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Evapotranspiration paradox at a semi-arid location in India

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ABSTRACT

Paradox of decreasing evaporation and evapotranspiration under increasing temperature conditions in the semi-arid tropics assumes greater importance as agriculture in these areas is more vulnerable to climate change. Trends in annual reference crop evapotranspiration (ET_0) at Patancheru, Andhra Pradesh indicated a reduction of about 200 mm from 1850 mm to 1650 mm during the past 35 years. Contribution of energy balance term to the total ET_0 has shown an increasing trend while aerodynamic term has a decreasing trend. Wind speed has shown a strong negative trend leading to the dramatic fall of the aerodynamic term and consequently the ET_0. Rate of reduction in evapotranspiration demand was about 10% for *kharif* (Jun-Oct) and about 14% for *rabi* (Nov-Feb). At Patancheru, measured temperature and solar radiation showed opposite trends and at locations where no measured solar radiation data available and if solar radiation is estimated from air temperature alone for use as an input in crop modelling, outputs under such conditions need to be interpreted with caution. Present study highlights the need for climate change impact studies at a local level in addition to those based on regional and global circulation models.

Key-words: Reference crop evapotranspiration, semi-arid tropics, trends, watersheds

Evaporation and evapotranspiration are important components in the water-heat balance of the earth's surface and hydrological cycle as their proportion to rainfall is generally larger than that of runoff. The Intergovernmental Panel for Climate Change (IPCC) projects that global average surface temperature continues to increase in the 21st century. Global warming may accelerate hydrological cycle and redistribute water resources worldwide. Increased temperature enhances saturation vapour pressure which will yield greater evaporation. Environments are becoming drier under enhanced greenhouse conditions and the IPCC has projected that in all cases, increases in potential evaporation were simulated, and in almost all cases, the moisture balance deficit became larger (Christensen *et al.*, 2007). Changes in rainfall and evaporation / evapotranspiration rates lead to erratic moisture balance conditions particularly in the semi-dry regions.

In India, rainfed agriculture plays and will continue to play important role for achieving food security and improved livelihoods as livelihood of 70% of people in these areas depend on agriculture. Integrated watershed management approach for enhancing crop productivity and water use efficiency in the semi-arid tropics (SAT) regions has been highlighted by several researchers (Wani *et al.*, 2003 and 2009). Climate change projections for the SAT indicate changes in temperature and rainfall regimes; which will affect the water balance and may lead to the reduced length of rainfed crop-growing period (LGP). Choice of crops and the cropping pattern in the SAT are guided by the amount of water available and its duration during the different stages of crop growth. Evapotranspiration is an important input for determining the LGP and for assessing water requirements. Evapotranspiration and water balance indices were used for agroclimatic characterization of watersheds (Kesava Rao *et al.*, 2009). Study of the trends in evaporation / evapotranspiration thus assumes greater importance in better crop planning and management for designing adaptation strategies for coping with the anticipated impacts of climate change.

Evaporation paradox

One expected consequence of global warming is the increase in evaporation. However, several long-term evaporation observations during the past few decades show a decreasing trend in the rate of evaporation in several parts of the world. The contrast between expectation and observation is called the 'evaporation paradox' and several researchers attempted to study the trends in evaporation / evapotranspiration.

Potential evapotranspiration (PE) was determined at ten locations in India by Penman (1948) equation using data for the period 1976-1990 and the analysis showed that both pan evaporation and potential evapotranspiration have decreased during the period (Chattopadhyay and Hulme, 1997).

Decreasing pan evaporation trends were reported in Japan (Jun Asanuma and Hideyuki Kamimera, 2004), Australia (Roderick and Farquhar, 2004) and Yangtze River basin (Wang *et al.*, 2006). Cong and Yang, 2008 concluded that from 1956 to 2005, pan evaporation paradox exists in China as a whole with decreasing in pan evaporation and the

Table 1: Monthly climatic characteristics at ICRISAT, Patancheru

Element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max.T °C	28.6	31.6	35.1	37.6	38.8	34.4	30.8	29.2	30.1	30.4	28.9	27.9
Min.T °C	13.8	16.2	19.3	22.6	24.8	23.6	22.4	21.8	21.5	19.4	16.0	13.0
RH1 %	89	79	69	64	58	78	87	90	91	90	89	89
RH2 %	36	29	24	26	27	47	61	68	63	52	44	37
Wind·km h^{-1}	7.0	7.7	8.0	8.7	11.4	16.3	15.1	11.8	7.4	5.7	6.1	5.8
Rain mm	9.0	8.0	20.0	28.0	30.0	111.0	189.0	233.0	155.0	92.0	23.0	4.0
Sunshine h	9.2	9.7	9.4	9.4	9.2	6.0	4.1	4.2	5.8	7.5	8.3	8.9
Evap mm	152.0	189.0	271.0	303.0	366.0	263.0	179.0	137.0	131.0	143.0	136.0	135.0
Sol-Rad MJ m^{-2}	16.7	19.0	20.9	22.2	22.6	18.2	15.7	15.1	17.1	17.4	16.4	15.8

Table 2: Percentage contribution of Penman-Monteith equation terms to reference crop evapotranspiration at ICRISAT, Patancheru

Period	Annual ET_0 (mm)	Percentage contribution by component (%)	
		Energy balance	Aerodynamic
1975-79	1871	56	44
1980-84	1834	58	42
1985-89	1829	59	41
1990-94	1717	60	40
1995-99	1717	62	38
2000-04	1687	63	37
2005-09	1614	68	32

warming though it does not exist in Northeast and Southeast.

Chen Shenbin *et al.*, (2006) analyzed time series (1961–2000) of Penman-Monteith potential evapotranspiration estimates for 101 stations on the Tibetan Plateau and reported that for the Tibetan Plateau as a whole potential evapotranspiration (PET) has decreased in all seasons. Using the Ecological Assimilation of Land and Climate Observations (EALCO) land surface model, an assessment of annual trends in actual evapotranspiration (AET) and associated meteorological inputs was performed at 101 locations across Canada (Richard Fernandes, 2007). Increases in annual AET of up to 0.73% per year were identified at 81 locations, and decreases of up to 0.25% per year were found at the remaining 20 stations. Statistically significant increasing trends were detected in 35% of the locations with the majority corresponding to Atlantic and Pacific coastal regions.

Several studies indicate different trends in evaporation / evapotranspiration both spatially and temporarily. Detailed analysis of trends in evapotranspiration in the SAT thus assumes greater importance in understanding the crop water requirements particularly in the changing climate scenario. In the present paper, such analysis is made based on the data from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, a representative location in the Indian SAT.

MATERIALS AND METHODS

ICRISAT, Patancheru is situated at 17.53°N latitude and 78.27°E longitude at an altitude of about 545 m and enjoys typical hot semi-arid climate. Annual average rainfall is 900 mm and is received in 51 rainy days. About 76% of the annual rainfall is received in the southwest monsoon period (Jun-Sep). August with a rainfall of 233 mm is the rainiest month.

Monthly climatic characteristics are presented in Table 1. Because of the altitude and away from the sea makes the location continental having high summer temperatures and very cool winters. Maximum air temperature in May can go up to 43 °C and during December-January the minimum air temperature can dip down to 5 °C. Strong winds are common during monsoon period, particularly in the beginning and average winds up to 30-32 km h^{-1} were observed on certain days of June. Bright sunshine varies from 4 to 10 hours per day during the year, lowest during July and August due to dense clouding in the monsoon season. January to May experience above 9 hours of bright sunshine. Both Alfisols and Vertisols dominate the SAT region of India and same is true in ICRISAT Patancheru campus.

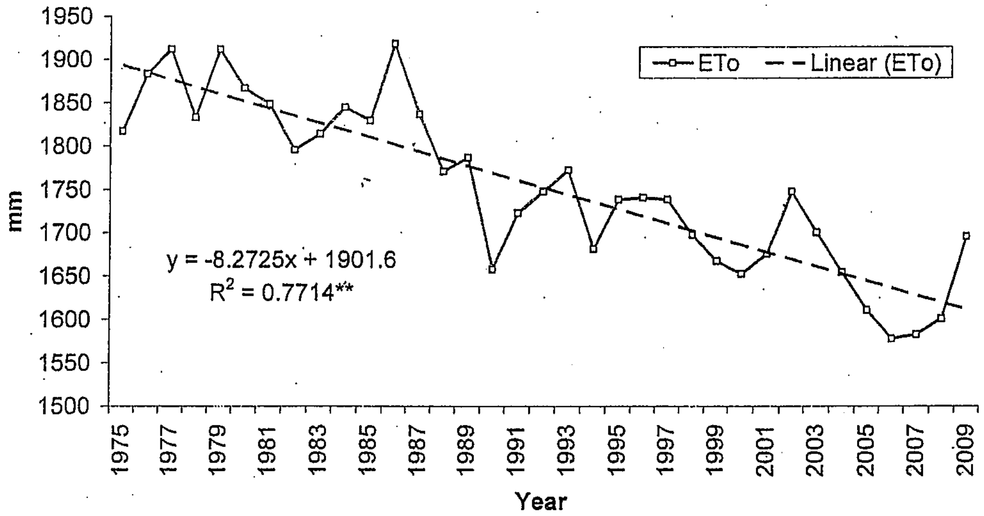

Fig. 1: Trend in reference crop evapotranspiration (ET_0) at ICRISAT, Patancheru

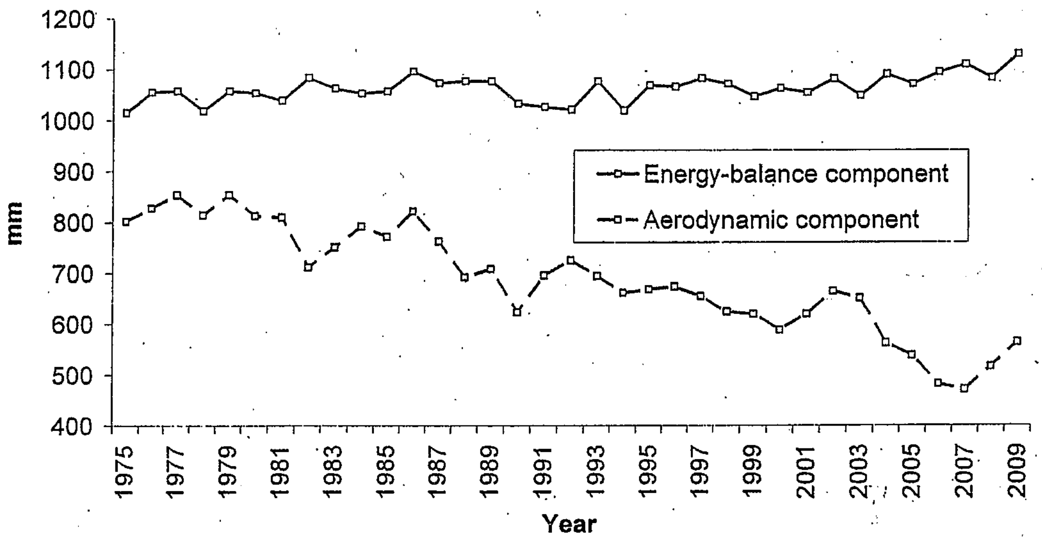

Fig. 2: Trend in evapotranspiration components at ICRISAT, Patancheru

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

Using weather data recorded at the Agromet Observatory, ICRISAT campus, daily reference crop evapotranspiration (ET_0) was computed for 35 years (1975-2009) following the FAO Penman-Monteith method (Allen *et al.*, 1998) as follows:

where

ET_o reference evapotranspiration [mm day^{-1}]

R_n net radiation at the crop surface [MJ m^{-2} day^{-1}]

G soil heat flux density [MJ m^{-2} day^{-1}]

T mean daily air temperature at 2 m height [°C]

u_2 wind speed at 2 m height [m s^{-1}]

e_s saturation vapour pressure [kPa]

e_a actual vapour pressure [kPa]

$e_s - e_a$ saturation vapour pressure deficit [kPa]

Δ slope of vapour pressure curve [kPa °C^{-1}]

γ psychrometric constant [kPa °C^{-1}]

The FAO Penman-Monteith method requires data on air temperature and humidity, radiation and wind speed. A software package was developed to output the radiation and aerodynamic components in the above equation separately as well as the final ET_0 on daily basis. Daily values were then converted in to monthly, seasonal and annual formats.

RESULTS AND DISCUSSION

Trends in annual reference crop evapotranspiration indicated a significant reduction of about 200 mm from 1850 mm to 1650 mm during 1975-2009 (Fig. 1). During the past 35 years annual ET_0 varied from 1919 mm (year 1986) to 1578 mm (year 2006). Average annual ET_0 decreased by 57 mm per decade or about 3% of the annual total. Chen Shenbin *et al.*, (2006) reported a decrease in the PET of 13.1 mm/decade or 2.0% of the annual total in the Tibetan Plateau.

Changes in the two components (energy and aerodynamic) of the ET_0 were examined to better understand the conspicuous decrease in the ET_0 and it is seen that the energy balance component showed a positive trend while the aerodynamic component showed a highly significant negative trend (Fig. 2). Annual energy component has increased from about 1000 mm to 1100 mm while aerodynamic component decreased from about 800 mm to 550 mm. Rate of increase for the energy balance component is about 29 mm per decade while the rate of decrease for the aerodynamic component is about 71 mm per decade. Percentage contribution of the two components to ET_0 for five-year (pentads) periods are shown in the Table 2. In the SAT region, the energy balance and aerodynamic components are generally in the ratio 55:45. At ICRISAT, Patancheru the contribution of energy balance has increased from 56 to 68% in the 35 years of study period while contribution of aerodynamic component decreased from 44 to 32%. This shows that in the present conditions, energy balance is contributing about 70% while aerodynamic component contributes only 30% to the ET_0.

Long-term changes in evaporation and potential evapotranspiration can have profound implications for hydrologic processes as well as for agricultural crop performance. Large changes in the evapotranspiration demand would change the water requirements and water balance in the crop growing seasons. The SAT in India is influenced by both the southwest and northeast monsoons and thus two agriculturally important seasons i.e., *kharif* (Jun-Sep) and *rabi* (Oct-Feb) are considered for understanding the temporal changes in the evapotranspiration demands (Fig. 3). Though both *kharif* and *rabi* have four months duration, as *rabi* coincides with winter, the ET_0 values are lower in *rabi* compared to *kharif*. In both the seasons, ET_0 showed a decreasing trend. However, during *kharif* the evapotranspiration demand decreased from about 720 to 650 mm, while during *rabi*, ET_0 decreased from 488 to 420 mm. Rate of reduction is about 10% for *kharif* and about 14% for *rabi*. The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration (ET_0). Evapotranspiration from actual crop depends on the stage and state of the crop, soil, ET_0 and water availability. Water requirements of crops primarily depend on ET_0 and the decreasing trend of this parameter indicates increasing potential for winter crops.

Changes in the ET_0 are due to changes in the weather parameters and it is necessary to identify the likely causative meteorological parameters. Table 3 presents trends in weather elements during 1975-2009. Maximum temperature, relative humidity in the morning and afternoon showed positive trends, while minimum temperature, wind speed and solar radiation have shown negative trends, while rainfall and sunshine hours exhibited no trends. Fig. 3 shows the significant trends in the annual wind speed and solar radiation. Wang Yangun et al., (2006) reported negative trends of pan evaporation, reference evapotranspiration and actual evapotranspiration in the Yangtze River basin though in the same period the air temperature in the basin showed a significantly increasing trend. Chattopadhyay and Hulme (1997) concluded that at selected locations in India, changes in potential evapotranspiration were most strongly associated with changes in relative humidity, particularly in the winter and pre-monsoon seasons. In the monsoon season, radiation was the dominant variable for regulating the PE variation at nearly all stations. Chen Shenbin *et al.*, (2006) reported that changes in wind speed and to a lesser degree relative humidity were found to be the most important meteorological variables affecting PET trends on the Tibetan Plateau while changes in sunshine duration played an insignificant role.

At ICRISAT, Patancheru among the various weather parameters analysed, wind speed has shown highly significant and negative trend followed by solar radiation during the past 35 years. Wind speed has reduced from about 11 to 7 km h^{-1} and solar radiation from 19 to 17 MJ m^{-2} and both elements appear to have stabilized and possibly continue with slight year-to-year variations. Though there is significant reduction in solar radiation, there is not much change in the sunshine hours. Chattopadhyay and Hulme (1997) conclude that decrease of radiation resulting from more cloudiness in the monsoon season could be the reason for reduction in potential evapotranspiration. Roderick and Farquhar (2002) also report that the decreasing solar radiation associated with the increased cloud amount and aerosols may have caused the decrease in pan evaporation.

SUMMARY AND CONCLUSIONS

There are reports that evapotranspiration rates are

Table 3: Trends in weather elements at ICRISAT, Patancheru

Period	MaxT °C	MinT °C	RH1 %	RH2 %	Wind Km h^{-1}	Rain mm	Sunshine h	Sol-Rad MJ m^{-2}
1975-79	31.7	20.0	78	42	11.0	917	7.8	18.9
1980-84	31.9	20.0	77	42	10.2	889	7.8	18.8
1985-89	32.0	19.9	80	41	9.8	846	8.0	18.2
1990-94	31.8	19.7	82	43	9.6	812	7.2	18.4
1995-99	31.9	19.4	83	44	8.8	966	7.5	18.2
2000-04	32.2	18.5	81	43	8.0	899	7.6	17.2
2005-09	32.2	19.4	85	45	7.3	976	7.4	17.3
Trend	Positive	Negative	Positive	Positive	Negative	None	None	Negative

RH1 & RH2 = Relative Humidity in the morning and afternoon; Sol-Rad = Solar Radiation

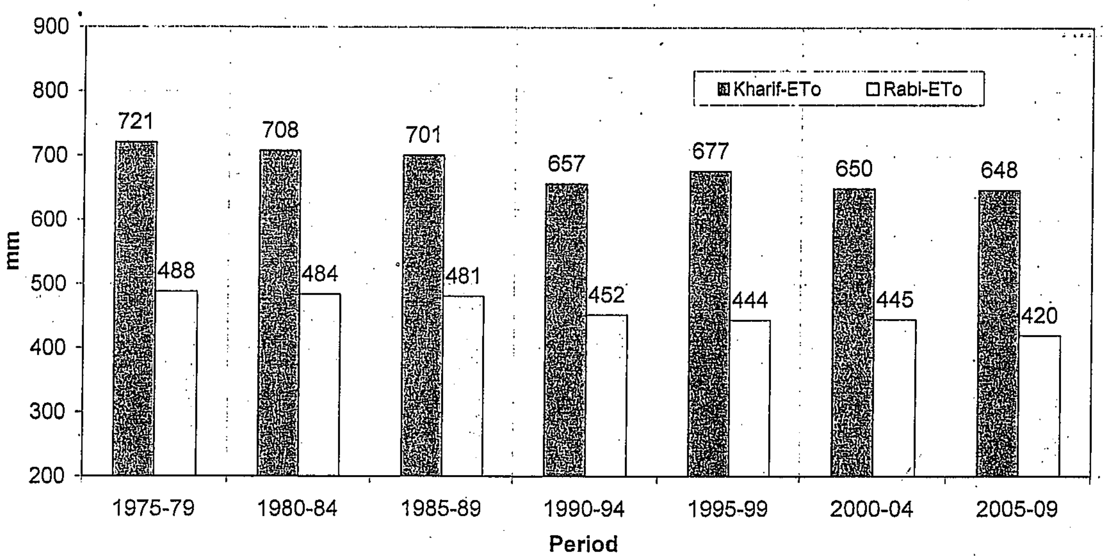

Fig. 3: Trend in ET_0 in *kharif* and *rabi* seasons at ICRISAT, Patancheru

changing during the past several years. In several parts of the world, a decreasing trend in evapotranspiration is observed. Under the projected climate change scenarios with increased temperatures, the implications of the evapotranspiration trends on the hydrological cycle are somewhat controversial. The paradox of decreasing evaporation and evapotranspiration demands under increasing temperature conditions exists. An analysis of the reference crop evapotranspiration (ET_0) trends at ICRISAT, Patancheru for the past 35 years (1975-2009) indicated a reduction of about 200 mm from 1850 mm to 1650 mm annually. Contribution of energy balance term to the total ET_0 has shown an increasing trend while aerodynamic term has a decreasing trend. Analyses of trends of other meteorological elements indicated that maximum temperature increased, while solar radiation decreased during the study period. The decreasing solar radiation, referred to as global dimming, is an interesting phenomenon and needs to be studied in detail in the SAT regions to have a better understanding of the trends in the evaporative demands. Wind speed has shown a strong negative trend which could be the reason for the dramatic fall of the aerodynamic term and the ET_0.

In both the *kharif* and *rabi* seasons, ET_0 showed a decreasing trend. Rate of reduction is about 10% for *kharif* and about 14% for *rabi*. Water requirements of crops primarily depend on ET_0 and the decreasing trend of this parameter indicates increasing potential for double cropping in the study area. It is also likely that there could be less frequent (fewer) soil moisture stress conditions and crop varieties that are less drought tolerant and having high yield potential might become promising especially during *rabi*.

ICRISAT, Patancheru has a typical Semi-Arid climate, however due to changes in the rainfall quantum and distribution, the climate occasionally shifts towards drier side to become arid or towards wetter side to become dry-subhumid. Due to the strong negative trend in the ET_0 observed, intensity of aridity is slowly falling. If this trend continues, in the near future this region may enjoy dry-subhumid type of climate more frequently. Temperature changes alone cannot indicate trends in ET_0, wind, humidity and solar radiation also need to be considered for reliable assessment of ET_0. Crop simulation models require measured solar radiation data for estimating the crop evapotranspiration and assessing the biomass production and other critical crop parameters. Non-availability of solar radiation measurements at a location compels modellers many a times to estimate solar radiation from temperature data alone. If the trends in temperature and solar radiation are opposite, solar radiation estimated from air temperature could be significantly different from the actual solar radiation. Under such conditions, model outputs need to be interpreted with caution. Present study highlights the need for climate change impact studies at a local level in addition to those based on regional and global circulation models.

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