661	0.9435	0.33	1.01	0.26	9.20	0.44	0.44	0.34	-0.0130	9
15	$e_a(k_1)$ - U_d	0.9496	0.9498	0.44	1.15	0.44	15.13	0.54	0.55	0.42	-0.2333	10
16	$e_a(k_2)$ - U_d	0.9271	0.9559	0.60	1.28	0.60	20.72	0.67	0.67	0.52	-0.4675	11
17	e_{sB} - U_d	0.6661	0.8190	1.97	3.75	1.97	68.53	2.12	2.12	1.77	-3.6227	16

Where, R_s = solar radiation (MJ m^{-2} day^{-1}); $e_a(k_0)$ = actual vapour pressure (kPa) estimated by taking dew point temperature equal to minimum temperature; $e_a(k_1)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 1° less than minimum temperature; $e_a(k_2)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 2° less than minimum temperature; U_l = long-term average wind speed (m sec^{-1}) of study area; U_d = default wind speed (m sec^{-1}); D = agreement index; R^2 = coefficient of determination; MAE = mean absolute error; MAXE = maximum absolute error; MBE = mean bias error (mm day^{-1}); PE = percent error of estimate (%); SEE = standard error of estimate (mm day^{-1}); WRMSD = weighted root mean square difference (mm day^{-1}); GPI = global performance indicator; Rank = ranking of combinations of two derived meteorological parameters.

Table: 5
Performance of FAO56-PM ET_0 estimates with combinations of three derived meteorological parameters against full meteorological dataset

S.No.	Combination(s) of derived parameters	Statistical indices									GPI	Rank
		D	R^2	MAE	MAXE	MBE	PE	RMSE	SEE	WRMSD		
1	$e_a(k_0)$-R_s-U_l	0.8802	0.8768	0.67	1.75	0.65	22.54	0.82	0.82	0.60	1.0978	1
2	$e_a(k_1)$-R_s-U_l	0.8328	0.8911	0.92	1.96	0.92	31.80	1.03	1.03	0.77	0.7008	3
3	$e_a(k_2)$-R_s-U_l	0.7836	0.9040	1.17	2.17	1.17	40.52	1.24	1.25	0.94	0.3130	6
4	e_{sB}-R_s-U_l	0.5089	0.7199	3.25	6.13	3.25	113.05	3.48	3.48	2.90	-5.4764	14
5	$e_a(k_0)$-R_s-U_d	0.8003	0.9237	1.34	2.59	1.34	46.46	1.43	1.43	1.20	-0.1956	9
6	$e_a(k_1)$-R_s-U_d	0.7937	0.9365	1.29	1.91	1.29	44.68	1.33	1.33	1.09	0.2025	7
7	$e_a(k_2)$-R_s-U_d	0.7708	0.9462	1.41	2.03	1.41	48.83	1.44	1.44	1.17	0.0200	8
8	e_{sB}-R_s-U_d	0.7721	0.9663	1.57	3.17	1.57	54.51	1.70	1.71	1.42	-0.6484	10
9	$e_a(k_0)$-e_{sB}-U_l	0.6612	0.8490	1.88	2.70	1.88	65.45	1.95	1.95	1.55	-1.3082	11
10	$e_a(k_1)$-e_{sB}-U_l	0.6239	0.8635	2.16	2.99	2.16	74.92	2.21	2.22	1.74	-1.8170	12
11	$e_a(k_2)$-e_{sB}-U_l	0.5917	0.8761	2.41	3.30	2.41	83.84	2.46	2.46	1.92	-2.3027	13
12	$e_a(k_0)$-e_{sB}-U_d	0.8649	0.9688	1.03	1.56	1.03	35.63	1.06	1.06	0.85	0.8222	2
13	$e_a(k_1)$-e_{sB}-U_d	0.8375	0.9722	1.16	1.71	1.16	40.42	1.19	1.19	0.95	0.5820	4
14	$e_a(k_2)$-e_{sB}-U_d	0.8112	0.9747	1.29	1.86	1.29	44.95	1.32	1.32	1.05	0.3381	5

Where, R_s = solar radiation (MJ m^{-2} day^{-1}); $e_a(k_0)$ = actual vapour pressure (kPa) estimated by taking dew point temperature equal to minimum temperature; $e_a(k_1)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 1° less than minimum temperature; $e_a(k_2)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 2° less than minimum temperature; U_l = long-term average wind speed (m sec^{-1}) of study area; U_d = default wind speed (m sec^{-1}); D = agreement index; R^2 = coefficient of determination; MAE = mean absolute error; MAXE = maximum absolute error; MBE = mean bias error (mm day^{-1}); PE = percent error of estimate (%); SEE = standard error of estimate (mm day^{-1}); WRMSD = weighted root mean square difference (mm day^{-1}); GPI = global performance indicator; Rank = ranking of combinations of three derived meteorological parameters.

Table: 6
Performance of FAO56-PM ET_0 estimates with combinations of four derived meteorological parameters against full meteorological dataset

S.No.	Combination(s) of derived parameters	Statistical indices									GPI	Rank
		D	R^2	MAE	MAXE	MBE	PE	RMSE	SEE	WRMSD		
1	$e_a(k_0)$-e_{sB}-R_s-U_l	0.7401	0.9606	1.68	2.76	1.68	58.53	1.74	1.74	1.40	-0.9295	4
2	$e_a(k_1)$-e_{sB}-R_s-U_l	0.7083	0.9635	1.86	2.94	1.86	64.66	1.91	1.92	1.53	-2.3134	5
3	$e_a(k_2)$-e_{sB}-R_s-U_l	0.6800	0.9653	2.03	3.13	2.03	70.39	2.08	2.08	1.65	-3.7217	6
4	$e_a(k_0)$-e_{sB}-R_s-U_d	0.7994	0.9718	1.39	2.31	1.39	48.29	1.44	1.44	1.16	2.7745	1
5	$e_a(k_1)$-e_{sB}-R_s-U_d	0.7743	0.9731	1.52	2.44	1.52	52.73	1.56	1.57	1.25	1.7439	2
6	$e_a(k_2)$-e_{sB}-R_s-U_d	0.7511	0.9737	1.64	2.56	1.64	56.89	1.68	1.69	1.34	0.7158	3

Where, R_s = solar radiation (MJ m^{-2} day^{-1}); $e_a(k_0)$ = actual vapour pressure (kPa) estimated by taking dew point temperature equal to minimum temperature; $e_a(k_1)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 1° less than minimum temperature; $e_a(k_2)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 2° less than minimum temperature; U_l = long-term average wind speed (m sec^{-1}) of study area; U_d = default wind speed (m sec^{-1}); D = agreement index; R^2 = coefficient of determination; MAE = mean absolute error; MAXE = maximum absolute error; MBE = mean bias error (mm day^{-1}); PE = percent error of estimate (%); SEE = standard error of estimate (mm day^{-1}); WRMSD = weighted root mean square difference (mm day^{-1}); GPI = global performance indicator; Rank = ranking of combinations of three derived meteorological parameters.

respectively, whereas combination e_{sB}-R_s-U_l with least GPI value of -5.4764 adjudged last.

Combinations of four derived meteorological parameters

From Table 6, it is clear that combination $e_a(k_0)$-e_{sB}-R_s-U_d produced highest value of D, followed by combinations $e_a(k_1)$-e_{sB}-R_s-U_d and $e_a(k_2)$-e_{sB}-R_s-U_d with values as 0.7994, 0.7743 and 0.7511, respectively, whereas $e_a(k_2)$-e_{sB}-R_s-U_l extended its lowest value as 0.6800. The highest value of R^2 was obtained with combination $e_a(k_2)$-e_{sB}-R_s-U_d, followed by $e_a(k_1)$-e_{sB}-R_s-U_d and $e_a(k_0)$-e_{sB}-R_s-U_d with values as 0.9737, 0.9731 and 0.9718, respectively. All statistical indices related to errors namely, MAE, MAXE, MBE, PE, RMSE, SEE, and WRMSD showed exactly opposite trend shown by agreement index (D) as lowest errors were obtained with $e_a(k_0)$-e_{sB}-R_s-U_d. This combination produced lowest values of MAE, MAXE, MBE, PE, RMSE, SEE, and WRMSD as 1.39 mm day^{-1}, 2.31 mm day^{-1}, 1.39 mm day^{-1}, 48.29%, 1.44 mm day^{-1}, 1.44 mm day^{-1}, and 1.16 mm day^{-1}, respectively. The combination $e_a(k_0)$-e_{sB}-R_s-U_d with highest GPI value (2.7745) was ranked first, followed by $e_a(k_1)$-e_{sB}-R_s-U_d and $e_a(k_2)$-e_{sB}-R_s-U_d with corresponding GPI values of 1.7439 and 0.7158, respectively. The combination $e_a(k_2)$-e_{sB}-R_s-U_l produced least GPI value (-3.7217) and ranked last among all six combinations of four derived meteorological parameters.

Overall ranking of derived meteorological parameters based on GPI

The pertinent result related to overall ranking of all 44 combinations of derived meteorological parameters based on GPI values (Table 7) shows that R_s ranked first with highest value of GPI as 1.8302 while combinations $e_a(k_1)$ and e_{sB} ranked second and third with corresponding GPI values of 1.8037 and 1.774, respectively. The last rank with lowest GPI value (-5.1231) was assigned to combination e_{sB}-R_s-U_l.

The present study established that for calculating sufficiently accurate FAO56-PM ET_0 estimates in humid locations with missing / ambiguous solar radiation data and actual vapour pressure (e_a), observed values of air temperature (minimum and maximum) and for saturation vapour pressure (e_{sB}), mean air temperature are the minimal and compulsory requirement along with long-term wind speed value of the area into consideration. The results obtained in this study are in accordance with findings of various researchers (Sentelhas *et al.*, 2010; Trajkovic and Kolakovic, 2009; Nandagiri and Kovoor, 2005; Kwon and Choi, 2011; Córdova *et al.*, 2015), who recommended necessity of these commonly observed meteorological parameters for ET_0 calculations.

The results of this study are in close proximity with findings reported by other authors (Todorovic *et al.*, 2013; Upreti and Ojha, 2017) that for getting precise T_{dew} values from observed T_{min} to calculate actual vapour pressure precisely at humid locations, T_{dew} value should be considered equal to T_{min} for getting remarkably accurate FAO56-PM estimates (Majidi *et al.*, 2015). Large variation with combinations of more than one missing meteorological parameter (Djaman *et al.*, 2017; Djaman *et al.*, 2018) were observed while intermediate results with combination of missing solar radiation with other missing meteorological parameters was also reported (daSilva *et al.*, 2018) which tallies with the results obtained in this study. The FAO56-PM model also performed better with missing solar radiation data (Koudahe *et al.*, 2018), which is in-line with findings of present study as, its values were obtained with greater accuracy using air temperature (minimum and maximum) data alone. In contrast to improved FAO56-PM ET_0 estimates with long-term wind speed (Paredes *et al.*, 2018a) and errors of different magnitude associated with it, better estimates were being obtained by Lopez-Moreno *et al.* (2009) and Christopher *et al.* (2010) with its default value as 2 m sec^{-1}.

Table: 7
Overall ranking of derived meteorological parameters and their combinations

S.No.	Derived parameters	GPI	Rank
	Meteorological parameters		
1.	R_s	1.1014	12
2.	$e_a(k_0)$	1.8302	1
3.	$e_a(k_1)$	1.8063	2
4.	$e_a(k_2)$	1.7727	5
5.	e_{sB}	1.7742	3
6.	U_l	1.6469	8
7.	U_d	-0.4400	25
	Combinations of two derived meteorological parameters		
1.	$e_a(k_0)$-R_s	1.0701	14
2.	$e_a(k_1)$-R_s	1.0998	13
3.	$e_a(k_2)$-R_s	1.1285	11
4.	e_{sB}-R_s	1.2376	9
5.	U_l-R_s	1.2342	10
6.	U_d-R_s	-0.9879	33
7.	$e_a(k_0)$-e_{sB}	1.7733	4
8.	$e_a(k_1)$-e_{sB}	1.7368	6
9.	$e_a(k_2)$-e_{sB}	1.7133	7
10.	$e_a(k_0)$-U_l	0.4175	18
11.	$e_a(k_1)$-U_l	0.1437	19
12.	$e_a(k_2)$-U_l	-0.1407	22
13.	e_{sB}-U_l	-4.6427	43
14.	$e_a(k_0)$-U_d	0.9530	15
15.	$e_a(k_1)$-U_d	0.7568	16
16.	$e_a(k_2)$-U_d	0.5485	17
17.	e_{sB}-U_d	-2.3450	41
	Combinations of three derived meteorological parameters		
1.	$e_a(k_0)$-R_s-U_l	0.1191	20
2.	$e_a(k_1)$-R_s-U_l	-0.1896	23
3.	$e_a(k_2)$-R_s-U_l	-0.4918	27
4.	e_{sB}-Rs-Ul	-5.1231	44
5.	$e_a(k_0)$-R_s-U_d	-0.8788	31
6.	$e_a(k_1)$-R_s-U_d	-0.5664	28
7.	$e_a(k_2)$-R_s-U_d	-0.7066	30
8.	e_{sB}-R_s-U_d	-1.2130	35
9.	$e_a(k_0)$-e_{sB}-U_l	-1.7998	39
10.	$e_a(k_1)$-e_{sB}-U_l	-2.1945	40
11.	$e_a(k_2)$-e_{sB}-U_l	-2.5713	42
12.	$e_a(k_0)$-e_{sB}-U_d	-0.0606	21
13.	$e_a(k_1)$-e_{sB}-U_d	-0.2493	24
14.	$e_a(k_2)$-e_{sB}-U_d	-0.4411	26
	Combinations of four derived meteorological parameters		
1.	$e_a(k_0)$-e_{sB}-R_s-U_l	-1.2172	36
2.	$e_a(k_1)$-e_{sB}-R_s-U_l	-1.4825	37
3.	$e_a(k_2)$-e_{sB}-R_s-U_l	-1.7415	38
4.	$e_a(k_0)$-e_{sB}-R_s-U_d	-0.6994	29
5.	$e_a(k_1)$-e_{sB}-R_s-U_d	-0.8874	32
6.	$e_a(k_2)$-e_{sB}-R_s-U_d	-1.0687	34

Where, R_s = solar radiation (MJ m^{-2} day^{-1}); $e_a(k_0)$ = actual vapour pressure (kPa) estimated by taking dew point temperature equal to minimum temperature; $e_a(k_1)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 1° less than minimum temperature; $e_a(k_2)$ = actual vapour pressure (kPa) estimated by taking dew point temperature 2° less than minimum temperature; U_l = long-term average wind speed (m sec^{-1}) of study area; U_d = default wind speed (m sec^{-1}); GPI = global performance indicator; Rank = ranking of derived meteorological parameters and their combinations.

4. CONCLUSIONS

With serious limitations associated with availability and reliability of good quality meteorological data to get at par FAO56-PM ET_0 estimates, the effect of non-availability of solar radiation data was found least for humid Dehradun district of Uttarakhand (India) as it can be estimated accurately from observed values of maximum and minimum air temperature. In case of non-availability of reliable relative humidity data, it will be appropriate to use dew point temperature equal to minimum air temperature to calculate actual vapour pressure (e_a) while mean air temperature values will be of great help to calculate saturation vapour pressure (e_{sB}) precisely. The analysis revealed that observed values of air temperature (minimum and maximum) along with long-term wind speed data of study area are compulsory requirement to obtain at par FAO56-PM ET_0 estimates in humid locations.

This study discovered that under missing meteorological parameters conditions, at par FAO56-PM estimates can be obtained using alternative procedures with observed values of air temperature (minimum and maximum) and long-term wind speed. The obtained results will encourage researchers to investigate, opt and adopt alternate procedures to determine acceptable value of missing meteorological parameters to get at par FAO56-PM ET_0 estimates obtained with full meteorological dataset.

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