*Journal of Agrometeorology 16 (1) : 44-51 (June 2014)*

# Effect of climate change and elevated $CO_2$ on reference evapotranspiration in Varanasi, India - A case study

**ANNU PRIYA, A. K. NEMA and ADLUL ISLAM[1]**

*Department of Farm Engineering, Institute of Agricultural Sciences, BHU, Varanasi- 221005*

*[1]ICAR Research Complex for Eastern Region, Bihar Veterinary College PO, Patna-800014*

***E-mail**:anupam_nema@rediffmail.com; annuagri11@gmail.com*

## ABSTRACT

Evapotranspiration (ET) is the major component of hydrological cycle, and will affect the crop water requirement and future planning and management of water resources under changing climate scenarios. In the present study, an attempt was made to study the sensitivity of reference evapotranspiration (ETo) to different climatic variables, and effect of temperature and elevated $CO_2$ on ETo using meteorological data (1973-2010) of the Banaras Hindu University (BHU), Varanasi. The FAO-56 Penman–Monteith method was used to estimate ETo, and sensitivity of ETo was studied in terms of changes in temperature, solar radiation, wind speed and vapour pressure deficit. The combined effect of temperature and elevated $CO_2$ levels was studied by varying the temperature from 1°C to 5°C, and the $CO_2$ level from 330 ppm to 660 ppm. The simulation results showed that the mean temperature (Tmean) influenced the annual ETo the most followed by solar radiation (Rs), vapour pressure deficit (VPD) and wind speed ($U_2$). There are about 18.20, 13.80, 7.90 and 5.40% increase in annual ETo with 25% increase in Tmean, Rs, VPD, and $U_2$, respectively. Simulating the combined effect of temperature and elevated $CO_2$ indicated that the effect of 2.5 °C rise in temperature is offset by doubling of $CO_2$ concentration. 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.

***Keywords:*** Evapotranspiration, Penman-Monteith equation, Stomatal resistance, Sensitivity analysis, Climate change

Evapotranspiration (ET) is the major component of the hydrological cycle and an important hydrological variable for irrigation water management, soil water balance studies, and hydrological modeling (Islam *et al.*, 2012a and Sentelhas *et al.*, 2010). The evapotranspiration demand is a function of various factors such as temperature, solar radiation, humidity, wind speed, and characteristics of the specific vegetation that is transpiring, which may vary significantly between vegetation types (Allen *et al.*, 1998). If a region becomes warmer, there will be increased evaporative demand and more irrigation water will be required to maintain crop yields. Goyal (2004) estimated an increase of 14.8% of total ET demand with increase in temperature by 20% in the arid zone of Rajasthan. Therefore, a reliable estimate of evapotranspiration demand, along with knowledge of rainfall and soil moisture storage capacity, is needed to quantify crop water requirements and schedule irrigation.

With the anticipated climate change, 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 stomatal conductance and transpiration per unit of leaf area (Allen, 1990). There are several experimental studies indicating that stomatal conductance of many plants will decline as atmospheric $CO_2$ increases resulting in a reduction of transpiration (Morison and Gifford, 1983; Field *et al.*, 1995; and Wullschleger *et al.*, 2002). Total leaf area of some plant types may increase with increased atmospheric $CO_2$ concentrations (Wand *et al.*, 1999 and Saxe *et al.*, 1998), leading to increased transpiration and potentially offsetting the effect of the reduction of stomatal conductance. Wand *et al.* (1999) reported 24% and 29% decrease in stomatal conductance and 15% and 25% increase in individual leaf area for C3 and C4 species, respectively, with doubling of $CO_2$ levels. Rosenberg *et al.* (1989) reported that the effect of elevated $CO_2$ concentration on stomatal functioning could result in moderating influence on ET that would probably not be counteracted entirely by an increase in plant size. If $CO_2$ fertilization occurs and leaf area index (LAI) increases, a stomatal response of > 20% can more than compensate for the effects of increased leaf area. If LAI decreases by 15%, a concurrent 60% increase in stomatal resistance ($r_s$) is sufficient to nearly or completely offset the impact of climate change on ET. Martin *et al*. (1989) found that the effect of higher temperatures on ET could be either moderated or exacerbated by changes in other climatic elements (radiation, humidity, wind) and in plant factors (leaf area index, stomatal resistance). They reported changes in evapotranspiration of about -20 to +40% depending on the ecosystem, climate and plant type. Kruijt *et al.* (2008) reported that $CO_2$-effect would lead to a much reduced desiccating effect of climate change. With increase in $CO_2$ concentration to 970 ppm and temperature by 6.4 °C, Ficklin *et al.* (2009) reported watershed-wide average (averaged over 50 years) decrease in evapotranspiration by 37.5%, resulting in increases of water yield by 36.5%, and streamflow by 23.5% as compared to the present day climate. 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 increased $CO_2$ concentrations of decreasing the potential evapotranspiration demand. Understanding the effects of climate change and rising $CO_2$ levels on evapotranspiration demand, and irrigation water requirements is essential for water resources planning and management.

There are several methods for estimation of reference evapotranspiration (ETo), and these equations differ in their data requirements and their performances vary in different environments (Gocic and Trajkovic, 2010). The International Commission on Irrigation and Drainage (ICID) and the Food and Agricultural Organization (FAO) Expert Consultation Committee on revision of FAO methodologies for crop water requirements recommended the FAO-56 Penman Monteith (PM) method as the standard method for estimation of reference potential evapotranspiration (ETo) (Allen *et al*., 1998). The FAO-56 method assumes the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s $m^{-1}$ and albedo of 0.23, closely resembling the evaporation from an extensive surface of actively growing green grass of uniform height which is adequately watered. This method can be used in a wide variety of climatic conditions without any need for adjustments of parameters (Allen *et al*., 1998). For climate change impact studies, this method is preferable as it includes the effects of changes in all important atmospheric variables and has been used in several studies (Goyal, 2004; Kay and Davies, 2008; Kingston *et al*., 2009; and Islam *et al*., 2012a). Further, the effect of elevated $CO_2$ concentration on evapotranspiration can also be simulated by modifying the stomatal conductance term in the Penman-Monteith equation (Ficklin *et al*., 2009; Parajuli, 2010; and Islam *et al*., 2012a). McKenny and Rosenberg (1993) demonstrated that sensitivity of potential evapotranspiration to changes in climate can vary by location, by time of the year, and by 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. As evapotranspiration demand varies spatially and temporally, it becomes imperative to study location specific evapotranspiration demand under changing climate scenarios. 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 of Varanasi (India).

## MATERIALS AND METHODS

### *Study area and data*

In this study daily meteorological data from Banaras Hindu University (BHU), Varanasi (Latitude: 25.2628° N, Longitude: 82.9919° E, and Altitude: 80.71 m) for the period 1973-2010 were used. The meteorological data collected included maximum temperature (Tmax), minimum temperature (Tmin), maximum relative humidity (RHmax), minimum relative humidity (RHmin), sunshine hour, and wind speed. Varanasi experiences a humid subtropical climate with large variations between summer and winter temperatures. It receives an average annual rainfall of 1110 mm. Summers are long, from early April to October, with intervening monsoon seasons and are also extremely hot with temperature ranging between 22 and 46 °C. There are large diurnal variations during winters, with warm days and downright cold nights and temperatures dipping below 5 °C are not uncommon in winter months of December to February.

### *FAO-56 Penman-Monteith equation*

The FAO-56 Penman-Monteith method to estimate ETo can be written as (Allen *et al*., 1998):

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

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 at 2 m height (°C); $U_2$ is the wind speed at 2 m height (m s$^{-1}$); $e_s$ is the saturation vapour pressure (kPa); $e_a$ is the actual vapour pressure (kPa); ($e_s$-$e_a$) is the vapour pressure deficit (kPa); $\Delta$ is the slope of vapour pressure curve (kPa °C$^{-1}$); and g is the psychrometric constant (kPa °C$^{-1}$).

As the stomatal conductance varies with $CO_2$ levels, this can be incorporated into Eq. (1) by modifying the stomatal resistance value for elevated $CO_2$ levels. To account for the $CO_2$ effect on ETo, Eq. (1) can be rewritten as (Islam *et al.*, 2012a):

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

where, "$CO_2$_factor" is the factor to account for the effect of elevated $CO_2$ levels. Based on the experimental observations of a 40% linear decrease in stomatal conductance between 330 and 660 ppm $CO_2$ concentrations (Morison and Gifford, 1983), the effect of $CO_2$ on stomatal conductance was estimated using the following relationship (Stockle *et al*. 1992 and Ficklin *et al.*, 2009):

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

where, $g_{CO_2}$ is the modified stomatal conductance due to elevated $CO_2$ levels (m s$^{-1}$), *g* is the stomatal conductance without the effect of $CO_2$ (m s$^{-1}$), $CO_2$ is the elevated future atmospheric $CO_2$ concentrations (ppm), and 330 represents the baseline atmospheric $CO_2$ concentration of 330 ppm. As $CO_2$ concentrations are expected to increase from the baseline concentrations of approximately 330 ppm to approximately between 550 and 970 ppm under different emission scenarios (IPCC, 2007), $CO_2$_factor is computed using equation (3) as the ratio of stomatal conductance at elevated $CO_2$ level and the stomatal conductance at the baseline atmospheric $CO_2$ concentration of 330 ppm.

In order to study the sensitivity of ETo to different climatic variable, mean temperature (Tmean), solar radiation (Rs), vapour pressure deficit (VPD), and wind speed ($U_2$) were varied in the range of -25% to 25% at an interval of 5%. For sensitivity analysis, one climate variable at a time was modified while keeping all other variables constant. The new values of climatic variable were then used to calculate ETo and compared with baseline ETo (ETo computed without modifying climatic variables). The combined effect of temperature and elevated $CO_2$ levels was studied by varying the temperature from 1°C to 5°C and the $CO_2$ level from 330 ppm to 660 ppm. In this study three levels (330, 495 and 660 ppm) of $CO_2$ concentrations were considered. The above ranges (1 to 5 °C) of temperature variations considered are based on the projections of different General Circulation Models (GCMs) (IPCC, 2007).

## RESULTS AND DISCUSSION

### *General weather characteristics of the study area*

Table 1 shows the long term mean monthly weather conditions of the study areas. The maximum, minimum, and mean temperature varied in the range of 21.9 (Jan) to 39.8 °C (May), 8.8 (Jan) to 27.3 °C (Jun), and 15.3 (Jan) to 32.7 °C (May) respectively. Relative humidity, wind speed, and sunshine hours varied in the range of 33.2 (Apr) to 78.5% (Aug), 2.0 (Nov) to 6.4 km h$^{-1}$ (Jun) and 5.0 (Jul) to 9.7 (Apr) hour, respectively. As there are temporal variations in different weather variables, any changes in these variables will impact ETo differently during different months and seasons.

The long term mean monthly ETo computed, without modifying any climatic variable, using the Penmann - Monteith method is shown in Table 1. The monthly ETo varied from 2.0 mm day$^{-1}$ (Dec) to 7.0 mm day$^{-1}$ (May). The monsoon, post-monsoon, winter, pre-monsoon and annual ETo was computed as 4.8, 2.7, 2.6, 6.0, and 4.2 mm day$^{-1}$. These values were used as baseline values for estimating changes under different scenarios.

### *Sensitivity of ETo 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 most sensitive to changes in mean temperature and least sensitive to changes in wind speed (Fig. 1). The change in annual ETo varied in the range of -16.55% to 18.20% with changes in the mean temperature from -25 to +25%. For similar changes in the wind speed (-25 to +25%), the changes in

**Table 1:** Mean monthly weather condition and ETo in Varanasi

| Month | Max. Temp. (°C) | Min. Temp. (°C) | Relative huumidity (%) | Sunshine duration (h) | Wind Speed (km $h^{-1}$) | ETo (mm $day^{-1}$) |
|---|---|---|---|---|---|---|
| Jan | 21.9 | 8.8 | 67.8 | 7.1 | 2.9 | 2.1 |
| Feb | 25.4 | 11.3 | 62.3 | 8.6 | 3.6 | 3.1 |
| Mar | 32.0 | 15.7 | 46.6 | 9.2 | 4.2 | 4.6 |
| Apr | 38.4 | 21.3 | 33.2 | 9.7 | 5.3 | 6.4 |
| May | 39.8 | 25.6 | 41.2 | 9.5 | 6.1 | 7.0 |
| Jun | 38.1 | 27.3 | 53.5 | 7.9 | 6.4 | 6.3 |
| Jul | 33.5 | 26.2 | 75.3 | 5.0 | 6.1 | 4.5 |
| Aug | 32.6 | 26.1 | 78.5 | 5.8 | 5.4 | 4.3 |
| Sep | 32.2 | 25.1 | 77.4 | 6.5 | 4.4 | 4.0 |
| Oct | 32.2 | 21.0 | 66.0 | 8.5 | 2.6 | 3.6 |
| Nov | 29.0 | 14.7 | 59.5 | 8.5 | 2.0 | 2.6 |
| Dec | 24.2 | 10.0 | 65.3 | 7.5 | 2.4 | 2.0 |

annual ETo varied in the range of -5.70% to 5.40%. Thus, effect of change in the mean temperature on ETo is almost double than that of the wind speed. Among the vapour pressure deficit and the solar radiation, the ETo is more sensitive to changes in solar radiation as compared to the changes in vapour pressure deficit. A 25% change (increase / decrease) in the vapour pressure deficit and solar radiation resulted in about 7.90 and 13.80% change (increase / decrease) in annual ETo, respectively. Thus, the relative effect of different climatic variables in annual ETo is in the order of Tmean > Rs > VPD > $U_2$. For example, a 25% increase in Tmean, Rs, VPD, and $U_2$ resulted in 18.20, 13.80, 7.90 and 5.40% increase in annual ETo, respectively.

Seasonal analysis showed that changes in mean temperature and solar radiation has maximum effect on ETo during monsoon season (JJAS), whereas wind speed and vapour pressure deficit influenced ETo most during the pre-monsoon (MAM) season (Fig. 1). A 25% rise in mean temperature and solar radiation resulted in increase in seasonal ETo in the range of 19.10 (monsoon) to 15.80% (winter (JF)), and 16.20 (monsoon) to 11.70% (pre-monsoon), respectively. There is an increase in seasonal ETo in the range of 7.60 (pre-monsoon) to 3.90% (monsoon) and 10.40 (pre-monsoon) to 5.80% (post-monsoon (OND)) with 25% increase in $U_2$ and VPD, respectively.

***Sensitivity of ETo to minimum, maximum and mean temperature***

As the maximum and minimum temperature are projected to change differently under different climate change scenarios (IPCC, 2007), it will impact ETo differently during different periods. While comparing the relative effect of minimum, maximum and mean temperature, it was observed that mean temperature influenced the annual ETo the most, followed by maximum and minimum temperature (Table 2). A 5 °C increase in minimum, maximum and mean temperature resulted in 3.7, 8.9 and 11.9% increase in annual ETo, respectively, whereas a 5 °C decrease in minimum, maximum and mean temperature resulted in 2.8, 7.8 and 11.2% decrease in annual ETo, respectively. Comparison of effect of changes in the Tmin, Tmax, and Tmean on seasonal ETo, showed that changes in minimum temperature resulted in maximum change in seasonal ETo during the post-monsoon season, while changes in Tmax and Tmean resulted in maximum change in seasonal ETo during the winter season.

***Effect of temperature and $CO_2$ concentration changes on ETo***

In general, there is an increase in reference evapotranspiration with rise in mean temperature. Every degree centigrade rise in mean temperature resulted in

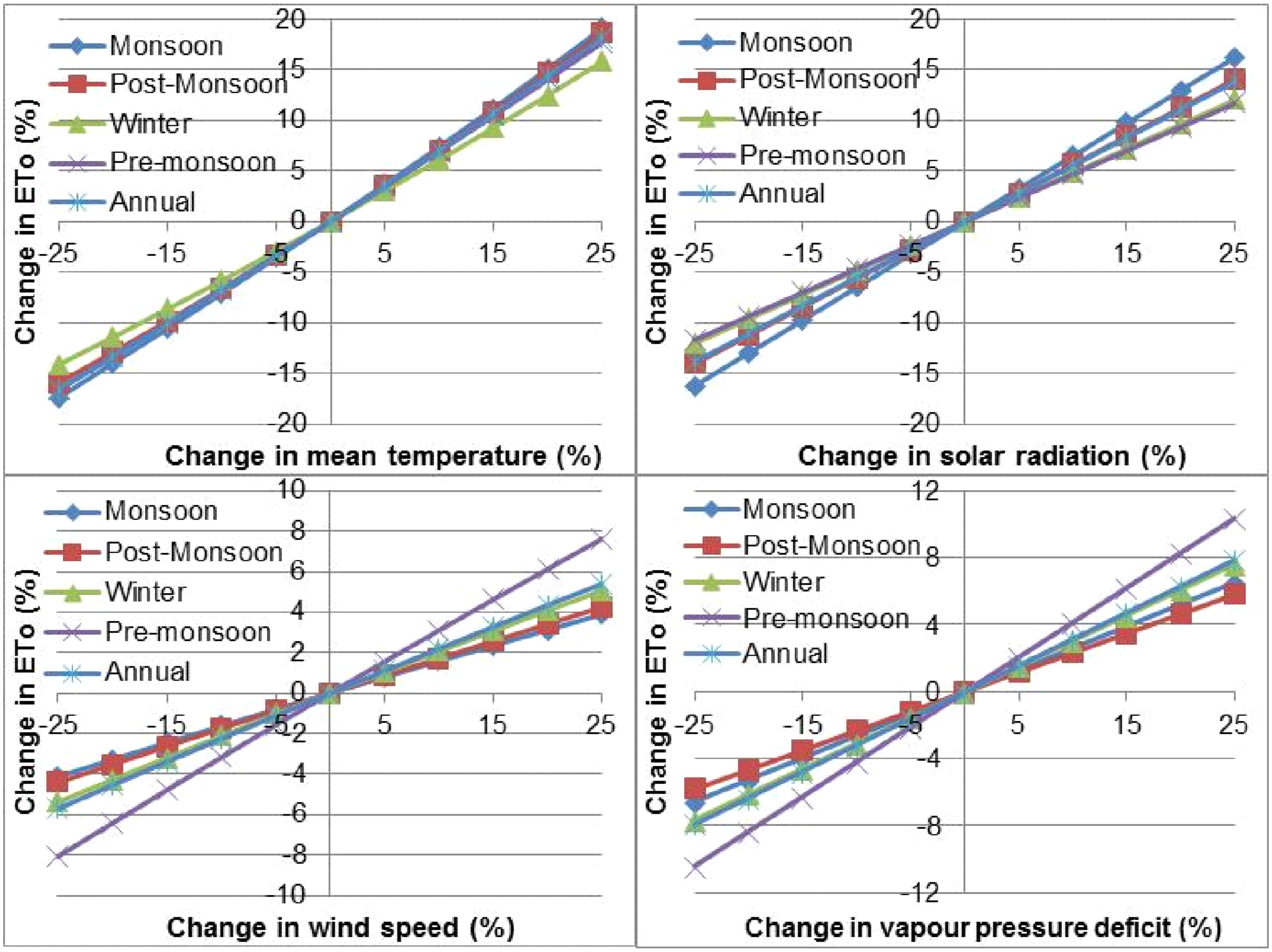


**Fig. 1:** Effect of changes in different climatic variables on seasonal ETo

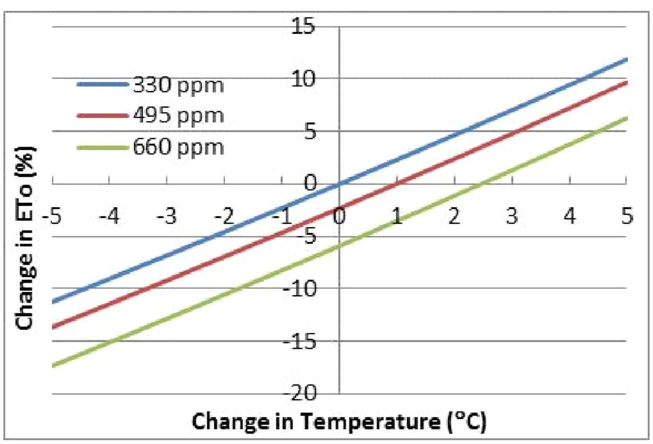


**Fig. 2:** Effect of changes in temperature and $CO_2$ concentration on ETo

increase in reference ETo by about 0.1 mm day$^{-1}$ (2.3% increase with respect to baseline) annually. Among different months, December and January recorded the minimum increases (approximately 0.06 mm day$^{-1}$ increase with 1 °C temperature rise) while April/May recoded maximum increases (approximately 0.13 mm day$^{-1}$ increase with 1 °C temperature rise). If temperature remains constant, then there is a decrease in reference evapotranspiration with increases in $CO_2$ concentration (Fig. 2). This decrease in reference ETo is due to decrease in stomatal conductance and increase in stomatal resistance with increase in $CO_2$ concentration. There is about 6% decrease in annual ETo demand with doubling (660 ppm) of $CO_2$ concentration, with temperature remaining constant. Simulating the combined effect of temperature and elevated $CO_2$ showed that the effect of about 1.0 °C rise in temperature is offset by increase in $CO_2$ levels upto 495 ppm, and 2.5 °C rise in temperature is offset by increase in $CO_2$ levels upto 660 ppm (Fig. 2). There is decrease in ETo in most of the months with 2.0 °C rise in temperature coupled with increase in $CO_2$ concentrations to 660 ppm. However, with 4.0 °C increase in temperature there is increase in monthly ETo even with increase in

**Table 2:** Changes in ETo with changes in minimum, maximum and mean temperature

| Season | Changes in ETo (%) with changes in temperature (°C) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 5 | 4 | 3 | 2 | 1 | -1 | -2 | -3 | -4 | -5 |
| | | | | | Tmin | | | | | |
| Monsoon | 4.2 | 3.3 | 2.4 | 1.6 | 0.8 | -0.7 | -1.5 | -2.1 | -2.8 | -3.4 |
| Post-monsoon | 5.0 | 3.9 | 2.8 | 1.8 | 0.9 | -0.8 | -1.7 | -2.4 | -3.1 | -3.8 |
| Winter | 4.3 | 3.3 | 2.4 | 1.6 | 0.8 | -0.7 | -1.4 | -2.1 | -2.7 | -3.3 |
| Pre-monsoon | 2.3 | 1.7 | 1.3 | 0.8 | 0.4 | -0.3 | -0.7 | -1.0 | -1.2 | -1.4 |
| Annual | 3.7 | 2.8 | 2.1 | 1.3 | 0.7 | -0.6 | -1.2 | -1.8 | -2.3 | -2.8 |
| | | | | | Tmax | | | | | |
| Monsoon | 8.0 | 6.3 | 4.7 | 3.1 | 1.5 | -1.5 | -2.9 | -4.3 | -5.7 | -7.0 |
| Post-monsoon | 10.0 | 7.9 | 5.8 | 3.8 | 1.9 | -1.8 | -3.6 | -5.3 | -7.0 | -8.6 |
| Winter | 11.5 | 9.1 | 6.7 | 4.4 | 2.2 | -2.1 | -4.2 | -6.2 | -8.1 | -10.0 |
| Pre-monsoon | 8.6 | 6.8 | 5.1 | 3.3 | 1.6 | -1.6 | -3.2 | -4.7 | -6.2 | -7.6 |
| Annual | 8.9 | 7.0 | 5.2 | 3.4 | 1.7 | -1.6 | -3.2 | -4.8 | -6.3 | -7.8 |
| | | | | | Tmean | | | | | |
| Monsoon | 11.6 | 9.2 | 6.9 | 4.6 | 2.3 | -2.2 | -4.5 | -6.7 | -8.8 | -11.0 |
| Post-monsoon | 14.4 | 11.4 | 8.5 | 5.6 | 2.8 | -2.7 | -5.3 | -7.9 | -10.5 | -13.0 |
| Winter | 15.1 | 12.0 | 8.9 | 5.9 | 2.9 | -2.9 | -5.7 | -8.5 | -11.3 | -14.0 |
| Pre-monsoon | 10.0 | 8.0 | 6.0 | 4.0 | 2.0 | -2.0 | -4.0 | -6.0 | -7.9 | -9.9 |
| Annual | 11.9 | 9.4 | 7.0 | 4.7 | 2.3 | -2.3 | -4.6 | -6.8 | -9.0 | -11.2 |

*Monsoon: JJAS; Post-monsoon: OND; Winter: JF; Pre-monsoon: MAM

**Table 3:** Effect of temperature and different levels of $CO_2$ on ETo

| Month | Change in ETo (%) with temperature and $CO_2$ change | | | |
|---|---|---|---|---|
| | Temperature increase = 2 °C | | Temperature increase = 4 °C | |
| | $CO_2$=495 ppm | $CO_2$=660 ppm | $CO_2$=495 ppm | $CO_2$=660 ppm |
| Jan | 3.8 | 0.2 | 10.2 | 6.6 |
| Feb | 3.1 | -0.8 | 9.0 | 5.1 |
| Mar | 2.2 | -1.6 | 6.9 | 3.2 |
| Apr | 1.3 | -2.4 | 5.1 | 1.5 |
| May | 1.4 | -2.4 | 5.3 | 1.6 |
| Jun | 1.5 | -2.4 | 5.7 | 1.9 |
| Jul | 1.9 | -2.2 | 6.6 | 2.5 |
| Aug | 2.4 | -1.3 | 7.5 | 3.8 |
| Sep | 3.1 | 0.0 | 8.4 | 5.4 |
| Oct | 3.9 | 1.8 | 9.5 | 7.4 |
| Nov | 4.2 | 2.1 | 10.1 | 8.0 |
| Dec | 4.2 | 1.2 | 10.5 | 7.5 |
| Annual | 2.4 | -1.1 | 7.2 | 3.8 |

$CO_2$ concentrations to 660 ppm, but the increase in ETo remained less than 10% in most of the months (Table 3). These results clearly indicate that effect of rising temperature is moderated by the increasing $CO_2$ concentrations, and are also in corroboration with previous studies (Martin *et al.*, 1989; Rosenberg *et al.*, 1989; Kruijt *et al.*, 2008; Ficklin *et al.*, 2009; Parajuli, 2010; and Islam *et al.*, 2012a and 2012b). Thus, crop water demand may not rise significantly under the climate change scenarios because of the moderating effect of rising $CO_2$ concentration on evapotranspiration demand. It may be noted that, most of the relationships describing the plant physiological response to elevated $CO_2$, including the Eq. (3) used in this study, are based on the controlled environment experiments data (Allen, 1990), and there are large differences in the reported changes in leaf area index and stomatal conductance among various experimental studies (Allen *et al.*, 1991). Thus, there remain uncertainties in the nature and magnitude of plant physiological response to elevated $CO_2$ and hence in the precise magnitude of simulated changes in ETo. However, these simulation results provide valuable information on possible impacts of climate change on evapotranspiration demand for planning future irrigation water management strategies.

## CONCLUSION

Evapotranspiration is the major component of the hydrological cycle and determines the crop water requirements. The evapotranspiration demand depends on temperature, solar radiation, humidity, wind speed, and plant characteristics such as stomatal conductance and leaf area index etc. For proper estimation of crop water demand and irrigation scheduling, it is essential to understand the relative effect of different climate variables on estimated ETo in the event of climate change. Increased atmospheric $CO_2$ levels also have important physiological effects on crop plants such as an increase in photosynthetic rate, leaf area, biomass and yield, and a reduction in stomatal conductance and transpiration per unit of leaf area. Hence, understanding the effects of climate change (rising temperature) and rising $CO_2$ levels on evapotranspiration demand, and then on irrigation water requirements and agricultural crop production, is critical for management of water resources and future crop planning. The study carried out using meteorological data (1973-2010) of the Banaras Hindu University (BHU), Varanasi showed that the mean temperature influenced the annual ETo the most, followed by the maximum and the minimum. Further, changes in minimum temperature resulted in maximum change in seasonal ETo during post-monsoon season, while changes in Tmax and Tmean resulted in maximum change in seasonal ETo during winter season. The relative effect of different climatic variables in annual ETo was found in the order of Tmean > $R_S$ > VPD > $U_2$. Simulating combined effect of temperature and elevated $CO_2$ indicated 6% decrease in annual ETo demand with doubling (660 ppm) of $CO_2$ concentration and temperature remaining constant. The effect of 2.5 °C rise in temperature is offset by increase in $CO_2$ levels up to 660 ppm. Thus, it is essential to consider expected changes in irrigation water requirement due to global warming while planning for development of future water resources and irrigation water management strategies.

## REFERENCES


Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998). Crop evapotranspiration. Guidelines for computing crop water requirements. *Irrig. Drain. Paper No. 56*, FAO, Rome, Italy.

Allen, L. H. (1990). Plant response to rising carbon dioxide and potential interaction with air pollutants. *J. Environ. Qual.,* 19(1): 15-34.

Ficklin, D. L., Luo, Y., Luedeling, E. and Zhang, M. (2009). Climate change sensitivity assessment of a highly agricultural watershed using SWAT. *J. Hydrol.,* 374(1-2): 16-29.

Field, C. B., Jackson, R. B. and Mooney, H. A. (1995). Stomatal responses to increased $CO_2$: Implications from the plant to the global scale. *Plant, Cell Environ.,*18(10): 1214-1225.

Gocic, M. and Trajkovic, S. (2010). Software for estimating reference evapotranspiration using limited weather data. *Comput. Electron. Agric*., 71: 158–162.

Goyal, R. K. (2004). Sensitivity of evapotranspiration to global warming: a case study of arid zone of Rajasthan (India). *Agric. Water Manag*, 69 (2004): 1–11.

IPCC(2007). *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, U.K.

Islam, A., Ahuja, L. R, Garcia, L. A., Ma, L. and Saseendran, A. S. (2012a). Modeling the effect of elevated $CO_2$ and climate change on reference evapotranspiration in the semi-aridCentral Great Plains. *Trans. ASABE,* 55(6): 2135-2146.

Islam, A., Ahuja, L. R., Garcia, L. A., Ma, L., Saseendran, A. S. and Trout, T. J. (2012b). Modeling the impact of climate change on irrigated corn production in the Central Great Plains. *Agric. Water Manag*, 110: 94-108.

Kay, A. L. and Davies, H. N. (2008). Calculating potential evaporation from climate model data: A source of uncertainty for hydrological change impacts. *J. Hydrol.,* 358(3-4): 221-239.

Kingston, D. G., Todd, M. C., Taylor, R. G., Thompson, J. R. and Arnell, N. W. (2009). Uncertainty in the estimation of potential evapotranspiration under climate change. *Geophysical Res. Letters* 36: L20403, doi: 10.1029/2009GL040267.

Kruijt, B., Witte, J. P. M., Jacob, C. M. J. and Kroon, T. (2008). Effects of rising atmospheric $CO_2$ on evapotranspiration and soil moisture: A practical approach for the Netherlands. *J. Hydrol.*, 349(3-4):257-267.

Martin, P., Rosenberg, N. J. and McKenney, M. S. (1989). Sensitivity of evapotranspiration in a wheat field, a forest, and grassland to changes in climate and direct effects of carbon dioxide. *Climatic Change,* 14(2): 117-151.

McKenney, M. S. and Rosenberg, N. J. (1993). Sensitivity of some potential evapotranspiration estimation methods to climate change. *Agric. Forest Meteorol.,* 64(1-2): 81-110.

Morison, J. I. L. and Gifford, V. (1983). Stomatal sensitivity to carbon dioxide and humidity: A comparison of two C3 and two C4 species. *Plant Physiol.,* 71(4): 789-796.

Parajuli, P. B. (2010). Assessing sensitivity of hydrological response to climate change from forested watershed in Mississippi. *Hydrol. Proc.,* 24(26): 3785-3797.

Rosenberg, N. J., Mckenney, M. S. and Martin, P. (1989). Evapotranspiration in a greenhouse-warmed world: a review and a simulation. *Agric. Forest Meteorol.,* 47: 303-320.

Saxe, H., Ellsworth, D. S. and Heath, J. (1998). Tree and forest functioning in an enriched $CO_2$ atmosphere. *New Phytol.*, 139(3): 395-436.

Sentelhas, P.C., Gillespie, T.J. and Santos, E.A. (2010). Evaluation of FAO Penman–Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada. *Agric. Water Manag.*, 97: 635–644.

Stockle, C. O., Williams, J. R., Rosenberg, N. J. and Jones, C. A. (1992). A method for estimating the direct and climatic effects of rising atmospheric carbon dioxide on growth and yield of crops: Part 1. Modification of the EPIC model for climate change analysis. *Agric. Syst.,* 38(3): 225-238.

Wand, S. J. E., Midgley, G. F., Jones, M. H. and Curtis, P. S. (1999). Responses of wild C4 and C3 grass (*Poaceae*) species to elevated atmospheric $CO_2$ concentration: A meta-analytic test of current theories and perceptions. *Global Change Biol.,* 5(6):723-741.

Wullschleger, S. D., Gunderson, C. A., Hanson, P. J., Wilson, K. B. and Norby, R. J. (2002). Sensitivity of stomatal and canopy conductance to elevated $CO_2$ concentration: Interacting variables and perspectives of scale. *New Phytol.,* 153 (3): 485- 496.

*Received : November 2013 ; Accepted : March 2014*

**PAPER 6**