Sensitivity of annual and seasonal reference crop evapotranspiration to principal climatic variables

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Reference evapotranspiration (ET_0) represents the evaporative demand of the atmosphere and depends on climatic parameters such as radiation, air temperature, humidity, and wind speed. Relative role of climatic parameter of ET_0 varies from one climate to another and within the climate, and depends on the location and time. Sensitivity analysis was conducted and sensitivity coefficients were determined to evaluate the impact of principal climatic parameters on ET_0 in Karnal district of India. Mean monthly ET_0 and yearly ET_0 from 1981 to 2011 were estimated from FAO-56 Penman–Monteith equation using the daily climate data collected from Central Soil Salinity Research Institute, Karnal. Results showed that seasonal and annual ET_0 were most sensitive to maximum temperature followed by sunshine hours. However, wind speed, relative humidity, and minimum temperature had varying effect on mean ET_0 . After maximum temperature and sunshine hours, ET_0 was more sensitive to wind speed followed by relative humidity and minimum temperature in summer. In monsoon, after maximum temperature and sunshine hours, ET_0 was more sensitive to minimum temperature followed by relative humidity and wind speed. However, in winter, after maximum temperature and sunshine hours, ET_0 was more sensitive to relative humidity followed by wind speed and minimum temperature. The study suggests that the climate variability would affect reference ET_0 ; however, its impact on ET_0 would be different for different parameters.

1. Introduction

Evapotranspiration is an important component of hydrologic cycle in semi-arid region. It represents the evaporative demand of the atmosphere at a given location and time. Water requirements of crops are generally estimated from reference crop evapotranspiration (ET_0). Accurate estimation of crop evapotranspiration is essential for irrigation scheduling and water resources management. Reference crop evapotranspiration depends on climatic parameters such as radiation, air temperature, humidity, and wind speed representing the evaporative demand of the atmosphere at a given location and time, and refers to evapotranspiration rate from a

reference surface, not short of water (Allen *et al.* 1998). Different approaches varying from the empirical to physical base are used for the estimation of the reference crop evapotranspiration (Bakhtiari and Liaghat 2011; Kumar *et al.* 2012). The Penman–Monteith method (Allen *et al.* 1998) is widely used for studying of ET_0 (Goyal 2004; Wang *et al.* 2006; Tong *et al.* 2007; Liang *et al.* 2008; Bakhtiari and Liaghat 2011). Global warming and associated changes in climate are expected to affect the climatic parameters to varying degrees. This in turn would affect the reference ET_0 . Sensitivity analysis is carried out to evaluate the role of each climate variable used in the computation of reference crop evapotranspiration (Saxton 1975). Sensitivity analysis quantifies the variations in output of a model

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with respect to variation in the model parameters (Saltelli *et al.* 2004). Sensitivity analysis is important to understand the connection between climatic conditions and ET_0 variability and between data availability and estimation accuracy of ET_0 (Gong *et al.* 2006). Normally sensitivity analysis is carried out by plotting the relative changes in dependent variable against the relative changes in independent variable. Sensitivity analysis can also be done by determining sensitivity coefficient, which is normally defined as increase/decrease in dependent variable per unit increase in independent variable. Sensitivity coefficient derived from observed data may be used to estimate ET_0 for areas where detailed meteorological records are lacking (Liang *et al.* 2008). Sensitivity of reference crop evapotranspiration to climatic variability has been investigated by various researchers. These are presented in table 1.

In this study, an attempt was made to analyze the sensitivity of reference crop evapotranspiration to the climatic variability in an agriculturally dominant district of Karnal under semi-arid region in Trans-Indo-Gangetic plains of India, which is under intensive agriculture cultivation. Most widely used FAO Penman–Monteith method was used to evaluate the sensitivity of computed ET_0 to principal climatic parameter.

2. Materials and methods

2.1 Study area

The analysis was performed in Karnal district, India. This district is a part of Trans-Indo-Gangetic plains of India and is located between $29^{\circ}25' - 29^{\circ}59'N$ latitudes and $76^{\circ}27' - 77^{\circ}13'E$ longitudes.

Table 1. *Sensitivity of ET_0 to climatic parameters.*

Authors	Country	Sensitivity of ET_0 in relation to climatic parameter
Goyal (2004)	Arid region of western Rajasthan in India	Most sensitive to maximum temperature followed by net solar radiation and wind speed
Saxton (1975)	Western Iowa in USA	Most sensitive to net radiation
Liang <i>et al.</i> (2008)	Tao's river basin of north-eastern China	Most sensitive to Relative humidity followed by sunshine hours, wind speed and air temperature
Gong <i>et al.</i> (2006)	Yangtze River, China	Most sensitive to relative humidity followed by shortwave radiation, air temperature, and wind speed
Bakhtiari and Liaghat (2011)	Kerman Province in southeast semi-arid region of Iran	Most sensitive to vapour pressure deficit followed by wind speed
Porter <i>et al.</i> (2012)	Bushland in Texas in USA	Most sensitive to wind speed and air temperature followed by incoming shortwave radiation
Irmak <i>et al.</i> (2006)	Arid, sub-humid, coastal humid, inland humid and island of USA (Scottsbluff, Nebraska, and Bushland, Texas, Santa Barbara, California, Fort Pierce, Florida, Rockport, Missouri, Nebraska, and Twitchell Island)	Most sensitive to vapour deficit followed by wind speed
Ambas and Baltas (2012)	Florina of Western Macedonia of Greece	Most sensitive to solar radiation with highest sensitivity coefficient, followed by temperature, wind speed and relative humidity
Sergio <i>et al.</i> (2014)	Spain	Relative humidity, wind speed, and maximum temperature had stronger effects on ET_0 than sunshine duration and minimum temperature indicating that aerodynamic component has more importance than radiative component to determine the atmospheric evaporative demand in Spain

Total geographical area of the district is 2520 km². The study area is agriculturally dominant with rice and wheat as major crops. The district is characterized by subtropical monsoon type climate with very hot summer and a very cold winter (Fujisaka *et al.* 1992). The normal annual rainfall of the district during 1981–2011 was 740 mm of which 80% occurred during the southwest monsoon (June–September). Average annual minimum and maximum temperatures are 16.99°C and 29.94°C, respectively. The average annual relative humidity and wind speed are 65.74% and 86.16 km d⁻¹. Mean monthly maximum and minimum temperature are 38.3° and 6.5°C in the months of May and January, respectively. Soils of the district are alluvial in nature and vary from sandy loam to clay loam. District has flat topography with an average elevation of 240 m above the mean sea level.

2.2 Data used and methodology

Data for the period of 1981–2011 consisting of minimum and maximum temperature, relative humidity, wind speed, and sunshine hour collected from meteorological observatory of Central Soil Salinity Research Institute (CSSRI), Karnal were used for computation of reference evapotranspiration (ET₀). Reference surface is a hypothetical crop with an assumed height of 0.12 m having surface resistance of 70 s/m and albedo of 0.23 resembling actively growing green grass of uniform height (Allen *et al.* 1998). We used the CROPWAT Package of the Food and Agricultural Organization (FAO) for estimation of ET₀. CROPWAT model of FAO uses the FAO Penman–Monteith (Allen *et al.* 1998) equation, which is maintained as the sole standard method for the computation of ET₀ from meteorological data. This equation was derived from the original Penman–Monteith equation, and the equations of the aerodynamic and surface resistance. In FAO Penman–Monteith equation, the saturation vapour pressure (e_s) is derived from $T_{\max}$ and $T_{\min}$, while the actual vapour pressure (e_a) is derived from the dew point temperature (T_{dew}), from maximum ($RH_{\max}$) and minimum ($RH_{\min}$) relative humidity, from the maximum ($RH_{\max}$), or from mean relative humidity (RH_{mean}) (Allen *et al.* 1998). The net radiation, R_n , is the difference between incoming and outgoing radiation of both short and long wavelengths. The soil heat flux, G , is the energy that is utilized in heating the soil. It is positive when the soil is warming and negative when the soil is cooling. Soil heat flux is small compared to R_n and is often ignored. The amount of energy gained or lost by the soil should theoretically be subtracted or added to R_n when estimating evapotranspiration. However, in calculating net radiation, the effect of soil

heat flux (G) is ignored for daily calculations as the magnitude of the flux in this case is relatively small. The net radiation, expressed in MJ m⁻² day⁻¹, is converted to mm/day (equivalent evaporation) in the FAO Penman–Monteith equation by using 0.408 as the conversion factor within the equation. In this method, evapotranspiration rate from a reference surface, with abundance of water, is considered as the reference crop evapotranspiration normally referred as reference evapotranspiration, and is denoted as ET₀. The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m⁻¹ and an albedo of 0.23. It resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s m⁻¹ implies a moderately dry soil surface resulting from about a weekly irrigation frequency. Standardized reference evapotranspiration equation suggested by Walter *et al.* (2000) is given by equation (1). The FAO Penman–Monteith model (Allen *et al.* 1998) uses equation (2) for estimation of reference ET₀.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (1)$$

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET₀ is reference evapotranspiration (mm d⁻¹), R_n is net radiation at the crop surface (MJm⁻²d⁻¹), G is soil heat flux density (MJ m⁻² d⁻¹), C_n is numerator constant that changes with reference type and calculation time step (K mm s³ Mg⁻¹ d⁻¹ or K mm s³ Mg⁻¹ h⁻¹), C_d is denominator constant that changes with reference type and calculation time step (s m⁻¹), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height (m s⁻¹), e_s is saturation vapour pressure (kPa), e_a is actual vapour pressure (kPa), $e_s - e_a$ is saturation vapour pressure deficit (kPa), Δ is slope vapour pressure curve (kPa °C⁻¹) and γ is psychrometric constant (kPa °C⁻¹).

In equation (2), psychrometric constant is estimated using equation (3)

$$\gamma = \frac{C_p P}{\varepsilon \lambda} = 0.665 \times 10^{-3} P \quad (3)$$

where γ is psychrometric constant [kPa °C⁻¹], P is atmospheric pressure, λ is latent heat of vapourization, 2.45 [MJ kg⁻¹], C_p is specific heat at constant pressure and its value for average atmospheric condition is 1.013 10⁻³ [MJ kg⁻¹ °C⁻¹], ε is ratio molecular weight of water vapour/dry air = 0.622. Values for the psychrometric constant as a function

of altitude are available in FAO 56 for use with CROPWAT.

Equation (2) can be used to compare the evapotranspiration at different periods of the year or in other regions and estimate the evapotranspiration of other crops (Allen *et al.* 1998).

In FAO Penman–Monteith, crop coefficient approach is used to estimate crop evapotranspiration (ET_c) from reference crop evapotranspiration (ET_0). ET_0 is multiplied by crop coefficient to get the ET_c . The crop coefficient, K_c , is the ratio of the crop ET_c to the reference ET_0 , and it represents an integration of the effects of crop height, albedo, canopy resistance, and evaporation from soil that distinguish the crop from reference grass. ET_0 represents an index of climatic demand whereas K_c predominately depends on crop characteristics and to a limited extent on climate. This enables the transfer of standard values for K_c between locations and between climates. This is the reason for the global acceptance and usefulness of the crop coefficient approach. If crop coefficient approach is used, then there is no need to change the C_n and C_d as the ET_0 of reference crop is converted into ET of taller crop by multiplying it with crop coefficient.

Evapotranspiration estimated from the FAO Penman–Monteith equation provides a standard to which ET in different periods of the year and in other regions can be compared and to which the evapotranspiration from other crops can be related (Pereira 2007). Mean daily and seasonal ET_0 for the period of 1981–2011 were estimated from mean values of climatic parameters using equation (1). The daily values of ET_0 were added to get the seasonal and annual values of ET_0 . This was referred

to as base line ET_0 and mean values of climatic parameters were referred to as base line values. Sensitivity analysis was done by varying the magnitude of climatic parameters namely temperature, wind speed, sunshine hours, and relative humidity one at a time by $\pm 5\%$, $\pm 10\%$, $\pm 15\%$ and $\pm 20\%$ over the base line values of climatic parameters (table 2).

2.3 Sensitivity coefficients

Sensitivity coefficients were calculated to measure sensitivity of calculated reference ET_0 to each climatic parameter using the method described in existing literature (Beven 1979; Gong *et al.* 2006; Liang *et al.* 2008). Normally, the results of sensitivity analysis are shown by plotting a curve between relative changes in a dependent variable and relative changes of an independent variable (Liang *et al.* 2008). For multi-variable models like Penman–Monteith method, different variables have different dimensions and different ranges of values, which make it difficult to compare the sensitivity by partial derivatives. To overcome this, a non-dimensional form of the sensitivity coefficient (Gong *et al.* 2006) is used (equation 4).

$$Sv_i = \lim_{\Delta V_i \rightarrow 0} \left(\frac{\Delta ET_0 / ET_0}{\Delta V_i / V_i} \right) = \frac{\delta ET_0}{\delta V_i} * \frac{V_i}{ET_0} \quad (4)$$

where Sv_i is the sensitivity coefficient for the i th variable and V is the climate variable analysed. A positive or negative sensitivity coefficient indicates that ET_0 will increase or decrease with the increase

Table 2. Mean value of principal climate parameters (1981–2011).

Season	Month	$T_{\min}$ ($^{\circ}\text{C}$)	$T_{\max}$ ($^{\circ}\text{C}$)	RH (%)	WS (kmd^{-1})	SSH (h)
Summer	March	12.6	27.5	64.0	88.0	8.2
	April	17.6	35.4	43.0	100.0	9.3
	May	23.0	38.3	43.0	136.0	9.3
	June	25.4	37.5	56.0	141.0	8.3
	Mean	19.7	34.7	51.5	116.3	8.8
Monsoon	July	26.2	33.8	76.0	116.0	6.5
	August	25.5	32.8	81.0	82.0	6.4
	September	23.1	32.6	77.0	67.0	7.5
	October	16.8	31.6	65.0	45.0	8.0
	Mean	22.9	32.7	74.8	77.5	7.1
Winter	November	11.3	27.3	63.0	45.0	7.3
	December	7.5	21.6	70.0	50.0	6.2
	January	6.5	18.6	76.0	73.0	6.0
	February	8.5	22.0	72.0	83.0	7.3
	Mean	8.5	22.4	70.3	62.8	6.7
Annual	Mean	17.0	29.9	66.0	86.0	7.5

$T_{\min}$: minimum temperature; $T_{\max}$: maximum temperature; RH : relative humidity; WS : wind speed; SSH : sunshine hours.

or decrease of a climatic variable (Liang *et al.* 2008). The values of sensitivity coefficient (Sv_i) for a particular climatic parameter indicated the level of sensitivity of ET_0 calculation to variation in that parameter. The larger the absolute sensitivity coefficient, the larger the effect of a given variable on ET_0 . Sensitivity coefficients were computed from the daily average values of 31 years of each climate variable. Thus each sensitivity coefficient is a daily average value of 31 years for each climate parameter for percent increase or decrease in respective climatic parameter. For example, to determine the sensitivity coefficients for the maximum temperature (T_{max}), the amount of increase or decrease in ET_0 at 5%, 10%, 15% and, 20% increase or decrease in maximum temperature were calculated as the difference between the computed

mean ET_0 and the new ET_0 values for each season (summer, monsoon, and winter) and for whole year. The difference between the computed ET_0 (with 5% increase or decrease in base ET_0) and base ET_0 was divided by the change in T_{max} . Similarly, the sensitivity coefficients were determined for other climate parameters. The sensitivity coefficients on seasonal and annual basis were determined for better understanding of relative effect of each variable on ET_0 in different seasons.

3. Results and discussion

Variations in mean monthly values of climatic parameters are shown in figure 1. The mean minimum and maximum temperature were 17.0° and

Figure 1. Mean monthly variations of major climatic parameters.

29.9°C, respectively. The mean monthly relative humidity, wind speed and sunshine hours were 66%, 86 km h⁻¹ and 7.5 h, respectively. The lowest and highest mean monthly minimum temperatures were observed in the months of January and July. The lowest and highest mean monthly maximum temperatures were observed in January and May. The lowest and highest mean monthly relative humidity was in the month of May and August. Solar radiation was maximum in the month of May followed by April and June.

Table 3 shows the relative change in the annual and seasonal ET₀ (mm) due to percent change in each climate parameters. The relative change in each variable has varying effect on seasonal ET₀. Change in ET₀ due to increase or decrease in climatic parameters were compared with the mean ET₀. The mean annual ET₀ was 1372 mm. The mean ET₀ in summer, monsoon and winter were 643, 505, and 229 mm, respectively. Increase in mean minimum temperature by 20%, increased the summer ET₀ by 2% (from 643 to 655 mm). If the mean minimum temperature was reduced by 20%, summer ET₀ reduced by 1% (from 643 to 634 mm). This indicates that the effect of increase in temperature was more on ET₀ than the decrease in

temperature. Variation in ET₀ due to change in mean minimum temperature was more in monsoon season (+5% for 20% increase in temperature and -3% for 20% decrease in temperature).

This suggested that ET₀ is more sensitive to mean minimum temperature in monsoon than in other seasons. In winter, the effect of increase or decrease in temperature on ET₀ was ≤ 1. Annual ET₀ increased by 4% (from 1372 to 1424 mm) for 20% increase in mean minimum temperature.

The effect of change in maximum temperature on ET₀ was more prominent as compared to the other parameters. The effect of change in maximum temperature on ET₀ was much more compared to other parameters. Increase in maximum temperature by 20% increased the ET₀ by 12% in all the seasons including annual ET₀. Decrease in mean maximum temperature by 20% decreased the ET₀ by 9 to 10% in different seasons. Change in relative humidity influenced ET₀ but the effect was less than the mean maximum temperature. The maximum change of ET₀ was ±5% in winter season for ±20% change in maximum temperature. Reference evapotranspiration was more sensitive to relative humidity during winter followed by monsoon and summer seasons. Annual ET₀ increased from 1372

Table 3. Changes in seasonal and annual ET₀ (mm) due to change in principal climatic parameters.

	Change in ET ₀ (mm) due to percent change in climatic parameter								
Season	+5%	+10%	+15%	+20%	Mean	-5%	-10%	-15%	-20%
Minimum temperature ($T_{\min}$)									
Summer	645 (0)	648 (1)	651 (1)	655 (2)	643	640 (0)	638 (-1)	636 (-1)	634 (-1)
Monsoon	510 (1)	516 (2)	522 (3)	528 (5)	505	500 (-1)	496 (-2)	492 (-3)	488 (-3)
Winter	230 (1)	231 (1)	231 (1)	232 (1)	229	228 (0)	223 (0)	227 (-1)	227 (-1)
Annual	1380 (1)	1391 (1)	1402 (2)	1424 (4)	1372	1365 (-1)	1358 (-1)	1351 (-2)	1347 (-2)
Maximum temperature ($T_{\max}$)									
Summer	661 (3)	681 (6)	700 (9)	720 (12)	643	625 (-3)	608 (-5)	591 (-8)	576 (-10)
Monsoon	518 (3)	532 (5)	548 (9)	563 (12)	505	492 (-3)	479 (-5)	468 (-7)	457 (-9)
Winter	235 (3)	242 (6)	249 (9)	256 (12)	229	223 (-2)	217 (-5)	211 (-8)	205 (-10)
Annual	1409 (3)	1453 (6)	1493 (9)	1537 (12)	1372	1336 (-3)	1299 (-5)	1267 (-8)	1234 -10
Relative humidity									
Summer	637 (-1)	633 (-1)	628 (-2)	623 (-3)	643	647 (1)	651 (1)	656 (2)	660 (3)
Monsoon	500 (-1)	495 (-2)	490 (-3)	485 (-4)	505	510 (1)	514 (2)	519 (3)	523 (4)
Winter	227 (-1)	224 (-2)	220 (-4)	218 (-5)	229	232 (1)	234 (2)	237 (4)	239 (5)
Annual	1361 (-1)	1347 (-2)	1336 (-3)	1321 (-4)	1372	1383 (1)	1394 (2)	1409 (3)	1420 (3)
Wind speed (WS)									
Summer	650 (1)	658 (2)	665 (4)	672 (5)	643	635 (-1)	627 (-2)	619 (-4)	611 (-5)
Monsoon	506 (0)	509 (1)	511 (1)	513 (2)	505	503 (0)	501 (-1)	499 (-1)	497 (-2)
Winter	231 (1)	233 (2)	235 (3)	237 (4)	229	227 (-1)	225 (-1)	223 (-2)	221 (-3)
Annual	1383 (1)	1394 (2)	1405 (2)	1416 (3)	1372	1361 (-1)	1351 (-2)	1336 (-3)	1325 (-3)
Sunshine hour (SSH)									
Summer	653 (2)	664 (3)	674 (5)	685 (7)	643	632 (-2)	621 (-3)	611 (-5)	599 (-7)
Monsoon	514 (2)	524 (4)	534 (6)	543 (8)	505	495 (-2)	486 (-4)	476 (-6)	466 (-8)
Winter	232 (1)	235 (3)	238 (4)	241 (5)	229	227 (-1)	223 (-2)	221 (-4)	217 (-5)
Annual	1394 (2)	1420 (3)	1442 (5)	1464 (7)	1372	1351 (-2)	1325 (-3)	1303 (-5)	1281 (-7)

(Values in parentheses show the percent change).

Figure 2. (a–d) Percent change in ET_0 with respect to percent change in climatic parameter.

to 1420 mm for 20% decrease in relative humidity. However, if relative humidity was increased by 20%, ET_0 decreased to 1361 mm. ET_0 was more sensitive to wind speed in summer followed by winter and monsoon season. The maximum change of $\pm 5\%$ was observed in summer for a change of $\pm 20\%$. Annual ET_0 increased from 1372 to 1416 mm for 20% increase in wind speed. However, if wind speed was decreased by 20%, ET_0 decreased to 1325 mm.

After maximum temperature, change in duration of sunshine hours affected the ET_0 most. Maximum change of $\pm 8\%$ was for $\pm 20\%$ change in sunshine duration. The maximum change of $\pm 8\%$ was observed in monsoon followed by summer (7%) and winter (5%). Annual ET_0 increased from 1372 to 1464 mm for 20% increase in duration of sunshine hours. However, if duration of sunshine hours was decreased by 20%, ET_0 decreased to 1281 mm. These results indicate that in all the seasons ET_0 was more sensitive to mean maximum temperature followed by duration of sunshine hours. This suggests that the maximum temperature and duration of sunshine hours are major climatic parameters that control the ET_0 in this region.

However, change in wind speed, relative humidity and minimum temperature had varying effect

on relative change in ET_0 . After maximum temperature and sunshine hours, ET_0 was more sensitive to wind speed followed by relative humidity and minimum temperature in summer. In monsoon, after maximum temperature and sunshine hours, ET_0 was more sensitive to minimum temperature followed by relative humidity and wind speed. However, in winter after maximum temperature and sunshine hours, ET_0 was more sensitive to relative humidity followed by wind speed and minimum temperature. In winter, ET_0 was less sensitive to minimum temperature compared to other seasons. Goyal (2004) reported that, in the arid zone of Rajasthan in India, evapotranspiration was more sensitive to temperature followed by wind speed, solar radiation, and vapour pressure. Whereas, in our study area (Trans-Indo-Gangetic plain), after temperature, duration of sunshine hour has more effect on ET_0 . This may be due to the fact that the arid zone of Rajasthan falls in famous Thar Desert and, therefore, temperature and wind speed are relatively higher as compared to the Trans-Indo-Gangetic plain. Vapour pressure which represents relative humidity had least effect on ET_0 in Rajasthan in contrast to Trans-Indo-Gangetic plains where wind speed and minimum temperature had least effect.

Table 4. *Seasonal and annual sensitivity coefficient.*

Season	Change in ET_0 due to percent change in climatic parameter							
	+5%	+10%	+15%	+20%	-5%	-10%	-15%	-20%
$T_{\min}$								
Summer	0.08	0.10	0.10	0.11	0.04	0.06	0.06	0.07
Monsoon	0.23	0.22	0.22	0.23	0.15	0.17	0.16	0.16
Winter	0.11	0.06	0.07	0.05	0.11	0.05	0.03	0.05
Annual	0.11	0.13	0.14	0.15	0.11	0.11	0.10	0.09
$T_{\max}$								
Summer	0.58	0.58	0.60	0.61	0.58	0.55	0.53	0.60
Monsoon	0.55	0.57	0.57	0.59	0.47	0.48	0.49	0.47
Winter	0.53	0.59	0.59	0.57	0.53	0.53	0.52	0.52
Annual	0.53	0.58	0.58	0.60	0.53	0.53	0.51	0.50
RH								
Summer	-0.16	-0.16	-0.15	-0.15	-0.12	-0.14	-0.14	-0.13
Monsoon	-0.20	-0.17	-0.20	-0.20	-0.19	-0.20	-0.19	-0.18
Winter	-0.20	-0.25	-0.23	-0.23	-0.22	-0.22	-0.25	-0.24
Annual	-0.18	-0.20	-0.20	-0.19	-0.13	-0.15	-0.18	-0.16
WS								
Summer	0.23	0.23	0.23	0.23	0.27	0.24	0.24	0.25
Monsoon	0.09	0.09	0.08	0.08	0.05	0.08	0.07	0.07
Winter	0.22	0.15	0.17	0.18	0.20	0.16	0.17	0.18
Annual	0.17	0.17	0.17	0.16	0.14	0.15	0.18	0.17
SSH								
Summer	0.38	0.32	0.33	0.32	0.38	0.33	0.33	0.35
Monsoon	0.35	0.35	0.38	0.37	0.46	0.37	0.40	0.38
Winter	0.18	0.25	0.22	0.25	0.23	0.25	0.27	0.27
Annual	0.30	0.32	0.32	0.31	0.40	0.37	0.34	0.33

The changes in ET_0 (mm) with respect to percent change in each climate variable are presented in the figure 2(a–d). Four separate lines are shown in each figure, which denote the change in ET_0 for percent increase or decrease in each climate variable annually and seasonally. It is observed that ET_0 response was linear with respect to percent change in all climate parameters with the exception of minimum temperature in winter season.

Table 4 represents the seasonal and annual changes in sensitivity coefficients. Ratios of change

in ET_0 to change in climate variable were reflected as sensitivity coefficients. All sensitivity coefficients showed a large degree of fluctuations in all three seasons. The sensitivity of ET_0 to the same climate variables showed significant differences within the seasons. In general, maximum temperature ($T_{\max}$) had large sensitivity coefficients throughout the season and year. Coefficients of wind speed were lower during the monsoon and higher during the summer season. Maximum temperature and the sunshine hour (SSH) had the largest sensitivity coefficient during the year and in all three seasons. The magnitude of the sensitivity coefficients were ranked as $S_{T_{\max}} > S_{SSH} > S_{WS} > S_{RH} > S_{T_{\min}}$ in summer, $S_{T_{\max}} > S_{SSH} > S_{T_{\min}} > S_{RH} > S_{WS}$ in monsoon season, $S_{T_{\max}} > S_{SSH} > S_{RH} > S_{WS} > S_{T_{\min}}$ in winter, and $S_{T_{\max}} > S_{SSH} > S_{RH} > S_{WS} > S_{T_{\min}}$ in a year. In which, S stands for sensitivity coefficient and $T_{\max}$ is maximum temperature, SSH is sunshine hours, WS is wind speed, RH is relative humidity, and $T_{\min}$ minimum temperature. The sensitivity coefficients indicated that ET_0 changes positively with maximum and minimum temperature, sunshine hour, and wind speed while reversely with the relative humidity. Plot of sensitivity coefficient *versus* climate variables for seasonal and annual time scale are shown in figure 3(a–d).

4. Conclusions

Sensitivity analysis of daily reference evapotranspiration was conducted on principal climatic variables, namely minimum and maximum temperature, relative humidity, wind speed, and sunshine hours using daily data of 31 years (1981–2011) of Karnal district of Haryana state. The response of ET_0 was linear to changes in all climatic variables with the exception of minimum temperature in winter season. Analysis revealed that mean seasonal and annual ET_0 was more affected by maximum temperature followed by sunshine hours. However, wind speed, relative humidity, and minimum temperature had varying effects on mean ET_0 . After maximum temperature and sunshine hours, ET_0 was more affected by wind speed, relative humidity, and minimum temperature in summer. In monsoon season, after maximum temperature and sunshine hours, ET_0 was more affected by minimum temperature, relative humidity, and wind speed. However, in winter, after maximum temperature and sunshine hours, ET_0 was more affected by relative humidity, wind speed, and minimum temperature. The change of temperature has slightly less effect on ET_0 during winter season as compared to other seasons because mean temperature in winter is low. ET_0 was less sensitive to the

Figure 3. (a–d) Plot of sensitivity coefficient *versus* climate variable.

decrease in temperature than the increase in temperature. Seasonal and annual reference evapotranspiration showed an increasing trend with decrease in the relative humidity and *vice versa*. Study suggests that climate variability would affect reference crop evapotranspiration; however, its impact on ET_0 would be different for different parameters. The study was carried out for Karnal district of Haryana using the data of only one station. However, the findings of the study will be applicable in the regions having similar climate. It would be interesting to see the results of the analysis in different districts in other regions of India. Procedures described in this paper can be used to carry out the analysis in other regions.

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