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Assessing sensitivity of reference evapotranspiration to changes in climatic variables : A case study of Akola, India

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सार – जलवायु परिवर्तन के परिदृश्यों को देखते हुए सिंचाई करने का समय-कार्यक्रम तथा जल संसाधनों की भावी योजना और प्रबंधन में फसल के लिए जल की आवश्यकता का समुचित आकलन करना अनिवार्य है। इस शोध पत्र में विभिन्न जलवायविक परिवर्तिताओं में परिवर्तनों के संदर्भ वाष्पन वाष्पोत्सर्जन (ETo) की संवेदनशीलता और अकोला में तापमान, परिवर्तन व ETo में उन्नत CO_2 के प्रभाव का अध्ययन करने का प्रयास किया गया। डॉ. पंजाबराव देशमुख कृषि विद्यापीठ (PDKV), अकोला के मौसम वैज्ञानिक आँकड़ों (1970-2008) का उपयोग करते हुए ETo का आकलन करने के लिए FAO- 56 पेनमेन- मॉनटीथ समीकरण प्रयुक्त किया गया। तापमान, सौर विकिरण, पवन गति और वाष्प दाब की कमी में परिवर्तन के रूप में ETo की अतिसंवेदनशीलता का अध्ययन किया गया। प्रत्येक जलवायु परिवर्तितायों में 5% के अंतराल पर-25% से 25% तक की भिन्नता थी और एक समय में केवल एक जलवायु परिवर्ती परिष्कृत की जाती है। 330 PPM से 660 PPM तक 1° से. से 5° से. और CO_2 के संयुक्त प्रभाव का अध्ययन किया गया। अनुकरण से प्राप्त परिणामों से पता चला है कि माध्य तापमान (T_{mean}) से वार्षिक ETo सबसे अधिक प्रभावित रहे, इसके बाद वाष्प दाब कमी (VPP), सौर विकिरण (Rs) और पवन गति (U_2), प्रभावित रहे। T_{min}, T_{max} और T_{mean} में परिवर्तनों से क्रमश: मॉनसून (जून से सितम्बर), शीतऋतु (जनवरी, फरवरी), मॉनसूनोत्तर ऋतु (अक्तूबर से दिसम्बर) में ETo सबसे अधिक प्रभावित रहे। तापमान परिवर्तन और उन्नत CO_2 सांद्रताओं के संयुक्त प्रभाव के अनुकरण से पता चला है कि 660 PPM तक CO_2 स्तरों में वृद्धि द्वारा तापमान में 4.0° से. का प्रभाव ऑफसेट रहा जिससे बढ़ते हुए तापमान का प्रभाव संवर्धित CO_2 सांद्रताओं द्वारा संतुलित रहा और जलवायु परिवर्तन परिदृश्यों के अन्तर्गत फसल के लिए जल की माँग उतनी अधिक मात्रा में नहीं उठी।

ABSTRACT. Accurate estimation of crop water requirement is essential for irrigation scheduling, and future planning and management of water resources under changing climate scenarios. In the present study, an attempt has been made to study the sensitivity of reference evapotranspiration (ETo) to changes in different climatic variables, and effect of temperature change and elevated CO_2 on ETo at Akola. The FAO - 56 Penman-Monteith equation has been used to estimate ETo using the meteorological data (1970-2008) of Dr. Panjabrao Deshmukh Krishi Vidyapeeth (PDKV), Akola. The sensitivity of ETo was studied in terms of changes in temperature, solar radiation, wind speed and vapour pressure deficit. Each of the climatic variables was varied from -25% to 25% at an interval of 5%, and only one climate variable was modified at a time. The combined effect of temperature change and elevated CO_2 was studied by varying the changes in temperature from 1 °C to 5 °C and the CO_2 levels from 330 ppm to 660 ppm. Simulation results showed that the mean temperature (T_{mean}) influenced the annual ETo the most followed by vapour pressure deficit (VPD), solar radiation (Rs) and wind speed (U_2). Changes in T_{min}, T_{max}, and T_{mean} affected ETo most during monsoon (June to September), winter (January, February), post-monsoon (October to December) seasons, respectively. Simulation of the combined effect of temperature change and elevated CO_2 concentrations indicated that the effect of 4.0 °C rise in temperature is offset by increase in CO_2 levels up to 660 ppm. Thus, the effect of rising temperature is moderated by the increasing CO_2 concentrations, and the crop water demand may not rise significantly under the climate change scenarios.

Key words – Evapotranspiration, Penman-Monteith equation, Stomatal resistance, Elevated CO_2, Climate change, Sensitivity analysis.

1. Introduction

Accurate estimation of crop water requirement is essential for irrigation scheduling, optimum allocation of water and energy resources, and improved irrigation planning and management practices. Reference evapotranspiration (ETo) adjusted with crop coefficient (Kc) is the most commonly used approach for estimation of crop water requirement. The evapotranspiration demand is a function of atmospheric variables such as air temperature, solar radiation, relative humidity, wind speed, and crop canopy characteristics such as canopy height, leaf area index, stomatal conductance (Allen *et al*., 1998). In the context of climate change, changes in temperature, wind speed, rainfall, solar radiation and other factors will lead to the change in ETo, thus affecting the crop water demand and agricultural water usage. Further, increased atmospheric CO_2 levels can have important physiological effects on crop plants such as an increase in photosynthetic rate, leaf area, biomass and yield, and a reduction in the stomatal conductance and transpiration per unit of leaf area (Allen, 1990). Understanding the effects of climate change and elevated CO_2 on evapotranspiration demand, and irrigation water requirements is of utmost importance for water resources planning and management.

There are a number of methods available for estimating reference evapotranspiration from standard meteorological observations. These equations differ in their data requirements, and their performances vary in different climatic conditions (Gocic and Trajkovic, 2010). The International Commission on Irrigation and Drainage (ICID) and the Food and Agricultural Organization (FAO) has recommended the FAO-56 Penman-Monteith (PM) method as the standard method for estimation of reference evapotranspiration (ETo) (Allen *et al*., 1998). The FAO-56 PM method assumes the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 sm^{-1} and albedo of 0.23, and the evaporation from this crop closely resembling the evaporation from an extensive surface of actively growing green grass of uniform height which is adequately watered. This is a physically-based method and can be used globally without any need for additional adjustments of parameters (Allen *et al*., 1998). A major drawback to apply the FAO-56 PM method is that it requires numerous weather data, *i.e*., maximum and minimum air temperature, wind speed, relative humidity, and solar radiation or sunshine duration. However, this method is preferable for climate change impact studies as it includes the effects of changes in all the important atmospheric variables (Kay and Davies, 2008; Kingston *et al*., 2009; Irmak *et al*., 2012; Islam *et al*., 2012a). The effect of elevated CO_2 concentration on evapotranspiration can also be simulated by modifying the stomatal conductance/ resistance term in the Penman-Monteith equation (Ficklin *et al*., 2009; Parajuli, 2010; Islam *et al*., 2012a).

Several studies have reported decrease in ETo contrary to the expected increasing trend in ETo due to well established increasing trends in air temperature under changing climate scenarios (Chattopadhyay and Hulme, 1997; Lawrimore and Peterson, 2000; Roderick and Farquhar, 2002; Chen *et al*., 2005; Irmak *et al*., 2012; Islam *et al*., 2012b). Martin *et al*. (1989) conducted sensitivity analyses using the Penman-Monteith equation and showed that evapotranspiration was highly sensitive to air temperature, solar radiation, humidity, and stomatal resistance. They also found that the effect of higher temperatures on evapotranspiration could be either moderated or exacerbated by changes in the other climatic elements (*e.g*., radiation, humidity, wind) and in plant factors (*e.g*., leaf area index, stomatal resistance). McKenny and Rosenberg (1993) demonstrated that sensitivity of potential evapotranspiration to changes in climate can vary depending on locations, time of the year and differences in the climatic factors considered. They also cautioned of extrapolating the results of a sensitivity analysis from one location to another or from one season to another. They reported changes in evapotranspiration of about -20 to +40% depending on the ecosystem, climate and plant type. Chattopadhyay and Hulme (1997) attributed the decrease in ETo in India to an increase in relative humidity. Goyal (2004) estimated an increase of 14.8% of total evapotranspiration demand with increase in temperature by 20% in the arid zone of Rajasthan. Xu *et al*. (2006) attributed the decrease in ETo to a combination of changes in solar radiation (Rs) and wind speed (U_2). Irmak *et al*. (2012) attributed decrease in ETo to significant increase in precipitation that resulted in significant reduction in Rs and net solar radiation (R_n). Islam *et al*. (2012b) reported that climate change might not increase the total water demand of the crop because of the reduced duration of the crop growing period and the effect of elevated CO_2 concentrations of decreasing the potential evapotranspiration demand.

As discussed above, for proper irrigation scheduling and crop planning, estimation of location specific evapotranspiration demand under changing climate scenarios is essential to account for temporal and spatial variation in evapotranspiration demand. In this paper, an attempt has been made to study the sensitivity of reference evapotranspiration to different climatic variables, and the combined effect of temperature change and elevated CO_2 on reference evapotranspiration at Akola (India).

2. Data and methodology

2.1. *Study area and data*

In this study daily meteorological data on maximum temperature (T_{max}), minimum temperature (T_{min}), maximum relative humidity (RH_{max}), minimum relative humidity (RH_{min}), sunshine hour, and wind speed were collected from Dr. Panjabrao Deshmukh Krishi Vidyapeeth (PDKV), Akola (Latitude : 20.70294° N,

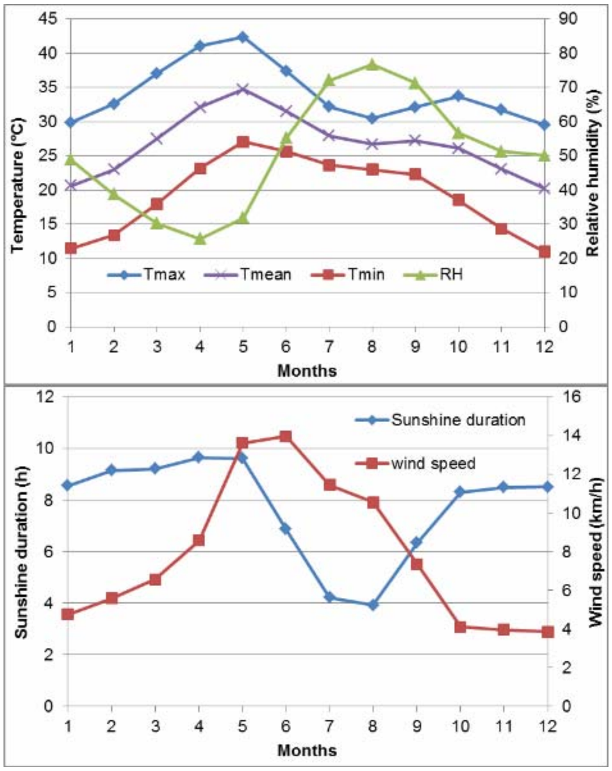

Fig. 1. Mean monthly weather condition at Akola

Longitude: 76.9994° E and Altitude: 285 m) for the period 1970-2008. Akola district comes under assured rainfall zone with an average annual rainfall of about 760 mm. In general, the daily temperature and evaporation rate gradually increases from February to June and then decreases from July onwards with slight increase in the month of October.

2.2. *FAO-56 Penman-Monteith equation*

The FAO-56 PM method has been employed to estimate the daily reference evapotranspiration using daily the meteorological data. The FAO-56 PM method is written as (Allen *et al.*, 1998):

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T+273} U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34U_2\right)} \tag{1}$$

where, ETo is the reference evapotranspiration (mm day^{-1}); R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^{2} day^{-1}); T is the mean daily air temperature (°C); U_2 is the wind speed at 2 m height (m s^{-1}); e_s is the saturation vapor pressure (kPa); e_a is the actual vapor pressure (kPa); (e_s-e_a) is the vapor pressure deficit (kPa);

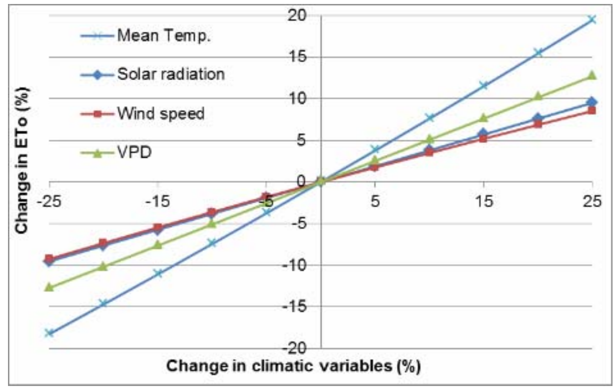

Fig. 2. Comparison of effect of different climatic variables on annual ETo

Δ is the slope of the vapor pressure curve (kPa °C^{-1}); and γ is the psychrometric constant (kPa °C^{-1}).

As the stomatal conductance varies with change in CO_2 levels, the effect of CO_2 can be incorporated into Eqn. (1) by modifying the stomatal resistance term in the PM equation. To account for the CO_2 effect on ETo, Eqn. (1) can be rewritten as (Islam *et al*., 2012a):

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T+273} U_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + \dfrac{0.34U_2}{CO_2\_factor}\right)} \tag{2}$$

where, "CO_2_factor" is the factor to account for the effect of elevated CO_2 levels, and is computed as the ratio of stomatal conductance at a given CO_2 level to that at the baseline atmospheric CO_2 concentration (330 ppm). The effect of CO_2 on stomatal conductance was estimated using the following relationship (Stockle *et al*., 1992):

$$g_{co_2} = g\left[1.4 - 0.4\frac{CO_2}{330}\right] \tag{3}$$

where, g_{co_2} is the modified conductance due to elevated CO_2 levels, g is the conductance without elevated CO_2 levels, and 330 represents the baseline atmospheric CO_2 concentration (ppm).

Sensitivity of ETo to different climatic variable was studied by varying mean temperature (T_{mean}), solar radiation (Rs), vapor pressure deficit (VPD), and wind speed (U_2) from -25% to 25% at an interval of 5%. One climatic variable at a time was modified while keeping all other variables constant. The modified values of climatic variable were then used to estimate ETo and compared with base ETo. The base ETo was computed without

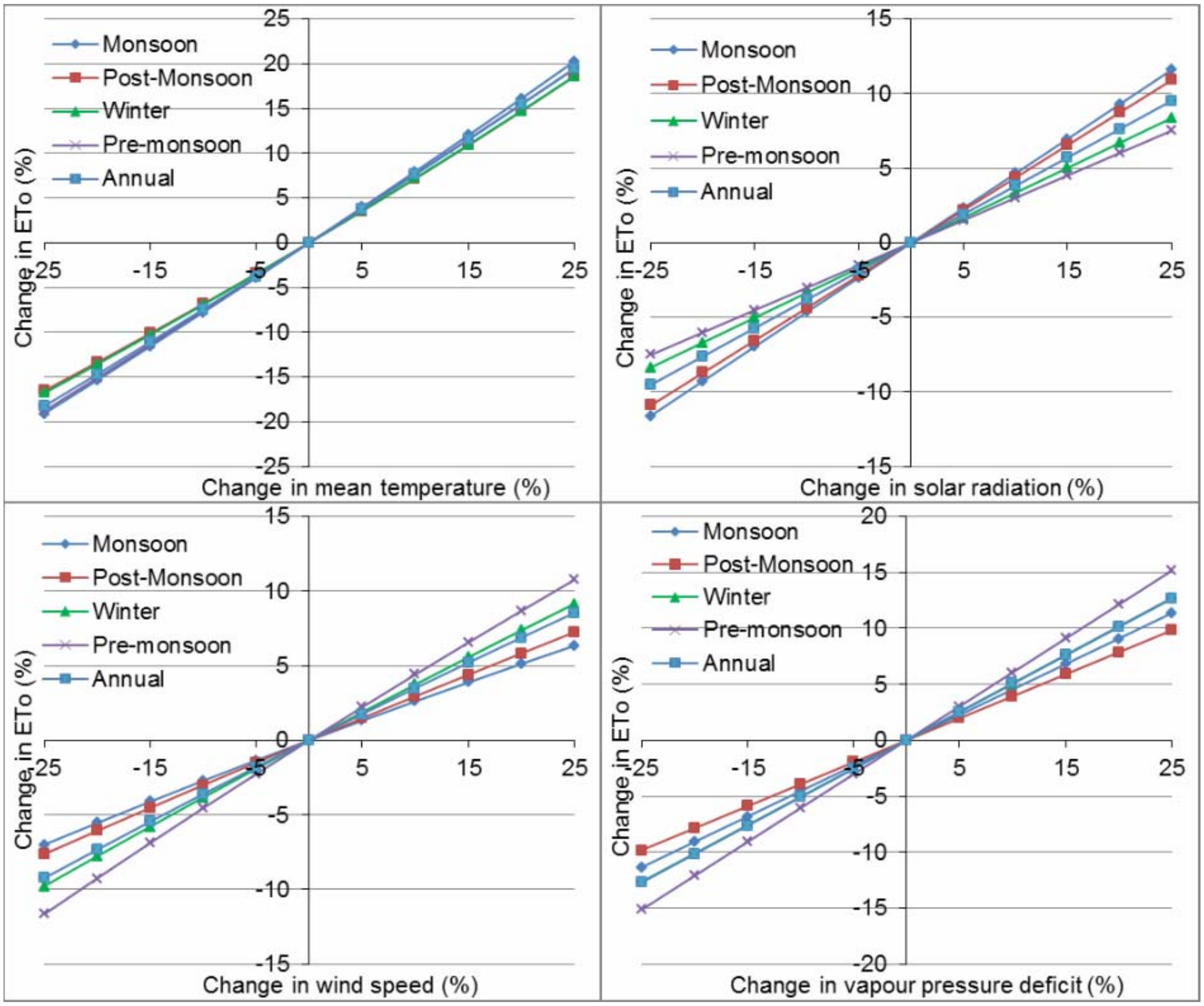

Fig. 3. Effect of changes in different climatic variables on seasonal ETo at Akola

modifying climatic variables. The combined effect of temperature change and elevated CO_2 levels was studied by varying the changes in temperature from 1 °C to 5 °C and the CO_2 level from 330 ppm to 660 ppm. The above selected ranges of temperature change (1 to 5 °C) are based on the projections of different General Circulation Models (GCMs) (IPCC, 2007).

3. Results and discussion

3.1. *General weather characteristics of the study area*

In general, Akola experiences warmer weather condition with mean temperature varying in the range of 20.3 (December) to 34.7 °C (May) (Fig. 1). The maximum temperature (T_{max}) and minimum temperature (T_{min}) varies in the range of 29.6 (December) to 42.3 °C (May) and 11.0 (December) to 27.0 °C (May), respectively. The mean relative humidity and duration of sunshine vary in the range of 25.8 (April) to 76.8% (August) and 3.9 (August) to 9.6 (April) hour, respectively. As far as wind speed is concerned, Akola experiences windy condition with wind speed varying in the range of 3.85 (December) to 13.95 km/h (June). As there are temporal variations in different weather variables, changes in any of these variable will affect ETo differently during different months and seasons.

3.2. *Sensitivity of ET_0 to different climatic variables*

While comparing the relative effect of changes in different climatic variables (mean temperature, wind speed, vapour pressure deficit and solar radiation) on annual ETo, it was observed that the annual ETo is the most sensitive to changes in mean temperature and the least sensitive to changes in wind speed (Fig. 2). Changes in the mean temperature from -25 to +25% resulted in

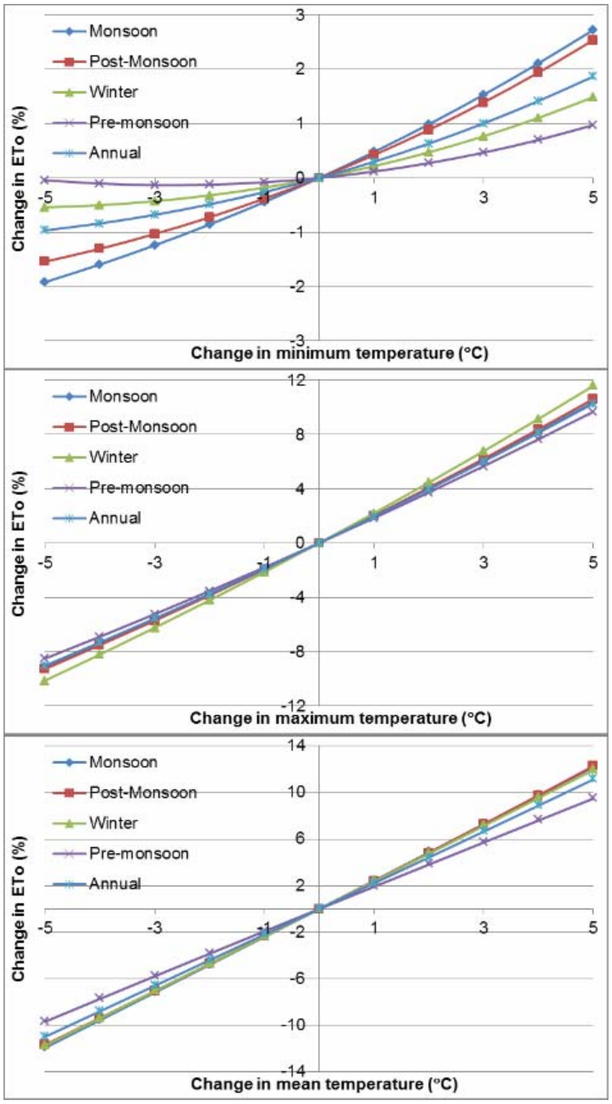

Fig. 4. Effect of changes in minimum, maximum and mean temperature on annual and seasonal ETo

change in annual ETo in the range of -18.25% to 19.45%, whereas similar changes in the wind speed resulted in changes in annual ETo in the range of -9.25% to 8.50%. Between the vapour pressure deficit and the solar radiation, the ETo is more sensitive to changes in vapour pressure deficit as compared to the changes in solar radiation. A 25% change in the vapour pressure deficit and similar changes in solar radiation resulted in 12.70 and 9.50% change in the annual ETo, respectively. Further, changes in wind speed and solar radiation resulted in almost similar changes in annual ETo.

Similar to the annual ETo, seasonal ETo is the most sensitive to changes in mean temperature followed by vapour pressure deficit, solar radiation and wind speed. Seasonal analysis showed that the changes in the solar radiation affected ETo most during monsoon season followed by post-monsoon, winter and pre-monsoon season, respectively; while wind speed and vapour pressure deficit influenced the ETo most during pre-monsoon period (Fig. 3) at Akola. A 25% increase in the solar radiation resulted in increase in ETo in the range of 11.60% (monsoon) to 7.50% (pre-monsoon). Similarly, there is an increase in ETo in the range of 10.80 (pre-monsoon) to 6.30% (monsoon) and 15.15 (pre-monsoon) to 9.80% (post-monsoon) due to 25% increase in U_2 and VPD, respectively. The changes in mean temperature (T_{mean}) have greater effect on ETo during monsoon season followed by pre-monsoon, winter and post-monsoon, and it varied in the range of 20.30 (monsoon) to 18.60% (post-monsoon) with 25% increase in T_{mean}. Similarly, a 25% decrease in T_{mean} resulted in the change in ETo in the range of -19.10 (monsoon) to -16.55% (post-monsoon).

3.3. *Sensitivity of ET_0 to minimum, maximum and mean temperature*

Fig. 4 depicts the changes in annual and seasonal reference evapotranspiration rate with the changes in the minimum, maximum and mean temperature. The mean temperature is found to influence the annual ETo the most, followed by maximum and minimum temperature, respectively. There is an increase of 1.9, 10.3 and 11.1% in annual ETo with 5 °C rise in T_{min}, T_{max} and T_{mean}, respectively. Similarly, a 5 °C decrease in T_{min}, T_{max} and T_{mean}, resulted in 1.0, 9.0 and 11.0% decrease in annual ETo, respectively. Comparison of effect of changes in the T_{min}, T_{max}, and T_{mean} on seasonal ETo showed that changes in minimum temperature resulted in maximum change during monsoon season (June to September), while changes in T_{max} and T_{mean} resulted in maximum change during winter season (January, February) and post-monsoon season (October to December), respectively.

The change in monthly ETo (%) with changes in temperature (°C), as represented by the slope (m) and the intercept (c) of the best fitted straight is line, is presented in Table 1. Monthly analysis showed variation in changes in ETo of Akola during different months due to changes in minimum, maximum, and mean temperature. The changes in ETo was least during the month of April due to changes in the minimum, maximum and mean temperature (Table 1) as evident from the slope of the best fitted straight line. The changes in ETo was maximum in the month of August due to changes in minimum and mean temperature, and in the month of January due to changes in maximum temperature. A 5 °C increase in minimum, maximum and mean temperature resulted in increase in ETo in the range of 0.90 (April) to 3.60% (August), 9.20

TABLE 1

Best fitted straight line describing changes in monthly ETo (%) with respect to changes in temperature (°C)

Months	T_{min}			T_{max}			T_{mean}		
	Slope (m)	Intercept (c)	R^2	Slope (m)	Intercept (c)	R^2	Slope (m)	Intercept (c)	R^2
Jan	0.244	0.196	0.952	2.257	0.311	0.999	2.497	0.080	1.000
Feb	0.165	0.183	0.913	2.097	0.273	0.999	2.259	0.004	1.000
Mar	0.100	0.177	0.803	1.851	0.232	0.999	1.949	-0.045	1.000
Apr	0.086	0.184	0.738	1.722	0.219	0.999	1.808	-0.051	1.000
May	0.112	0.193	0.812	1.870	0.244	0.999	1.980	-0.030	1.000
June	0.249	0.177	0.962	2.016	0.261	0.999	2.262	0.013	1.000
Jul	0.506	0.149	0.993	1.964	0.243	0.999	2.466	0.041	1.000
Aug	0.638	0.144	0.996	1.911	0.233	0.999	2.545	0.066	1.000
Sep	0.620	0.164	0.995	1.863	0.233	0.999	2.481	0.124	1.000
Oct	0.511	0.189	0.989	1.788	0.229	0.999	2.299	0.130	1.000
Nov	0.380	0.204	0.978	2.021	0.277	0.999	2.400	0.119	1.000
Dec	0.294	0.205	0.963	2.214	0.311	0.998	2.505	0.109	1.000

ΔETo = m(ΔT) + c, where $-5 \leq \Delta T \leq 5$, ΔETo = change in ETo (%), and ΔT = change in temperature (°C)#

TABLE 2

Effect of temperature change and different levels of CO_2 on ETo

Period	Changes in ETo (%) with temperature (°C) and CO_2 (ppm) change					
	Temperature increase = 2 °C			Temperature increase = 4 °C		
	CO_2 = 330 ppm	CO_2 = 495 ppm	CO_2 = 660 ppm	CO_2 = 330 ppm	CO_2 = 495 ppm	CO_2 = 660 ppm
Jan	5.0	2.1	-2.4	10.1	7.2	2.8
Feb	4.5	1.4	-3.4	9.0	6.0	1.3
Mar	3.9	0.8	-3.9	7.7	4.7	0.2
Apr	3.6	0.3	-4.7	7.1	3.9	-0.9
May	3.9	-0.5	-7.0	7.9	3.6	-2.8
Jun	4.5	-0.4	-7.5	9.1	4.3	-2.8
Jul	4.9	0.3	-6.6	9.9	5.3	-1.5
Aug	5.1	0.6	-6.0	10.3	5.9	-0.7
Sep	5.0	1.7	-3.3	10.1	6.9	1.9
Oct	4.6	2.5	-0.7	9.4	7.3	4.1
Nov	4.8	2.5	-1.1	9.8	7.5	4.0
Dec	5.0	2.5	-1.3	10.2	7.7	3.9
Annual	4.4	0.8	-4.6	8.9	5.4	0.0

(April) to 12.10% (January) and 8.90 (April) to 12.90% (August), respectively. Similarly, a 5 °C decrease in minimum, maximum and mean temperature resulted in decrease in ETo in the range of 0.02 (April) to 2.80% (August), 8.10 (April) to 10.50% (January) and 9.20 (April) to 12.60% (August), respectively.

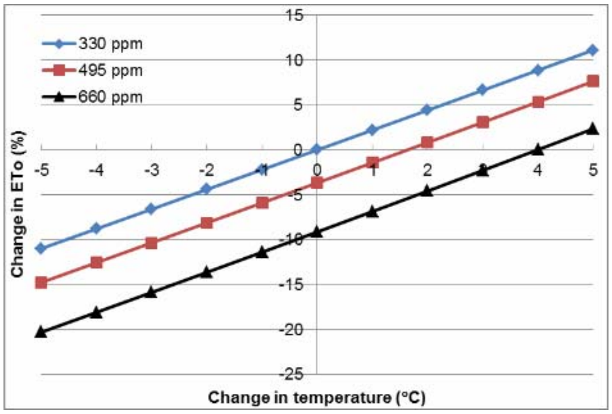

Fig. 5. Effect of changes in temperature and CO_2 concentration on reference evapotranspiration

3.4. *Effect of temperature and CO_2 concentration changes on reference evapotranspiration*

As shown in Fig. 5, there is an increase in reference ETo with rise in mean temperature. For a given CO_2 concentrations, annual reference ETo rate increased by about 0.12 mm/day (2.2% with respect to baseline) with every degree centigrade rise in temperature at Akola. Monthly analysis showed minimum increase (approximately 0.08 mm/day increase with per °C temperature rise) during December and January, while May recorded maximum increase (approximately 0.21 mm/day increases with per °C temperature rise). There is a decrease in reference evapotranspiration with increases in CO_2 concentration, while temperature remaining constant (Fig. 5). This decrease in ETo is due to decrease in stomatal conductance and increase in stomatal resistance with increase in CO_2 concentration. There is about 10% decrease in annual ETo demand with doubling (660 ppm) of CO_2 concentration, while temperature remaining constant. Simulating the combined effect of changes in temperature and elevated CO_2 showed that the effect of about 1.65 °C rise in temperature on annual ETo is offset by increase in CO_2 levels up to 495 ppm, whereas the effect of 4 °C rise in temperature is offset by increase in CO_2 concentrations up to 660 ppm. With 2°C increase in temperature and increase in CO_2 concentration to 495 ppm, there is increase in ETo in most of the months, except for the month of May and June (Table 2). However, 2 °C increase in temperature coupled with increase in CO_2 concentration to 660 ppm resulted in decrease in ETo in all the months. The changes in monthly ETo remained below 5% with 4 °C rise in temperature coupled with CO_2 concentration of 660 ppm, with most of the months showing increase in ETo except during the months of April to August. These results suggest that effect of increasing temperature on ETo is moderated by the elevated CO_2 concentrations, and are also in confirmation with previous studies (Martin *et al*., 1989; Ficklin *et al*., 2009; Parajuli, 2010; and Islam *et al*., 2012a and 2012b). Thus, crop water demand may not increase significantly under the climate change scenarios because of the moderating effect of elevated CO_2 on evapotranspiration demand. It is worth mentioning that the most of the relationships describing the plant physiological response to elevated CO_2 are based on the controlled environment experimental data (Allen, 1990). There are uncertainties in the nature and magnitude of plant physiological response to elevated CO_2 concentrations, and hence in the precise magnitude of simulated changes in ETo. Nevertheless, these simulation results provide valuable information on possible impacts of changes in climatic variables on evapotranspiration demand for planning irrigation water management strategies.

4. Summary and conclusion

Evapotranspiration (ET) is an important hydrological variable for irrigation water management, soil water balance studies, and hydrological modeling. The evapotranspiration demand depends on temperature, solar radiation, relative humidity, wind speed, and plant characteristics such as stomatal conductance and leaf area index. It is essential to understand the relative effect of different climate variables on estimated ETo in the event of climate change. Simulation study conducted using long-term meteorological data of Akola showed that the mean temperature influenced the annual ETo the most, followed by the maximum and the minimum temperature. Further, changes in T_{min}, T_{max}, and T_{mean} affected ETo the most during monsoon, winter, monsoon/ post-monsoon seasons, respectively. Every degree centigrade rise in temperature resulted in increase in annual reference ETo rate by about 0.12 mm/day. However, doubling of CO_2 concentrations (660 ppm), with temperature remaining constant, resulted in about 10% decrease in annual ETo demand. Simulation of the combined effect of temperature change and elevated CO_2 concentrations showed that the effect of 4.0 °C rise in temperature is offset by increase in CO_2 levels up to 660 ppm. Thus, the effect of rising temperature is moderated by the increasing CO_2 concentrations, and the crop water demand may not rise significantly under the climate change scenarios.

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