CHAPTER 5

IMPACT OF CLIMATE CHANGE ON EVAPORATION AND EVAPOTRANSPIRATION

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5.0. Introduction

A steady increase in the green house gases and consequent enhancement of the greenhouse effect has resulted in a phenomenon called "global warming"; causing temperatures to rise globally and associated climatic changes. According to the 5thassessment report of the IPCC, the earth surface temperature exhibited an increase by 0.85°Cover the period 1880-2012 (IPCC, 2015) (Fig. 5.1). Each of the decades has been observed to be relatively warmer than the preceding decade since 1850 and the period from 1983 to 2012 has been observed to be the warmest three decade (30 yrs) period for the Northern Hemisphere during the last 1400 years (IPCC, 2015). Earlier IPCC report (IPCC, 1990) had predicted an increase of 1 to 3.5 °C in temperature by the year 2100 if greenhouse gas emission is not controlled.

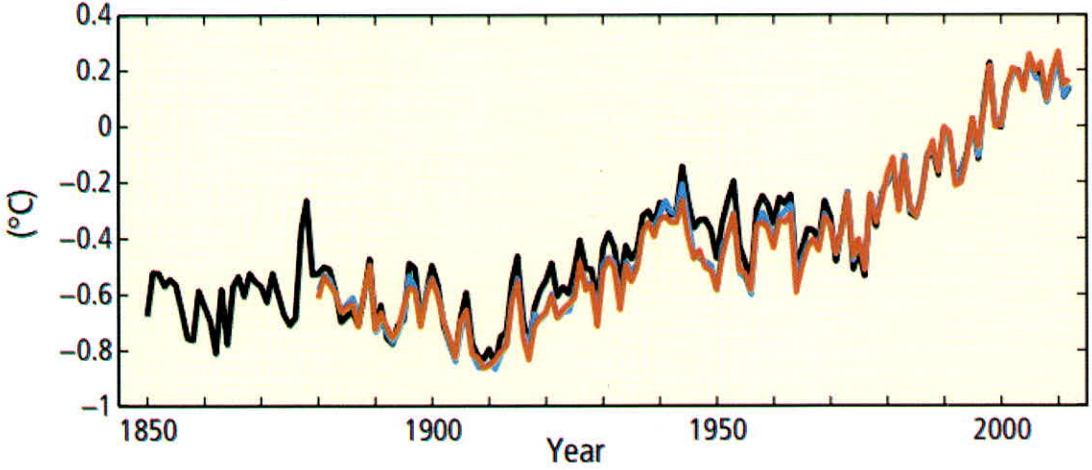

***Figure 5.1**: Globally averaged surface temperature (IPCC, 2014) (different colours indicate different data sets)*

As far as India is concerned, a rising trend in temperature has been reported by many researchers. An increasing trend of 0.57°C for the period 1881-1997 has been reported by Pant and Kumar (1997) while a study by Hingane et al. (1985) had earlier given a rising trend of 0.4 °C for the period 1901-1982. Arora et al. (2005) investigated the trends in temperature for 125 stations spread all over India using time series data of last hundred years and observed the mean maximum temperature, mean minimum temperature and annual mean temperature to increase at the rate of 0.92, 0.09 and 0.42 °C respectively. The mean temperature for the post-monsoon season has been observed to increase by 0.94 °C and that of winter season by 1.1 °C.GCM based studies by Lal (2001) have indicated a rise of 3.5 to 5.5 °C for the annual mean surface temperature for the Indian sub-continent by the year 2080, the range of rising for winter and summer monsoon being 4-6 °C and 2.9-4.6 °C respectively. Variations have, however, been observed for local scale (for example Das et al., 2008).Amore recent analysis of the surface temperature data for the period of 1901 to 2016 by Ross et al. (2018) indicates a rising trend in daily maximum, minimum and mean temperature for the northwestern and southern India and a falling trend over the belt spreading from northeastern to central India, from the 1950s to2000s.Annual mean temperature shows increasing trends in most part of the country (Figure. 5.2).

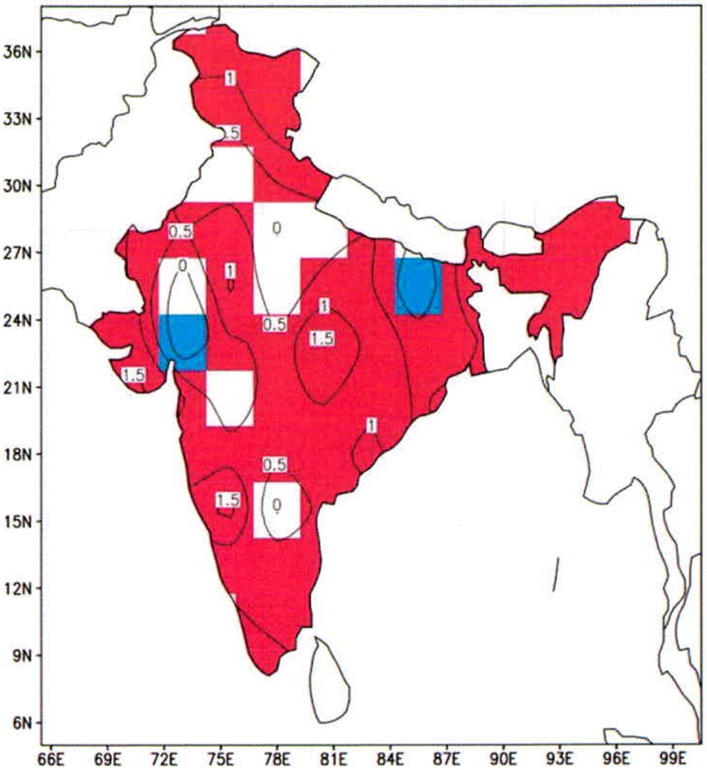

***Figure 5.2**: Trends in annual mean temperature significant at the 95% level over India during 1901–2016(after Ross et al., 2018) (red colour indicates increasing trends while blue colour indicates decreasing trend)*

Evapotranspiration is one of the key components of the hydrologic cycle. Precipitation which falls on the land is subjected to evaporation and evapotranspiration before it reaches back to the oceans, causing a significant loss of the available water. Increasing scarcity of water due to increased ET losses may lead to difficulties in meeting the various demands of the growing population and its development needs. Most of the water bodies in the warm tropical regions undergo heavy evaporation losses. Delclaux et al., 2007, for example, observed that annual evaporation is about 90% of the total output losses from the Lake Titicaca. Annual evaporation losses from reservoirs in Australia have been estimated to be about 40% of the storage capacity (Helfer et al., 2012). As per the CWC (2006) report, average annual evaporation loss from reservoirs/water bodies in India is about 27,000 MCM.

Being a key link between the global water and energy cycles (Yang et al., 2011), any change in evapotranspiration is likely to significantly affect the global hydrologic as well as energy cycle (IPCC, 2013). Being a cause of significant water loss, evapotranspiration plays a major role in determining the stream flow regime (Liu et al., 2013). Therefore, understanding the impact of temperature rise or climate change on evapotranspiration is essential for a proper understanding of the impact of climate change on the hydrological regime of the stream and water availability in the basin or water body. It shall provide a proper assessment of how much more or less water shall be available and, if less water is available, then how much additional water shall be required to meet the various demands.

5.1. The Processes of Evaporation and Evapotranspiration

For a better and proper understanding of the possible impact of climate change on the processes of evaporation and evapotranspiration, it is first important and pertinent to have an understanding of the processes of evaporation and evapotranspiration. Evaporation is a surface phenomenon that takes places from the surface of the various types of water bodies such as the oceans, seas, lakes, reservoirs, ponds, rivers and other surfaces such as wet canopy and moist soils etc. Solar radiation provides the required energy for the process of changing liquid water to gaseous form (vapours). If this form of energy is not available, internal energy stored as heat energy is used by the water body for evaporation. As evaporation continues, vapour molecules get accumulated over the surface leading to an increase in partial vapour pressure, which continues till the saturation level is reached. At saturation vapour pressure, neither evaporation nor condensation occurs (equilibrium state). However, due to the various transport processes occurring in the atmosphere such as the wind, equilibrium never occurs. The other important process that causes loss of water is transpiration by the plants, which involves removal of water from the plant tissues and its subsequent release to the atmosphere. It takes place through the stomata present in the leaves. Most of the water available in plants is lost through the process of transpiration (Allen et al., 1998).Both evaporation and transpiration take place together and distinguishing between the two is not an easy task.

5.2. Factors Affecting Evapotranspiration

Temperature is often thought to be the only causal factor for evaporation. However, this is far from the reality. Evaporation takes place only when there is a vapor pressure deficit and needs a source of energy for removal of water vapours from the evaporating surfaces. Energy, as mentioned above, is supplied by the sun. Higher solar radiation causes higher evaporation rates and vice versa. Wind is another important factor in evaporation which is responsible for creating the evaporative demand by maintaining the vapour pressure deficit. In the absence of wind there would be no evaporation. Increase in wind would increase the evaporation rate till the critical value is reached, beyond which evaporation would not be affected by the wind (Reddy, 1997). Other influencing factors are atmospheric pressure and sunshine hours. Atmospheric pressure has a negative correlation with evaporation. Factors like water quality (turbidity, salinity) may also influence evaporation, although their role is not significant (Reddy, 1997). If one is interested in the volume and not rate of evaporation, then size of the water body could also be an important determinant.

Where the evaporating surface is the soil surface, the degree of shading of the crop canopy and the amount of water available at the evaporating surface are other additional factors that need to be considered (Allen et al., 1998).With the depletion in soil moisture in the top soil, evaporation decreases. It ceases completely as the soil becomes void of moisture (Allen et al., 1998).In the cropped area, crop characteristics also influence the transpiration rate, besides the moisture content of the soil and amount of solar radiation reaching the soil surface. This leads to different evapotranspiration rates for different types of plants (Allen et al., 1998).This is further affected by the cultivation practices followed. Since the amount of solar radiation reaching the soil surface is determined by the amount of canopy cover, the role of factors like stages of crop growth and development become an important factor in the process of evapotranspiration from the cropped area (Figure 5.3)ET losses could be almost completely due to evaporation in the initial stages of the crop growth whereas transpiration could become a significant factor at the full crop growth or harvesting time accounting for almost 90% of the total water loss from the cropped area(Allen et al., 1998).

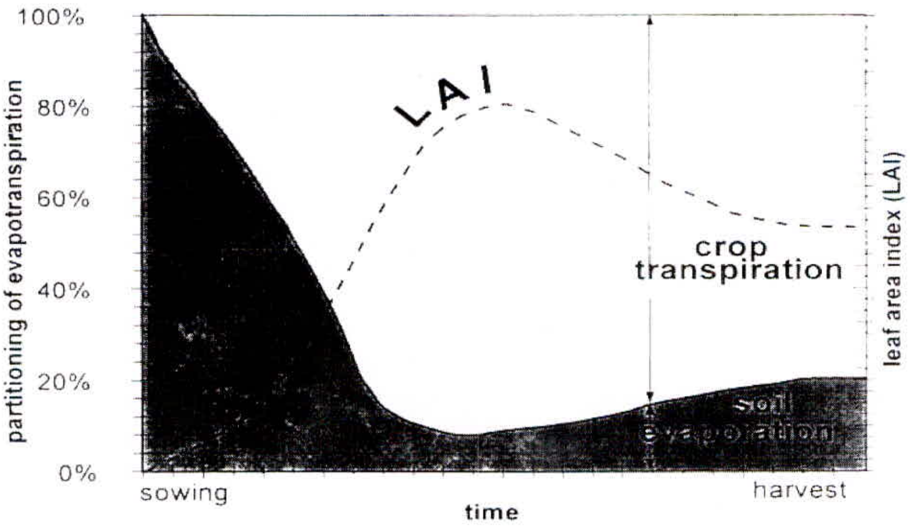

Figure 5.3: Relative contribution of evaporation and transpiration in evapotranspiration during crop growth period (after Allen et al., 1998)

5.2.1 Temperature Dependence of the Factors

The most important factors determining the evaporation rates and which are considered in most evaporation and evapotranspiration models are radiation, temperature, humidity, vapour pressure deficit, atmospheric pressure, sunshine hours and wind speed. Many of these factors are temperature dependent. The net radiation is indirectly affected by temperature through its effect on the long-wave radiation. Vapour pressure deficit (VPD) is determined by temperature by determining the vapour pressures of air and water. While vapour pressure of pure water is a function of temperature, the saturation vapour pressure also depends on temperature only (Dingman, 1994). Temperature also determines the latent heat of vaporization. Factors like winds speed and sunshine hours are, however, not directly or significantly dependent on the local temperature variations. The various meteorological factors affecting evaporation and evapotranspiration, which are used in evaporation and evapotranspiration models, can be grouped into three categories: (i) factors affected directly by the temperature changes, for example saturation vapour pressure; (ii) factors affected indirectly by the temperature changes, for example vapour pressure deficit; and (iii) factors not affected by the temperature changes, for example sunshine hours.

5.2.2 Variability of ET and Relative Roles of Different Factors

Evapotranspiration is a very complex process involving complex interactions and interrelationships of a number of meteorological, atmospheric and physical factors. This complexity results in variation of evaporation rates. The pattern of monthly evaporation is also not always consistent from year to year. A variation ranging from 10 to 89% was observed by Rosenberry et al. (1993) for Lake Williams, Minnesota. In many places there are annual variations, seasonal variations, and intra-seasonal variations (Lenters et al., 2005). Even diurnal variations in evaporation have also been observed (Yin and Nicholson, 2000). Studies have also shown that evaporation rate may vary even across a lake, in case of large lakes (Mahrer and Assouline, 1993) and may also depend on the geometry of the water body (Sacks et al., 1994), with deep and shallow water bodies exhibiting different controlling factors.

The role of different factors controlling evapotranspiration rate vary from place to place and also temporally for the same place. Mohan and Arumugam (1996) based on the study of eight stations of Karnataka and Tamilnadu in India, observed that relative humidity, temperature and wind speed are the most influencing factors controlling the evapotranspiration process, while rainfall and sunshine duration have less influence. Lenters et al. (2005) observed that the seasonal variations are largely due to changes in temperature and net radiation. According to them, the most important individual climatic influence on inter-seasonal variations in evaporation is relative humidity, followed by lake-air temperature difference, wind speed and air temperature. Antonopoulos (2007) from their study on Lake Vegoritis in Greece observed that evaporation rates are determined mostly by the long-wave radiation regime while for the Lower Mekong River basin in Combodia, Kumiko et al. (2008) observed rainy season to have a high evaporation potential due to large amount of net radiation. Wen et al. (2012) observed that for Chuxiong City in China, annual reference ET is determined by wind speed, sunshine hours, relative humidity and temperature in that order while for Varansi in India Annu Priya et al. (2014) observed that annual reference ET is affected most by mean temperature followed in order of importance by solar radiation, vapour pressure deficit and wind speed. Thus, it is important to have a proper knowledge and understanding of the various factors in causing variations in evaporation in different climatic settings so that proper interpretations are done while studying the impact of climate change on evaporation and evapotranspiration.

5.3 Impact of Climate Change on Evapotranspiration

5.3.1 Evaporation Paradox

It is a general perception that rises in temperature should increase the evapotranspiration rate (Abtew et al., 2015, Fiklin et al., 2015). For example, as per WMO/ICSU/UNEP (1989) report evapotranspiration is expected to increase globally by about 10–20% due to global warming. However, subsequent research has shown it to be not true always ast he rate of evapotranspiration is actually declining in many parts of the world during the last few decades, as indicated by many studies (Stocker et al., 2013). This contradiction of evapotranspiration declining despite the rising temperature is known as the "evaporation paradox" (Xing et al., 2016). It was first noted and reported by Peterson et al. (1995), whose analysis of the 40 years (1950-1990) of pan evaporation data of Russia and USA clearly indicated a declining trend in the pan evaporation time series data. This is referred to as "evaporation paradox" because decrease in evapotranspiration means decrease in water vapours generated. This should lead to decrease in precipitation. But this has not been observed ingeneral. Scientists have, therefore, been wondering about the possible causes of this "evaporation paradox". The answer, according to some researchers, lies in the fact that evaporation and evapotranspiration are consequence of the complex interactions of the various atmospheric, meteorological and physical processes, as discussed earlier. The same argument is put forward by Mcvicar et al. (2012). Jiménez Cisneros et al. (2014) based on the review of the various reported studies have attributed the steady decreases in global and regional actual evapotranspiration and pan evaporation since the 1960s to changes in precipitation, diurnal temperature range, aerosol concentration, (net) solar radiation, vapor pressure deficit and wind speed. Earlier, studies by Dankers and Christensen (2005) for Finland and Norway indicated that impact of climate change on evapotranspiration even varies with altitude. Chattopadhyay and Hulme (1997) identified increases in the vapor pressure deficit regime as the cause of the paradox while Bandopadhyay et al. (2009) observed increase in the relative humidity and decrease in wind speed as the major reason for the declining trends in reference evapotranspiration throughout India. Studies by Khobragade (2009) brings out that for the semi arid region of Udaipur in India, evaporation regime is likely to be affected most by the changes in vapor pressure deficit regime followed by the changes in the regimes of maximum temperature, net long-wave radiation, saturation vapour pressure and net radiation in that order, when the mean temperature is increased by 1^0C. According to the sensitivity study of Serrano et al. (2014), relative humidity, wind speed and maximum temperature have higher correlation with changes in reference evapotranspiration whereas minimum temperature and duration of sunshine have a lower correlation. Sharifi and Dinpashoh (2014), from their study on eight stations in Iran observed the reference evapotranspiration to be related most to the changes in mean temperature for the six of the eight stations while it was least related to the change in vapour pressure regime for most of the stations. Studies for Tibetan Plateau by Xie and Zhu (2012) produced totally different set of inferences with the wind being indicative as the major factor responsible for the declining reference evapotranspiration followed by changes in vapour pressure and net radiation which together negate the increase in rates of reference evapotranspiration caused by the increase in mean temperature. Studies by Liu et al. (2017) for the 3H plains in China bring out that the combined effects of relative humidity and insolation dictate declines in reference evapotranspiration during the summer, autumn and spring while in winter the changes in the wind velocity together with the decrease in relative humidity are responsible for the declines. However, although most of these studies indicate a consistent decline in potential evapotranspiration or reference evapotranspiration rates, yet there are many studies which indicate otherwise. This means that the evaporation paradox is not observed at every place. Serrano et al. (2014), for example, observed increasing trends in monthly reference evapotranspiration for 46 meteorological stations in Spain based on the data of 1961 to 2011.

Based on the findings of the various studies it is apparent that the reasons for the evaporation paradox being not observed at every place in the world is the varying nature of the various controlling factors of evapotranspiration and their varying relative significance at different places and times. However, it surely does not clearly explain as to why there is no decreasing trend in rainfall in most parts of the world if there is a declining trend in evaporation? How could there be same or more rainfall if the amount of total air moisture is decreasing? Scientists are still pondering over this mystery. Brutsaert and Parlange (1998) have come up with an explanation to resolve the mystery. According to them, the paradox arose because of misinterpretation of the pan evaporation measurements which does not account for the role of humidity already present in the air. They claim that the declining trends in the pan evaporation data in many cases are actually indicative of the global warming, if we are able to factorize the land surface moisture and properly process and interpret the raw data of pan evaporation time series. Although the theory has not been rejected by any researcher, not many researchers seem to have accepted the explanation too and the paradox still appears to have remained an unresolved mystery.

5.3.2 Impact Indicators from Different Parts of the World

A plethora of literature is available now from the numerous studies carried in different parts of the world on the possible impacts of temperature rise and climate change on the hydrologic cycle and its consequences for the water resources of the world. Unfortunately only a limited number of these studies are related to the assessment of the impact specifically on the process of evapotranspiration. Itcan be illustrated from the fact that IPCC (2001) report provided only a handful of references on evapotranspiration although it provided a long list of references on the studies related various aspects of impact of global warming and climate change. Although, the IPCC report (2001) is almost two decades old now, one would be surprised to know that not too many studies have been reported on this aspect thereafter. Even the 5th assessment report of IPCC does not contain many references. Many of the reported studies related to climate change impact are based on trend analysis of the evaporation data, particularly the pan evaporation data. These studies report mixed findings with increase predicted for some regions and decrease for some other. Decline in evaporation has been reported for USA, Russia, Eurasia, China, Australia and New Zealand (Peterson et al., 1995; Thomas, 2000; Golubev et al., 2001; Liu et al., 2004; Roderick and Farquhar, 2004;Roderick and Farquhar , 2005; Huo et al., 2013;Jiao and Wang, 2018) while increasing trend has been reported for some parts. Dinpashoh et al. (2018), for example, observed increasing trend in monthly ET_0 for 86% stations out of 36 stations studied in NW Iran. Statistically significant increasing trends in Evapotranspiration have also been found for the Okavango Delta in Botswanaby Moses and Hambira (2018). Some mixed trends have been observed in East Asia, northeast Brazil, Israel and Togo (Xu, 2001; Cohen et al., 2002, da Silva, 2004, Djaman et al., 2017). No specific trend was observed for the study site in Cyprus by Christou et al. (2017).

Most of these studies are based on the trend analysis of reference or potential evapotranspiration. Few studies have also been reported using the output from the global or regional circulation models and coupling it with the hydrological models. In one of the earliest such attempts, Rind and Lebedeff (1984) investigated the effect of doubling the CO_2 content on evaporation rates and reported that it would increase proportionately, although it is otherwise reported that increase in CO_2 content decreases stomatal density (Woodward, 1987) which should result in decrease in transpiration rates. Ramirez and Finnerty (1996) from their sensitivity analysis for the San Luis Valley of Colorado carried out considering both theCO_2 and temperature changes, observed a decrease of 18.5 % in potential evapotranspiration when a combination of 100% increase in CO_2concentration and a 3^0C rise in temperature is considered. Dankers and Christensen (2005) predicted increased rates of evapotranspiration for a sub-arctic basin with RCM. Lenderink et al. (2007) also predicted significant increase in evaporation for central Europefor the period of 2071-2100 based on their analysis carried out using the regional circulation models. Based on their analysis of the data of 20 stations in Egypt, carried out using GCM (HadCM3) considering the four emission Scenarios (A1, A2, B1 and B2), Khalil (2013) predicted an increase in ET for the future periods of 2040, 2060, 2080 and 2100 when compared to the present (normal)values obtained based on the period of 2000-2009. Jarabicová et al (2015) analyzed the impact of climate change on actual soil evaporation using CGCM3.1 global model (considering SRES A2 andB1 scenarios) and, KNMI and MPI regional models for the Poiplie wetland ecosystem in Slovakia and predicted an increase in the range of 19-24% for the future periods of 2020, 2050 and 2080 based on the reference data period of 1977–1996. Similarly, Dahal et al. (2016) projected an increase in evapotranspiration for southern plains of Nagmati river basin in Nepal using GCM analysis. More recently, Liu et al (2017) investigated the impact on reference evapotranspiration for 40 weather stations of Huang-Huai-Hai Plain (3H Plain) in China along with the RCP 8.5 scenario. Their results indicate a statistically significant decreasing trend in reference evapotranspiration for only the summer season as well as annual time scale, when historical data are used. However, using the RCP8.5 scenario an increasing trend was observed for all the seasons as well as the annual time scale. The annual increase in reference evaporation has been projected to be 3.37 mm/annum.

Temperature determines the vapour pressure deficit (VPD) by determining the vapour pressures of air and water. As long as this deficit exists evaporation takes place. However, since water temperature data are generally not available, saturation vapour pressure of air is assumed as equivalent of vapour pressure of water and used in most evaporation models. However, for water bodies, a more realistic assessment of the impact of climate change can be arrived at by analyzing the possible impact of global warming on the temperature of the water body which is not feasible using the Penman-Monteith model or other evaporation models, if water temperature data are not available. Analysis of the energy budget of the water body is, therefore, required for such a purpose. Such an attempt has been made by Helfer et al (2012) who investigated the impact of climate change on the water temperature of the lake and its subsequent impact on lake evaporation for the Wivenhoe Dam which is a big reservoir in Australia. Their results show that the reservoir evaporation rate shall increase by about 8 percent during 2030-2050 and by about 15 % during 2070-2090 (Helfer et al.,2012) (Fig. 5.4).

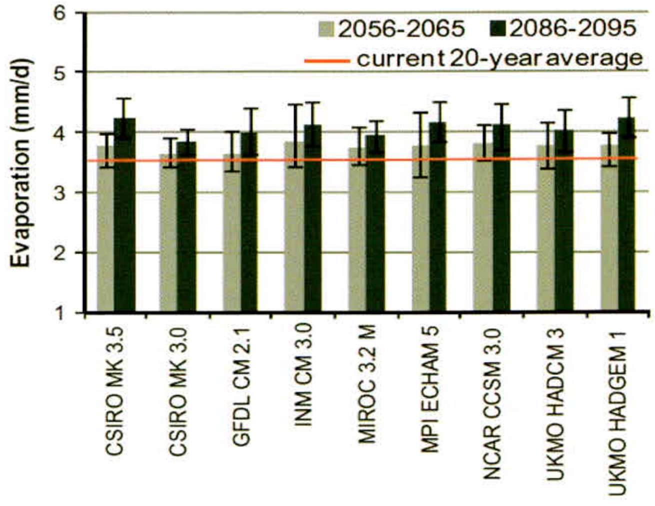

Figure 5.4. *Projected average daily evaporation for Wivenhoe Dam, Australia (after Helfer et al., 2012)*

5.3.3 The Indian Scenario

As far as India is concerned, although one of the initial studies on climate change impact on evaporation using GCM simulations was reported in the last decade of the previous millennium by Chattopadhyay and Hulme (1997), which projected a decrease in the potential evapotranspiration, not may studies using GCM or RCM data have been reported since then. Most impact studies related to evaporation or evapotranspiration deal with analysis of trends in pan evaporation or reference evaporation data. Verma et al. (2008) from their studies on trend analysis of evapotranspiration data of the period 1971-2000 for 22 stations from different parts of India observed a significant decreasing trend in 17 stations. Jaswal et al. (2008) also observed a significant decrease in pan evaporation for most of the 58 stations from all over India analyzed using the pan data of 1971-2008. Jhajharia et al. (2009) also got similar results for eight out of the nine stations from the humid climatic regions of north-east India analyzed for trends in annual pan evaporation. Results of trends analysis carried out by Bandopadhyay et al. (2009) for 32 years data of reference evapotranspiration for 133 locations spread all over India belonging to the period 1971–2002 also gave a decreasing trend. A significant declining trend in pan evaporation data has also been reported by Padmakumari et al. (2013) for 58 locations spread all over India based on the data of 1971-2010, with annual declining rate in dry months of October to May being significantly higher (about 9 mm/yr) compared to the humid monsoon months of June to September (about 6 mm/yr)(Fig. 5.5). More recently, Goroshi et al. (2017), based on the trend analysis carried out using NOAA satellite derived gridded average ET data for India, for the period of 1983-2006, have observed a decrease in average evapotranspiration at a rate of 0.22 mm/yr, with the decrease being much higher at 1.75/yr for the semi arid and arid regions. Studies based on climatic variability approach by Khobragade (2009) indicate that 1^0C rise in temperature is likely to increase the daily evaporation rates for the semi arid Udaipur region in India by about 30% during monsoon and about 8% in winter while it is likely to decrease by about 5% during summer. Annu priya et al. (2014) from their analysis using climatic variability approach observed an increase of 2.3% in annual reference ET for every 1 degree rise in mean temperature for Varansi, if CO_2 concentration is not considered. However, they have observed that if temperature remains constant, there is a decrease in reference evapotranspiration with increases in CO_2 concentration, which according to them is due to the decrease in stomatal conductance and increase in stomatal resistance caused by the increase in CO_2 concentration. Thus, combined effects of increase in temperature and CO_2 concentration does not result in any significant rise in evapotranspiration.

From the above review, it can be clearly seen than evaporation paradox has been observed in most parts of India, if we go by the analysis of evaporation trends as reported by the various studies. More and more studies using the projected outputs from the atmospheric circulation models and using them as input in the Penman-Monteith model and considering also the impacts of increasing CO_2 concentration, are required for the picture to become clearer.

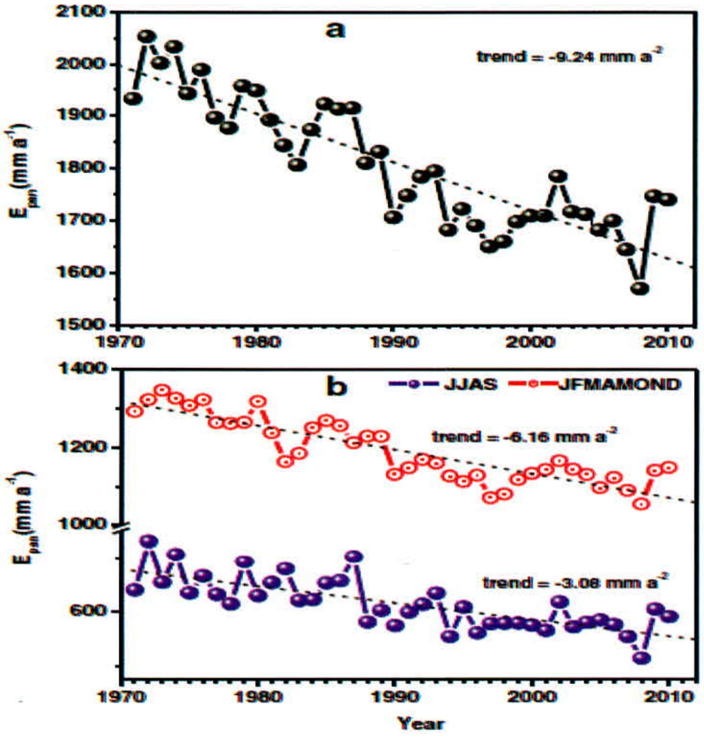

Figure 5.5: *Declining trends in pan evaporation averaged over India (after Padmakumari et al., 2013).*

5.4 Some Issues in Assessment of the Impact

Unlike other components of the hydrologic cycle such as stream discharge or change in ground water levels or magnitude of precipitation, evapotranspiration is not measured directly but estimated indirectly using the various available models, the calibration of many of which for local conditions is not easy. The same is, therefore, true for the assessment or quantification of the impact of climate change on evaporation or evapotranspiration. The various approaches which are in use such as use of atmospheric circulation models or coupling the outputs of the atmospheric models to hydrologic models or use of an assumed hypothetical climatic variability as input to the hydrological models (Ramirez and Finnerty, 1996; Singh and Bengtsson, 2005) have their own limitations, as discussed by Khobragade (2009). The representative character of the data downscaled from the atmospheric models for a local scale is also in question (Wigley et al., 1990). Furthermore, all the variables that are required as input to the evapotranspiration model such as the Penman-Monteith are not made available by the various atmospheric models as rightly pointed out by Kay and Davies (2008).One should keep these limitations in mind while interpreting the results obtained from the various impact analyses.

Another important factor that needs to be considered is the type of model used for data projection. According to Graham et al. (2007) the type of circulation model used is more important than the emissions scenarios selected in projecting the impact.The impact assessment is likely to be different with different models used. The same may be true for the choice of hydrological models or ET models. Similar observations are also made by Dallaire et al. (2019). Guo et al. (2017) from their study of 30 locations in Australia carried out using two different PET models namely Penman-Monteith and Priestley-Taylor observed that while both the models consistently indicated temperature to be the most important variable for PET, they showed large differences in the relative importance of the remaining climate variables. For the Penman-Monteith model, wind and relative humidity were the second-most important variables for dry and humid catchments, respectively, whereas for the Priestley-Taylor model solar radiation was the second-most important variable, with the greatest influence in warmer catchments. Studies by Delghandi et al. (2017) and Lin et al. (2018) show that even the selection of scenarios can be important.

A number of simple models of ET such as those which use only temperature data are available and have been used with fair degree of satisfaction in some studies (Oudin et al., 2005; Kannan et al., 2007). However, the use of simple models that use only a single or limited number of input parameters is not desirable, particularly for climate change impact assessment on evaporation or evapotranspiration because in many places other atmospheric factors may be more important than temperature (Kay and Davis, 2008). Also, it is reported that the sensitivity of the same evaporation and evapotranspiration models to different input parameters varies from region to region depending upon the relative significance of other causal factors (Irmark et al., 2006; Gong et al. 2006) which cannot be duly accounted for by the simpler models. It is for this reason that the IPCC (2001) report explicitly advises the use of such models that consider as many controlling meteorological factors as possible. For the same reason Kay and Davis (2008) suggest the preference of Penman-Monteith model over other ET models for assessment of climate change impact on evapotranspiration, as it considers most of the atmospheric variable that affect the process of evapotranspiration. However, it must also be noted that the models like Penman-Monteith are more suitable for evapotranspiration for the cropped area or potential evapotranspiration from shallow water bodies. In deep water bodies like a deep and large lake or reservoir which undergoes thermal stratification and mixing, the better choice would be energy balance model which would take into account the impact of temperature rise on lake water temperature and thermal regime, and its subsequent impact on lake evaporation which the Penman-Monteith model cannot do if the water temperature data are not available.

It should further be noted that while analyzing the effects of climate change on evapotranspiration, the combined effects of temperature and CO_2 concentration must be taken into account. This is because studies indicate that the effect of increasing evapotranspiration due to temperature rise may be compensated by the effect of increasing CO_2(Snyder et al., 2011) which may result in low stomatal conductance thereby decreasing the transpiration losses (Annu Priya et al., 2014). The development of stomata is known to be repressed by elevated CO_2 in diverse plant species (Engineer et al., 2016). However, more detailed review of investigations on physiological response of plant to elevated levels of CO_2 are required to understand the nature and magnitude of uncertainties involved as pointed out by Annu Priya et al. (2014).

Although significant changes in land use and land cover have occurred all over the world in recent decades, there are few studies on separating their impacts on ET from the impacts of climate change. A review of paired catchment studies on impacts of vegetation changes on water yield, does indicate changes in ET regime (Brown et al., 2005). Teuling et al. (2019) have reported strong shifts in the continental-scale patterns of evapotranspiration during 1950 to 2010 for Europe on account of changes in climate and land use land cover. Hamilton et al. (2018), however, observed that ET losses in the upland portion of the Augusta Creek catchment in southwest Michigan has been remarkably resilient across a 50-year period despite decreasing cropland, increasing perennial vegetation cover and warming temperatures. But they do not rule out the possibility that changes in the meteorological parameters could have offset the effects of land cover changes on ET. Further, as pointed out by Hamilton et al. (2018) it should be remembered that extrapolation of observations from small catchments that are entirely covered by one kind of vegetation to complex mixtures of vegetation may not be as straightforward as it would seem. In one of the few reported studies on separation of the impacts, Yang et al. (2018) have tried to separate the impacts of climate change and human activities on actual evapotranspiration in Aksu River Basin ecosystems, Northwest China based on the spatiotemporal distribution of actual ET during2000-2015, using the Vegetation Interfaces Processes model and Moderate Resolution Imaging Spectroradiometer-Normalized Difference Vegetation Index. They concluded that human activity caused 89%, 98%, and 80% of the changes in actual ET of forest, grass, and arable land, respectively, while climate change caused 11%, 2%, and 20% of the changes in actual ET, in the Aksu River Basin. In another such study Zou et al. (2017) observed that for Heihe agricultural region in China, the contribution of human agricultural activities to increased ET was significantly greater than that of climate change. They observed that both human activity (including agronomy and irrigation factors) and climate change (including precipitation and relative humidity) contribute to increases in ET per unit area at rates of 60.93% and 28.01%, respectively. Human activity, including the same factors, and climate change, including factors for relative humidity and wind speed, contribute to increases in total ET at rates of 53.86% and 35.68%, respectively.

Another important issue is related to the type of data used for the impact analysis. Guo et al. (2017) analyzed the implications of baseline climate conditions on the sensitivity of PET to a large range of plausible changes in meteorological parameters using a global sensitivity analysis for 30 Australian locations representing different climatic zones. Their study reveals that baseline climate can have a substantial impact on overall PET sensitivity. In particular, approximately 2-fold greater changes in PET were observed in cool-climate energy-limited locations compared to other locations in Australia. It hasalso been reported that the role of controlling factors in evaporation variability varies with the time scale of the data(Xu and Singh, 1998; Lenters et al., 2005).The time scale must therefore be invariably considered while drawing inference from the impact analysis. Also, it must not be forgotten that since evapotranspiration is indirectly estimated, so the quality of data shall have a great role to play in the accuracy of the estimation. Besides the issues of accuracy of downscaling to local scales, there are number of uncertainties involved in the investigations particularly due to possible errors of measurement and instrumentation, errors in regionalization from point measurements, errors due to averaging of data. These errors are likely to affect the calibration and validation of the atmospheric circulation models which in turn would affect the output of the models leading to errors in quantification of the impact. The research to quantify the impact of climate change on evaporation and evapotranspiration should, therefore, necessarily endeavour to minimize these uncertainties and model the process, to achieve a more precise impact assessment.

5.5 Concluding Remarks

Climate change and the associated temperature rise is expected to significantly affect the hydrologic cyclein general and its various components in particular, necessarily including evapotranspiration. The knowledge of the possible impact of climate change on evaporation and evapotranspiration is particularly important because in water stressed regions of the world any increase in future ET losses may play a significant or even a deciding role in the water availability and management of such regions. Evapotranspiration is a complex process which depends on the interaction of many physical, meteorological and atmospheric factors, the relative significance of which varies both temporally and spatially. As such, variation in evaporation rates due to variation in various causal factors needs to be understood properly and adequately for a variety of climatic setting so that the results obtained from the impact analysis are properly interpreted.

Although it is a general perception that increasing temperature necessarily leads toan increase in evapotranspiration, this may not always be true as the number of trend analysis of the pan evaporation data and some other studies actually exhibit decreasing trends in many parts of the world. To solve this mystery of "evaporation paradox" more impact studies based on the ET models such as the Penman-Monteith model which use GCM or RCM derived projected data of as many parameters (which affect the process of evapotranspiration) as used in the Penman-Monteith model should be carried out. It is important because many of the causal factors of evapotranspiration are temperature dependent with varying degree of induced variability caused by temperature variations in different climatic settings. This induced variations in them due to change in temperature regime needs to be accounted for properly for a realistic assessment. Studies based on simpler temperature-based models may provide grossly erroneous results as these models do not account for these induced variations in various causal factors. Similarly, assessment of the impact based on trend analysis of pan data is likely to be less realistic as pan data may be affected by the humidity regime of the surrounding area, by a degree which may not be the same when the compared to a scale of a cropped area or a land surface or a water body. However, even using the projected atmospheric data obtained using atmospheric models and using them in ET models or coupling them with hydrologic models, one should remember the various limitations of such models while interpreting the results. It is also important consider the impacts of increase in CO_2 concentration as they are likely to reduce transpiration losses thereby affecting the overall impacts due to temperature rise. It should not be forgotten that not all observed impact in ET regime may be due to climate change alone and there may be some impact of the land use changes such as changes in vegetation type and cover, and human activities such as agronomic practices and irrigation. Efforts be made to separate these impacts for the impact analysis to be more realistic.

As far as water bodies such as lakes and reservoirs are concerned, it is advised that impact of climate change on the water temperature of these water bodies should be taken into account for assessing the impact. Assessment based on the assumption of considering vapour pressure of water surface as equivalent of saturation vapour pressure of air may lead to unrealistic assessment of the impact. Also, for large and deep lakes and reservoirs that exhibit stratifications and mixing, these aspects must be considered and impact of climate change on the thermodynamics of these water bodies may be assessed through analysis of the impact on their energy budgets, for a more precise assessment of the impact.

While considering the various issues discussed above it must also be remembered that any conclusions on the climate change impact assessment on evaporation and evapotranspiration must be invariably stated in terms of the time scale of the data used, as the role of controlling factors in evapotranspiration variability has been found to vary with the time scale considered.

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