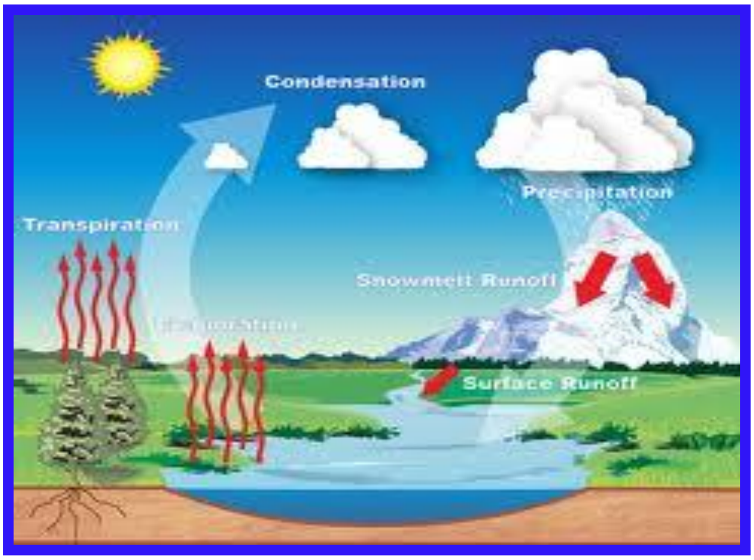
DRAFT FINAL REPORT

ASSESSMENT OF SENSITIVITY OF OPEN WATER EVAPORATION TO INCREASE IN TEMPERATURE FOR DIFFERENT CLIMATIC REGIONS OF INDIA



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1.0 INTRODUCTION

A number of gases like water vapour, carbon dioxide, ozone, methane, and nitrous oxide, together called 'greenhouse gases', occur naturally in the earth's atmosphere in small quantities which trap the solar energy and maintain the temperature of the atmosphere. However, a steady increase in these 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. An increase of $0.5^{0}C$ in the near surface air since the nineteenth century has been reported (WMO, 1987) while the increase by 0.3 to 0.6 ^{0}C has been reported over the past 100 years (Jones et al., 1990). According to the IPCC (1990), if countries around the world do not reduce emissions of greenhouse gases, temperatures are expected to increase between 1 and 3.5 ^{0} C, by the end of the next century, depending on population and economic growth. The temperature increase is expected to have a significant impact on the various components of the hydrologic cycle. As per WMO/ICSU/UNEP (1989) report evapotranspiration is expected to elevate globally by 10–20%.

Global warming and its associated impacts on hydrologic cycle and water resources have attracted increased attention of researchers in the past two decades. Evaluation of such possible impacts is particularly important for a developing nation like India, whose primarily agricultural economy depends to a large extent on the availability and management of water resources. Of particular significance to the water resources planners and managers, is the knowledge of water loss due to evaporation, as it could be a deciding factor in the water resources planning and management even in the no-climate change scenario. As such, it is necessary to have an idea about the possible impact of rising temperatures caused by global warming, on future evaporation regime of a region or a location.

2.0 OBJECTIVES

The present study has been undertaken with the following objectives:

(a) To assess the impact of rising temperature on some temperature dependent factors affecting open water evaporation

(b) To assess the impact of rising temperature on open water evaporation in different climatic regions of India using routinely observed data

(c) To compare the variation in impact on open water evaporation under different climatic settings for different scenarios of temperature rise

3.0 REVIEW OF LITERATURE

A number of studies have been reported in different parts of the world on the assessment of possible impacts of global temperature rise on water resources and hydrologic cycle (Singh and Kumar, 1997; Arnell, 1999; Jones, 1999; Middelkoop et al., 2001; Andreasson et al., 2004; Dibike and Coulibaly, 2005; Fowler et al., 2005). There are even attempts to relate the water levels of large lakes to climate change (Awange et al., 2008). Few studies have, however, emphasized the assessment of the impact of global warming primarily on evaporation. This is also epitomized by the fact that the IPCC (2001) report which provides a very long list of reference on studies related to various aspects of climate change, has only a few references quoted on impact of climate change on evaporation from water surfaces. Although, the IPCC report (2001) referred above is about eight years old now, not many studies of impact of climate change on evaporation have been reported in last few years. However, some of the reported studies on impact assessment for water resources do make reference to aspects of evaporation and evapotranspiration (Adloye et al., 1998, Dankers and Christensen, 2005; Lenderink et al., 2007, Singh and Bengtsson, 2005; Graham et al., 2007).

Rind and Lebedeff (1984) analyzed the effect of doubling the CO_2 content, on hydrological variables, using a GCM model and concluded that evaporation rates would increase proportionately. Ramirez and Finnerty (1996) carried out sensitivity analysis of potential evapotranspiration rates under both CO_2 and air temperature changes using a soil-crop-climate model for San Luis Valley of Colorado. Sensitivity of soil moisture to changes in temperature and CO_2 concentrations and the effects of CO_2 on plant photosynthesis and crop yield were also considered. PET was modeled with Penman-Monteith equation. A wide range of climate change scenarios were considered. It was found that combined effects of a 100% increase in CO_2 concentration and a 3^0C temperature increase results in an 18.5 % reduction in PET. Dankers and Christensen (2005) studied the impact of climate change on a sub-arctic basin in northernmost Finland and Norway using a distributed hydrological model coupled to a regional model, to predict the climate change scenario by the century end, and observed increased ET rates for summer. Further, hydrological responses to climate change were observed to have local difference within the basin and highest increase in ET rates was observed for high altitudes. Lenderink et al. (2007) evaluated nine different regional climate models (RCM) to simulate temperatures for the period 1961-90 and future predictions of surface energy budget components for years 2071-2100 and projected the evaporation to increase greatly for central Europe.

As far as India is concerned, a number of studies on climate variability and trend analysis have been reported from different parts with a visible initial bias towards the trend analysis of the rainfall. No significant trend in the rainfall series has been observed (Rao and Jaganathan; 1963; Parthsarthy, 1984; Rajgopalachari et al., 1984; Thapliyal and Kulshreshta, 1991; Gupta and Das, 2006; Jaswal et al., 2008). Studies on temperature trends, however, do indicate a rising trend. A study by Pant and Kumar (1997) using data for 1881-1997 has shown a significant warming trend of 0.57^0C per hundred years while a study by Hingane et al. (1985) had earlier given a rising trend of 0.4 ^{0}C over the period of 1901-1982. More recently, Arora et al. (2005) investigated the trends in average annul and seasonal temperature time series for 125 stations distributed all over India using non-paramteric Mann-Kendel test. They have observed that annual mean temperature, mean maximum temperature and mean minimum temperature have increased at the rate of 0.42, 0.92 and 0.09 ^{0}C respectively over the last hundred years. The seasonal mean temperature has increased by 0.94 ^{0}C for the post monsoon season and by 1.1 ^{0}C for winter season, over the hundred years. Studies by Lal (2001) using four different scenarios of climate change for the Indian subcontinent using GCM have indicated a rise in area averaged annual mean surface temperature by 3.5 to 5.5 ^{0}C by the year 2080, the range of rise for winter and summer monsoon being 4-6 ^{0}C and 2.9-4.6 ^{0}C respectively.

Studies on local scale, however, show variations (for example Das et al., 2008). Studies on climate change impact assessment using global circulation models or regional circulation models in India are still only few (for example Chattopadhyay and Hulme, 1997; Lal and Bhaskaran, 1993; Lal, 2001) probably due to the paucity of technical expertise required for handling the sophisticated Atmospheric Circulation Models. Few attempts have, however, been made to assess the possible impacts of climate change on water resources and hydrology of the country using conceptual hydrological models (Mehrotra and Divya, 1994; Singh and Kumar, 1997; Singh and Bengtsson, 2005; Gosain et al., 2006). Divya and Mehrotra (1995) and Lal (2001) have discussed the possible impacts of climate change on hydrology and water resources of India.

Work related to impact of global warming on evaporation is meager in India. It is gaining importance only recently, but is still limited to analysis of trends. The only reported study on impact assessment using GCM is that of Chattopadhyay and Hulme (1997) who had projected decrease in potential evaporation across India from GCM simulations of climate. The projected decreases in potential evaporation were related largely to increases in the vapor pressure deficit resulting from higher temperature. Verma et al. (2008) carried out linear trend analysis of 30 years data (1971-2000) of evapotranspiration calculated by Penman-Monteith method for 22 locations in India. A significant decreasing trend in annual PET was found in 17 out of the 22 locations. Jaswal et al. (2008) have analyzed 30 years (1971-2008) of pan evaporation data for 58 stations from all over India for trend. Their analysis shows that for the country as a whole, the evaporation has significantly decreased in all seasons. Out of the 58 stations, numbers of stations having significant decrease in evaporation are 45 for annual evaporation, 30 for winter, 42 for summer and 35 for monsoon and post monsoon. Decadal analysis carried out by them shows that variability of evaporation towards the decreasing trend is steadily maintained throughout the period but more in the decade 1991-2000.

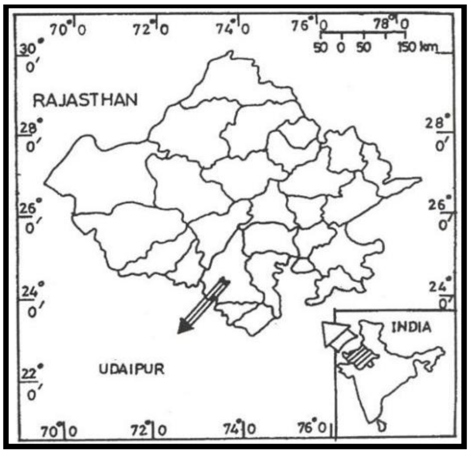
Analysis of trends in evaporation has also been reported for many regions of the world and the findings vary from region to region. Evaporation has been found to decrease over USA, former Soviet Union, and Eurasia during 1950-1990 (Peterson et al., 1995; Golubev et al., 2001). Decreases in evaporation have also been reported for China (Thomas, 2000; Liu et al., 2004), Australia and New Zealand (Roderick and Farquhar, 2004; 2005) while some mixed trends have been noticed in East Asia (Xu, 2001), Israel (Cohen et al., 2002) and northeast Brazil (da Silva, 2004).

There are three approaches in practice for assessing the impact of global warming on the various components of hydrologic cycle. (i) studies using atmospheric circulation models; GCM's and RCM's (ii) studies using the hydrologic models by using the outputs of the circulation models as inputs (Dibike and Coulibaly, 2005; Graham et al., 2007), and (iii) studies using hydrological models with assumed hypothetical climatic variability (Ramirez and Finnerty, 1996; Singh and Bengtsson, 2005). While studies using the GCM's are more realistic for global scales, the grid system is too large to assess the impact on regional or local scale. Downscaling of the GCM output to local scales may create lot of errors and, the results and inferences based thereon, may be erroneous. Also, they are inherently unable to represent local sub-grid scale features and dynamics (Wigley et al., 1990). Moreover, not all the variables required for the calculation of more complex evapotranspiration formulae are available from all climate models (Kay and Davies, 2008). Graham et al. (2007) observed that choice of GCM has a larger impact on projected hydrological change than the selection of emissions scenario. Hydrological models are, hence, claimed to be more useful and suitable for regional and local scales, as they have the ability to incorporate projected variations in climatic variables as well as other hydrological parameters. However, contrary to the claim, it is worthwhile to note that although hydrologic models do facilitate for introduction of variability in input parameters, they generally do not have sub modules for estimating the variability in parameters caused by their other dependent variables. For example, there are provisions to have variability in net long-wave radiation data or actual vapour pressure data as inputs, but there are no provisions to estimate the variability in net radiation or vapour pressure data due to variability in the temperature data, although temperature is a dependent variable for them. This is particularly true of those hydrologic models that use simpler form of evaporation and evapotranspiration formulae. Although in some cases satisfactory results have been achieved even with the simpler models (for example Oudin et al., 2005; Kannan et al., 2007, who have used simple temperature based models), use of such simpler models is not desirable as they do not consider all the controlling variables of evaporation. As rightly observed by Kay and Davis (2008) *'in the context of climate change, when considering the changes in PE between current and future climates,* *it may be that changes in atmosphere variables other than temperature could have an important effect on overall changes in PE"*. Studies have also indicated limited sensitivity of hydrological models to evaporation and evapotranspiration inputs. For example, Oudin et al. (2005) through their study on the comparative performance of the four rainfall-runoff models using 27 alternative formulae of evapotranspiration, observed that the formulae performed similarly, although most of the other studies on comparative performance of the ET models show that their performance varies with regions and within regions (as discussed in section 2.4). Arnell (1999) studied the sensitivity of changes in runoff in Europe to ET by considering two models of ET namely Penman-Monteith and Priestly-Taylor and obtained different results. Studies also indicate variation in sensitivities of the different evaporation and evapotranspiration models to different input parameters for different regions (Irmark et al., 2006; Gong et al. 2006).

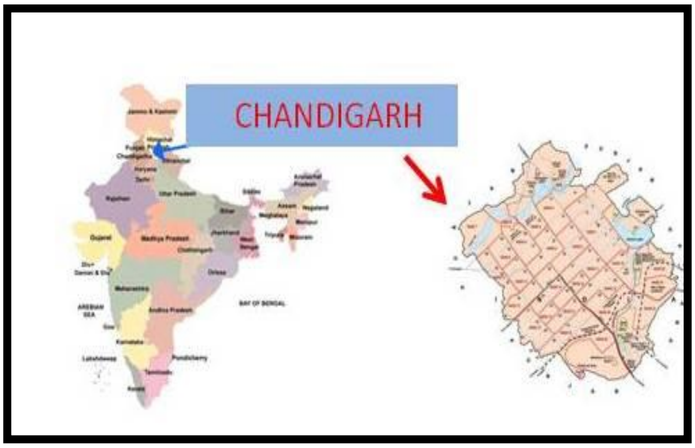
Thus, it can be summarized that though general hydrologic models may be useful for studying variations in stream flow or water levels, but for the purpose of studying impact of global warming on a more specific component like evaporation, they have their limitations and a specific evaporation model needs to be used for the purpose. The model to be used should have as many input parameters as the factors affecting the process, with a scope for estimating and introducing variability in various parameters caused by the dependent variables. As pointed out by IPCC (2001*) "equations that do not consider explicitly all meteorological controls may give very misleading estimates of change'.* As such, it is desirable that a specific evaporation model like the modified Penman model, which is a combination of the mass transfer and energy balance terms, must be used for the purpose. In the words of Kay and Davis (2008) "*for climate change impact study, the use of more physical based PE formulae such as Penman-Monteith could be preferable as they would include the effect of changes in more atmospheric variables.".* Moreover, use of GCM's and RCM's, as well as other sophisticated hydrological models, requires technical expertise that may not always be available locally. For such situations there is a need for development of a simple methodology to assess the sensitivity of local evaporation to rising temperature using routinely observed meteorological data.

4.0 STUDY AREA

Under the present study it was proposed to carry out the analysis for 3-4 different climatic regions of India depending upon the data availability. Accordingly analysis has been carried out for Udaipur, Chandigarh and Mumbai regions. Udaipur represents the semi-arid climate; Chandigarh represents the humid climate while Mumbai represents the coastal climate. Fig. 1 shows the location map of the study areas. The climatic characteristics of the study area are discussed below:



Udaipur



Chandigarh

Mumbai

Fig. 1: Location map of study areas

4.1 UDAIPUR

The city of Udaipur is located at 24^0 34' N latitude and 73^0 41' E longitude at an altitude of 587 m above the mean sea level. The study area is a semi arid climatic region. There are three distinct seasons viz. winter, summer and monsoon. The winter season from October to February is followed by a summer season which lasts till middle of June. The period from middle of June to September is the period for south-west monsoon bringing rain. Maximum temperature can be around 43^0 C in May-June while minimum is noticed during December-January. It is generally around 5-7 % but it can sometimes be as low as 1.5^0 C. The normal annual rainfall is 635 mm. Most (about 80%) of the rainfall occurs during the monsoon months of June-September. Distribution of annual rainfall is uneven and shows large spatial and temporal variations. The highest rainfall of 1222.76 was recorded during 1917 whereas years 1936 and 1966 recorded low rainfall of 300.04 mm and 297.30 mm respectively. During the drought year of 1987, the rainfall was only 263.00 mm. Air is generally dry except for the south-west monsoon period when the humidity is around 70%. Summer months are the driest ones of the year when the humidity is about 20-25%. Winds are generally light with some strengthening in the latter half of summer and the monsoon. In the period from May to September winds blow from directions between east and west. In the post monsoon season, the winds are predominantly from directions between north-west and south-east. Winds are variable in the cold season but winds from direction between east and south are rather rare. By the beginning of the summer, south westerly or westerly winds begin to blow and they become predominant with the advance of the season. Dust-storms and thunderstorms occur sometimes in the hot months of summer.

4.2 CHANDIGARH

Chandigarh is located in northern India at the foothills of Shivalik hills of Lower Himalaya. The region has a humid subtropical climate. There are four distinct seasons: (i) Summer or hot season (mid-March to Mid-June) (ii) Rainy season (late-June to mid-September); (iii) Post monsoon autumn/transition season (mid September to mid-November) and (iv) Winter (mid November to mid-March) (www.chandigarh.nic.in). Average annual rainfall is 1121.6 mm with a variation of 23.1 % (Agnihotri et al., 2006). 80% rainfall occurr in the three monsoon months of July to September (Grewal., 2009). May and June are the hottest months of the year with the mean daily maximum and minimum temperatures being about 37^{0}C & 25^{0}C, respectively (www.chandigarh.nic.in). However, maximum temperatures can rise up to 44^{0}C. January is the coldest month with mean maximum and minimum temperatures being around 23^{0}C and 3.6^{0}C respectively (www.chandigarh.nic.in). Highest annual maximum temperature (during 1962-2005) was received as 46.5^{0}C in 1964, while the lowest annual minimum temperature was also recorded as (-) 1.8^0 C in the same year (Agnihotri et al., 2006). Annual pan evaporation ranges between 1467-2035 mm, with an annual average of 1754 mm. Annual pan evaporation over the years shows a decreasing trend. (Agnihotri et al, 2006). Winds are generally light and blow from northwest to southeast direction with exception of easterly to southeasterly winds that blow on some days during the summer season (www.chandigarh.nic.in).

4.3 MUMBAI

Mumbai, is the capital city of Maharashtra. It lies in the western coast at 18° 58′ 30″ N latitude and 72° 49′ 33″ E longitude. Mumbai has a tropical climate, specifically a tropical wet and dry climate, with seven months of dryness and peak of rains in July. The cooler season from December to February is followed by the summer season from March to June. The period from June to about the end of September constitutes the south-west monsoon season, and October and November form the post-monsoon season. Between June and September, the south west monsoon rains lash the city. Pre-monsoon showers are received in May. Occasionally, north-east monsoon showers occur in October and November. The maximum annual rainfall ever recorded was 3,452 mm for 1954. The highest rainfall recorded in a single day was 944 mm on 26 July 2005. The average annual temperature is 27.2 °C and the average annual precipitation is 2,167 mm. In the Island City, the average maximum temperature is 31.2 °C, while the average minimum temperature is 23.7 °C. In the suburbs, the daily mean maximum temperature range from 29.1 °C to 33.3 °C, while the daily mean minimum temperature ranges from 16.3 °C to 26.2 °C. The record high is 40.2 °C on 28 March 1982,[133] and the record low is 7.4 °C on 27 January 1962.

5.0 DATA USED

Daily data of various meteorological parameters such as maximum and minimum temperatures, wet bulb and dry bulb temperatures, maximum and minimum humidity, bright sunshine hours, actual vapour pressure , wind velocity, have been used in the present study. For Udaipur region, the data were obtained from the meteorological observatory at the College of Technology and Engineering, Maharana Pratap University of Agriculture and Technology, Udaipur. Daily data of 6 years (2002-2007) were used in the study. Wind data are being collected using an anemometer installed at a height of 3.0 m above the ground. Since the wind data are obtained at 3 m above the ground surface, they were converted to 2 m height as per the requirement of the various evaporation models used in the study, using the equation of Allen et al., (1998) as:

$$U_2 = U_z * \frac{4.87}{\ln(67.8 * z - 5.42)}$$

where,

U_2 = wind speed at 2 m above the ground surface [ms^{-1}];

U_z = measured wind speed at z m above the ground surface [ms^{-1}];

z = height of the measurement above the ground surface [m].

For Chandigarh region, meteorological data have been collected from the meteorological observatory of Central Soil and Water Research and Training Institute, Chandigarh. Monthly data of 10 years for the period 2000-2009 have been collected and used in the analysis.

For Mumbai region, meteorological data have been collected from IMD. Monthly data of 10 years for the period 2000-2009 have been collected and used in the analysis.

6.0 METHODOLOGY

In the present study a simple climatic variability approach has been adopted to assess the sensitivity of local evaporation to possible change in temperature due to global warming, using a routinely observed minimum meteorological data so that the approach can be easily applied to other areas. First the major factors which are of importance in the process of evaporation and which are dependent on temperature have been identified.

These include temperature parameters such as maximum and minimum temperatures, dry bulb and wet bulb temperatures; vaporur pressure parameters such as actual vapour pressure, saturation vapour pressure, slope of the saturation vapour pressure curve and vapour pressure deficit; and radiation parameters such as net long wave radiation and net radiation. Average values of the various parameters obtained by taking average of the data have been used. Evaporation has been first estimated using these average values of various meteorological using a Penman model. These estimates are considered as present average (normal) monthly rates of evaporation. To evaluate the sensitivity of evaporation to rise in temperature, a hypothetical increase of 1^0C in daily mean temperature has been assumed. Using these increased values of mean temperature changes in all the temperature dependent parameters have been estimated using standard equations. Then using these estimated values of the various parameters as inputs to the Penman model again, future evaporation rates have been obtained. The present and projected evaporation rates are then compared to analyze the variations. The modified Penman Combination model as per Nokes (1995) has been used in the study Most of the parameters used in the Penman equation are obtained as per Allen et al (1998). The albedo or reflection coefficient for water has been calculated as function of solar radiation according to the equation developed by Coeberg, 1964). The latent heat of vapourization has been estimated as per Nokes (1995). The present investigation assumes the same number of average sunshine hours as observed at present. The wind is also assumed to be the same, as it is difficult to predict using the present methodology.

In this methodology, the projected data of relative humidity is not known, as it would be difficult to predict from the projected mean temperature data, because of the highly non linear relationship between relative humidity and temperature. Correlation analysis carried out with the present data indicates that the relationship cannot be expressed as linear relationship, as very poor results were obtained with linear regression. So, a simpler approach of estimating actual vapour pressure data from the dry bulb and wet bulb temperatures as suggested by Allen et al (1998) is adopted, as the two show high linear relation. For this dry bulb and wet bulb values are projected for future scenario using the data on future minimum temperature, maximum temperature and mean temperature using their present correlation.

7.0 RESULTS AND DISCUSSIONS

This section discusses the various results obtained during the study. The results for individual stations as well as their inter-comparison have been discussed.

7.1 RESULTS FOR UDAIPUR REGION

Change in mean temperature implies that there will be a change in the daily maximum and daily minimum temperatures. To predict the future values of minimum and maximum temperature from the future values of mean temperature, the present relationship between the maximum (T_{max}), minimum (T_{min}) and mean temperatures (T_{mean}) for the study area was analyzed. It was observed that daily maximum and minimum temperatures have strong linear relationship with the daily mean temperature. So, linear regression was carried out to predict maximum and minimum temperatures from mean temperatures from the data. Following equations were derived:

$$T_{max} = 0.7261\ T_{mean} + 14.183 \qquad (R^2=0.76,\ n=2191)$$

$$T_{min} = 1.2730\ T_{mean} - 14.159 \qquad (R^2=0.91,\ n=2191)$$

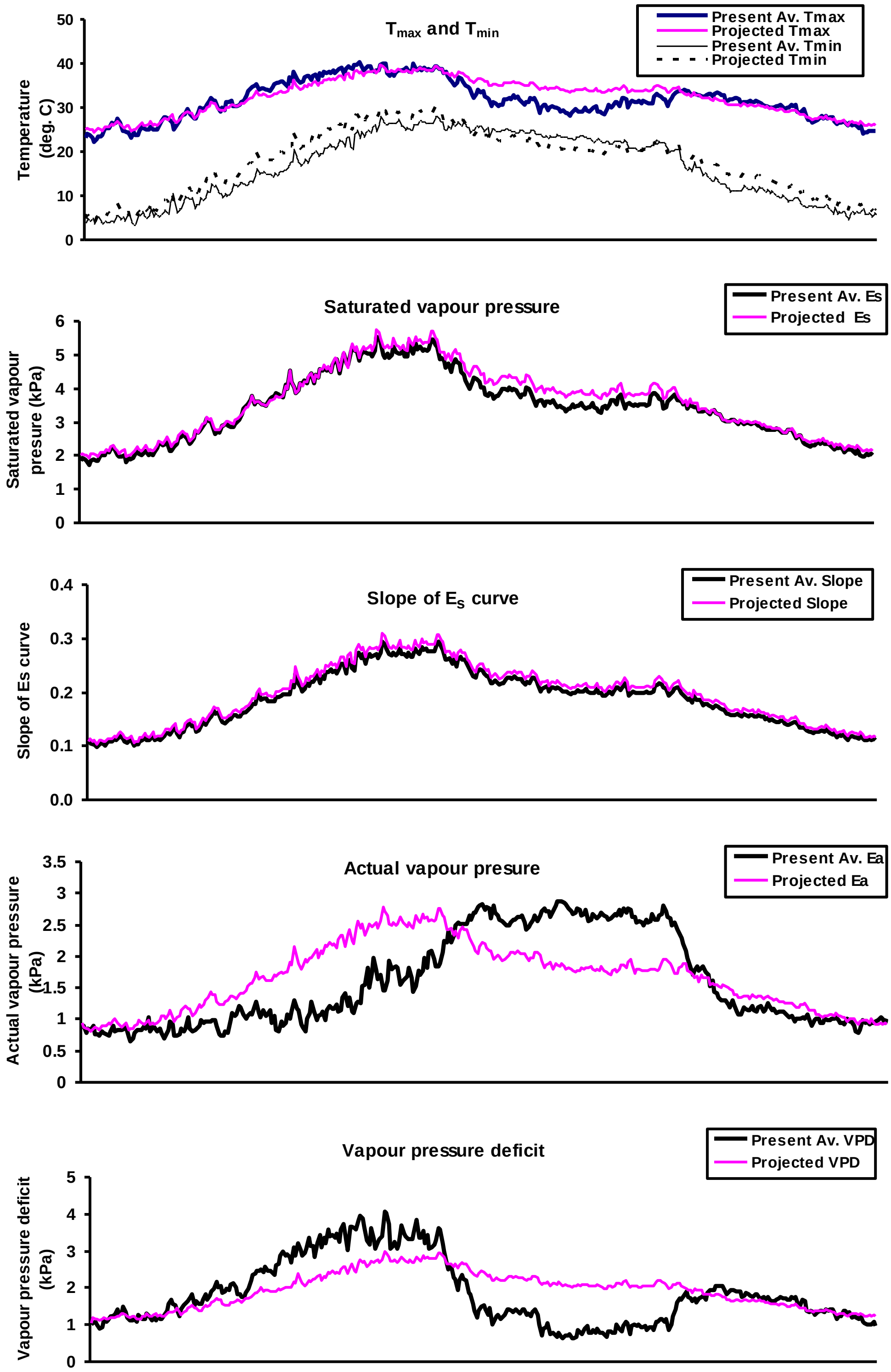
These equations were used to predict the future T_{max} and T_{min} from future T_{mean} data**.** Using these values **s**aturation vapour pressure was projected as per the equation suggested by Allen et al (1998).

To predict the projected values of dry bulb and wet bulb temperatures from air temperature data, following simple linear regression equations have been developed:

$$T_{dry\ bulb} = 1.0156 * T_{mean} + 0.209 \quad (r^2 = 0.9429,\ n=2191)$$

$$T_{wet\ bulb} = 0.6415 * T_{min} + 7.0907 (r^2 = 0.87,\ n=2191)$$

Fig. 2 shows the projected variations in the various temperature dependent variables as a result of 1^0C increase in the average mean temperature while the average absolute percent change for different parameters for different months are presented in Table 1.



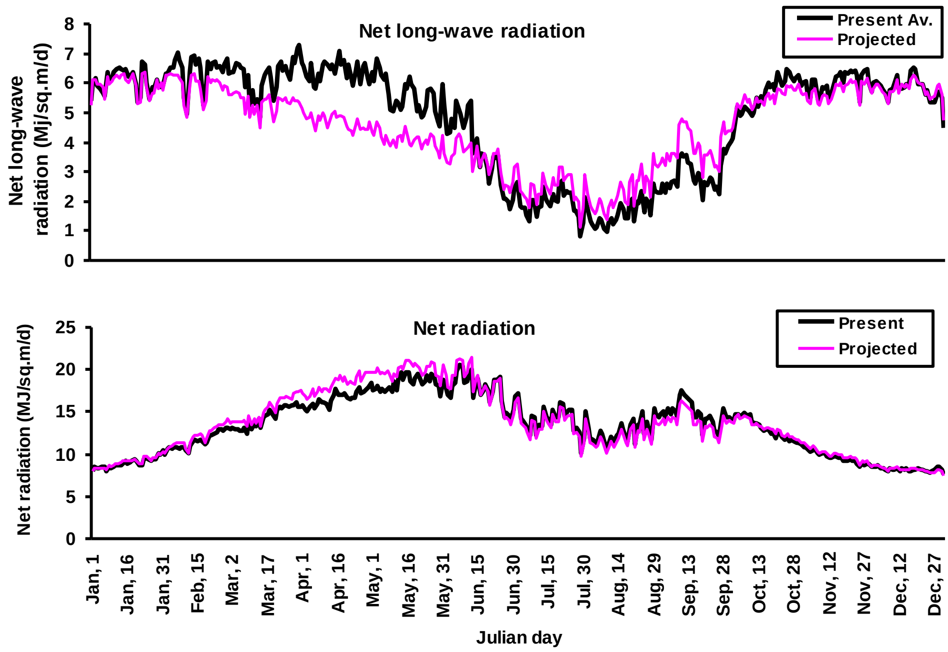


Fig. 2: Projected variations in temperature dependent parameters at Udaipur

Projected variations in daily maximum and minimum temperatures indicates that variations in one parameter (either T_{min} or T_{max}) in a season are expected to be almost double the magnitude of variations in the other parameter (T_{max} or T_{min}) in the same season. Moreover variations are observed to be more pronounced in summer and monsoon season than in winter. Most of the values of T_{max} are expected to increase during the monsoon season by upto 5^0C while the summer and winter values of T_{max} are likely to come down by upto 2^0C. Some increase (upto 2^0C) is also expected from mid December up to first week of February. The minimum value of T_{max} is likely to go up by about 2 ^{0}C than the present average value (i.e.22.2 ^{0}C). T_{min} is projected to vary in the range 3.7-30.3^{0}C as against the present range of 3.4-28.3 ^{0}C. On an average, the absolute percent change for the whole year is expected to be 2.67% for T_{max} values and 12.47% for T_{min} values. However, this distribution is expected to further vary from month to month (Table 1). For T_{min}, the highest change is projected for November (27%) while lowest (3%) for September. The values are expected to actually fall below the present average T_{min} values during July to September. For T_{max}, except for the months of July, August and September, when the rise is expected to be on an average about 12, 16 and 8%, for the remaining months the average values of T_{max} are expected to change by less than 5%. The values are actually expected to fall during March, April and May, and again in October and November.

Table 1: Projected mean average absolute percent change in different parameters

Month	T_{max}	T_{min}	e_s	e_a	Δ	VPD	R_{nl}	R_n
JAN	4.73	21.95	6.47	12.00	5.80	7.71	2.49	1.72
FEB	2.37	23.35	3.72	29.85	5.63	11.27	7.27	4.06
MAR	3.39	23.43	1.79	49.30	5.40	19.77	14.03	6.19
APR	4.58	19.43	3.01	85.87	5.17	28.66	26.25	10.16
MAY	2.24	10.79	3.01	61.24	5.01	21.62	26.45	8.22
JUN	2.85	5.33	5.50	23.82	5.02	23.68	16.52	3.59
JUL	11.90	7.05	9.92	23.21	5.17	83.02	26.94	3.60
AUG	15.47	11.01	11.50	33.10	5.25	170.57	40.36	5.08
SEP	8.18	3.30	8.76	29.11	5.24	109.81	33.29	6.31
OCT	2.49	20.09	1.83	12.71	5.37	11.35	5.56	2.44
NOV	2.19	26.56	1.56	16.40	5.53	7.95	4.75	3.00
DEC	2.44	22.50	4.88	7.84	5.71	7.35	2.14	1.51

Since saturated vapour pressure (e_s) is directly a function of temperature, projected changes in values of maximum and minimum temperatures are expected to cause changes in the projected mean values of the saturated vapour pressure (Fig. 2). However, the changes are expected to be only marginal. However, some fall in the daily mean e_s values (compared to the present) is expected around mid March to mid April and again in the second half of October. Since mean saturated vapour pressure is calculated as average of saturated vapour pressure at maximum and minimum temperatures, the variations are different in different months due to the corresponding variations in the maximum and minimum temperatures (Table 1). Thus, on monthly basis, the maximum e_s values are expected to rise by about 3% to 7% for most months except July and August when the rise is expected to be 23.3% and 29.41% respectively. $e_{s\ min}$ is, however, expected to show much wider variations (Table 1). The slope of the saturation vapour pressure is not expected to change significantly nor is any change in its pattern expected (Fig 2). The average daily absolute percent variations are expected to be 5.36 % The variations are expected to be more or less similar for all the months (Table 1).

Unlike the saturated vapour pressure, which is totally dependent on the temperature, actual vapour pressure, which is dependent not only on temperature but also on humidity, show more pronounced variations in the projected values (Fig. 2). This can be considered as the indirect effect of evaporation on the air moisture which would change the values of relative humidity. Unlike the present scenario where the average values of actual vapour pressure remain more or less similar (or vary in a low range) during the monsoon months of July to September, it is expected that the temperature rise would change this pattern. A shift in occurrence of peak of e_a is also expected from the present period of monsoon to projected peak summer period (May to mid June). From Fig. 2 it is further clear that while the values are expected to go up from January to June and again from October to December, these are expected to come down during the monsoon months of June end to September. Averages values of absolute percent change for different months (Table 1) indicate that the change (increase) is expected to be higher during summer months of March to May while it (increase) is going to be low during cooler months of October to January. The fall in the e_a values which is expected during mainly June to September, is projected to be within the range of 23-33%.

Consequent upon the changes in saturated vapour pressure and actual vapour pressure, the vapour pressure deficit is bound to change. However, since projected changes in saturated vapour pressure are far less significant than the corresponding changes in actual vapour pressure, the projected variations in vapour pressure deficit appear to be more drastically influenced by the actual vapour pressure. As a result, the daily absolute percent change on an average is expected to be around 42%. The average absolute percent change, however, does not speak about the true picture because it does not reflect the wide variations which are expected to be more than 200% on some days during the monsoon months and less than 1% on some days during December-January. From Table 1 it can be seen that the monthly average values show great variations. In general, high variations are expected during monsoon and low during winter. It should also be noted that the percent change in the VPD during the months of February to mid June and again during mid October to Mid June actually mean a decrease (fall), although the 'absolute percent' term does not reflect that.

Some change in average daily net long-wave radiation (R_{nl}) is also anticipated for the study area. Net long-wave radiation is projected to vary within a range of 1.14 – 6.36 MJ/sq.m/d as against the present average range of 0.80-7.27 MJ/sq.m/d. Thus, a fall in the upper bounds and a rise in the lower bounds is anticipated. Percent change in daily values is expected to vary from -36.67% (decrease) to 48.4% (increase). Like the other parameters discussed above, the variations are different for different months (Table 1). Maximum variations are expected in monsoon months of July-September when the net long-wave radiation is expected to rise due to rise in maximum temperatures. The rise is expected to be highest for August. All the remaining non monsoon months are projected to see a fall in the net long-wave radiation, again mainly due to the fall in corresponding T_{max} values, with maximum fall of about 26% in April and May. Variations in net long-wave radiation of cooler months of October to February are expected to be low (less than 8%). Besides T_{max}, actual vapour pressure also seems to affect the net radiation and the effect is in a negative way. Thus, while actual vapour pressure is expected to significantly rise in monsoon months and fall in the remaining months, the opposite is expected for the net long-wave radiation in terms of pattern. In terms of magnitude, however, both seem to vary in more or less the same proportion.

Although, solar radiation being an extraterrestrial factor, is not expected to be affected by the rise of global or local temperatures, due to variations in net long-wave radiations, the net radiation, which could be a deciding factor for evaporation rates particularly in dry semi arid tropics, is projected to change (Fig. 2). However, since magnitude of net long-wave radiation is smaller compared to the net solar radiation (short-wave), the overall impact on radiation balance is not very profound, except for the warmer summer months. Mean average absolute percent changes for different months are expected to be in a range of 1.51 to 10.16%. The net radiation is expected to actually decrease during June end-mid October and increase in the remaining months.

Fig. 3 shows the variations in projected evaporation vis-à-vis the present while Fig. 4 presents the daily absolute percent change in evaporation. As can be seen, daily evaporation estimate are expected to rise significantly (upto 30%) during the monsoon month of June to September and to some extent (upto 8%) during the cold winter months of December and January. But contrary to the general perception, evaporation rates are actually expected to fall during the summer, although the variations are expected to be about only 5% or less. A little fall in evaporation rates is also expected during October-November as well as during February. The average evaporation for the year is expected to be 6.12 mm/d as against the present average of 5.95 mm/d. The average absolute daily percent change in evaporation is projected to be 6.49%. Monthly variations in mean average absolute percent change (Fig. 5) indicate that highest change is expected in monsoon months of July, August and September. It is also revealed that the expected change in all the other months on an average are less than 5%. Highest variations of 23.25 % on an average are expected in August while lowest are expected in November (1.26%).

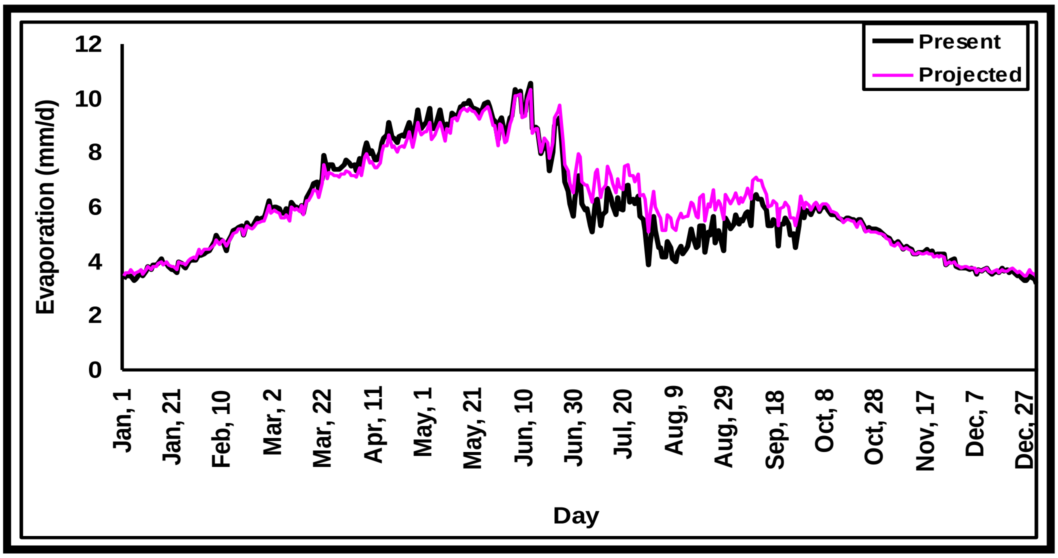


Fig. 3. Present versus projected evaporation for Udaipur region

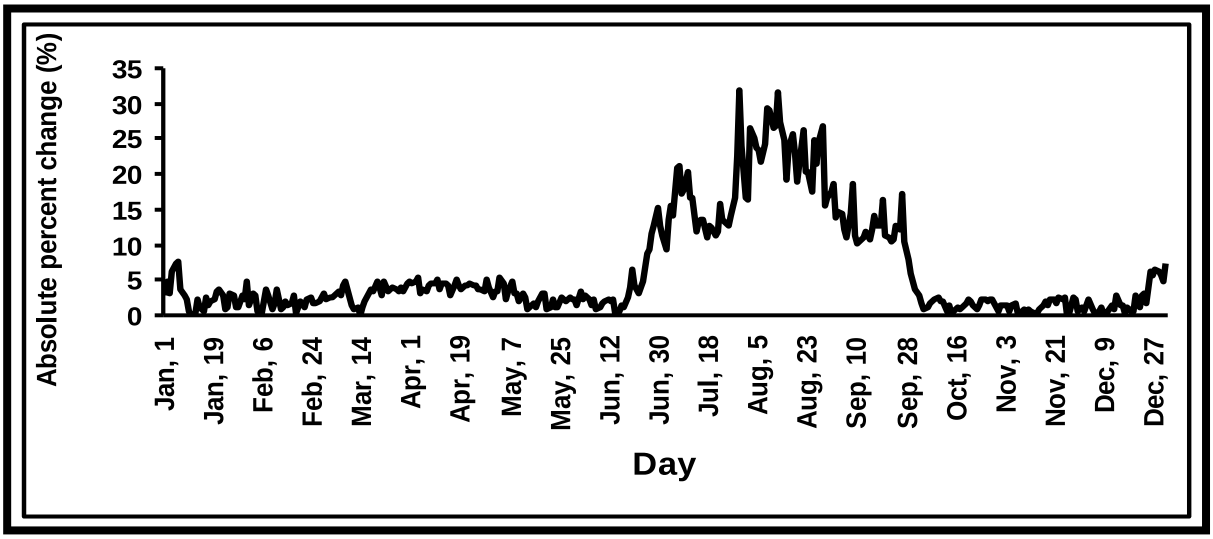


Fig. 4 Projected absolute daily percent change in evaporation estimation for Udaipur region

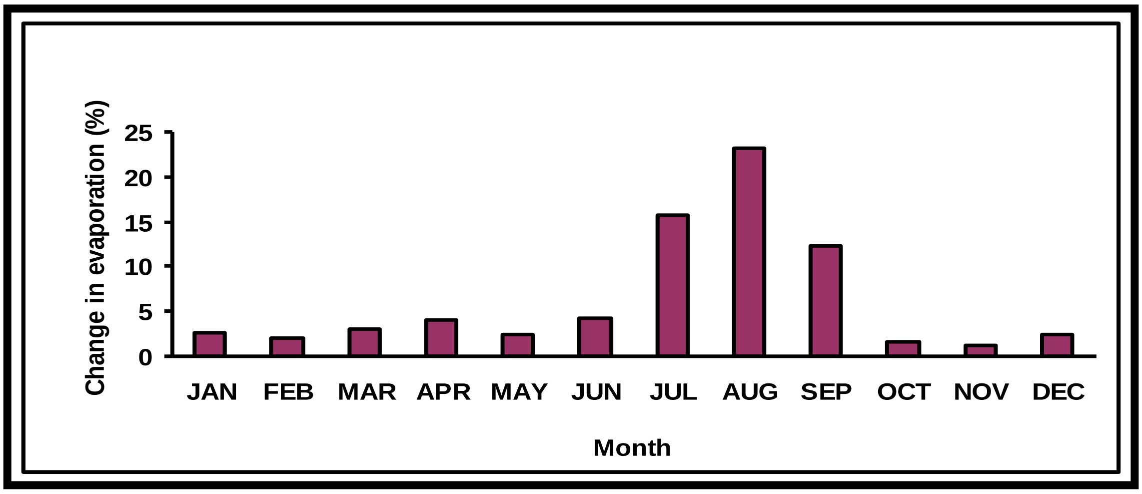


Fig. 5. Projected percent variations in different months for Udaipur

Analysis of the daily percent change in evaporation and the daily percent change in other parameters indicates that changes in evaporation regimes in the study area would be directly or indirectly controlled by changes in the T_{max}, radiation regime and VPD. However, since changes in VPD are expected to be upto more than 200% while those of net radiation would be upto only 30%, change in VPD would dominate in impact on the changes in projected evaporation. Thus, it can be said that the rising temperatures are going to affect the future evaporation rates significantly only during monsoon period while for the remaining period, the projected changes are very little.

7.2 RESULTS FOR CHANDIGARH REGION

To predict the future values of minimum and maximum temperature from the increased (future) values of mean temperature, linear regression equations between maximum temperature (T_{max}) and minimum temperature (T_{min}) with mean temperatures (T_{mean}) were developed based on present day correlation. Following linear equations were developed.

$$T_{max} = 0.892*T_{mean} + 9.412 \quad (r^2 = 0.93)$$

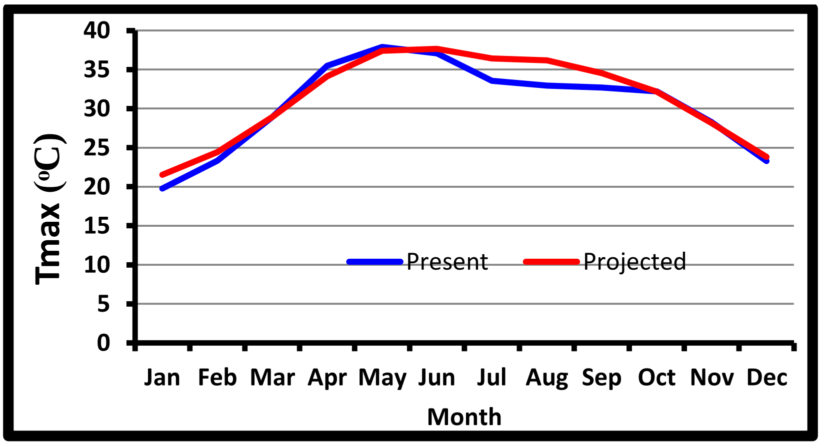
$$T_{min} = 1.107*T_{mean} - 9.412 \quad (r^2 = 0.95)$$

To predict the projected values of dry bulb and wet bulb temperatures from air temperature data, following simple linear regression equations have been developed:

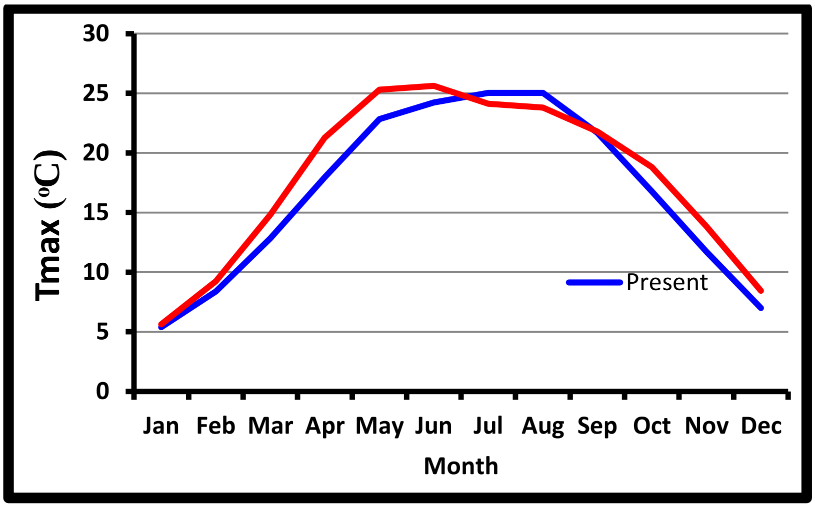
$$T_{dry\ bulb} = 1.198*T_{mean} - 8.787 \quad (r^2 = 0.98)$$

$$T_{wet\ bulb} = 0.962*T_{min} + 0.297 \quad (r^2 = 0.98)$$

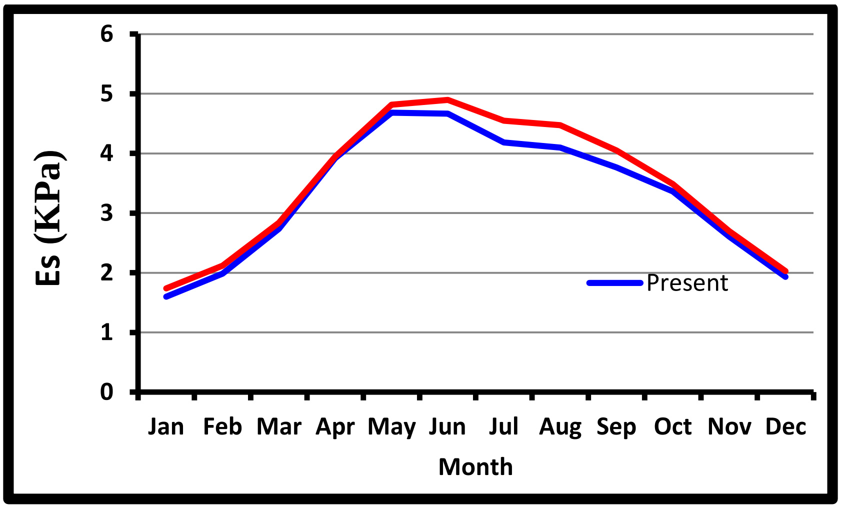
Induced variation in various temperature dependent parameters has been shown in Fig. 6.



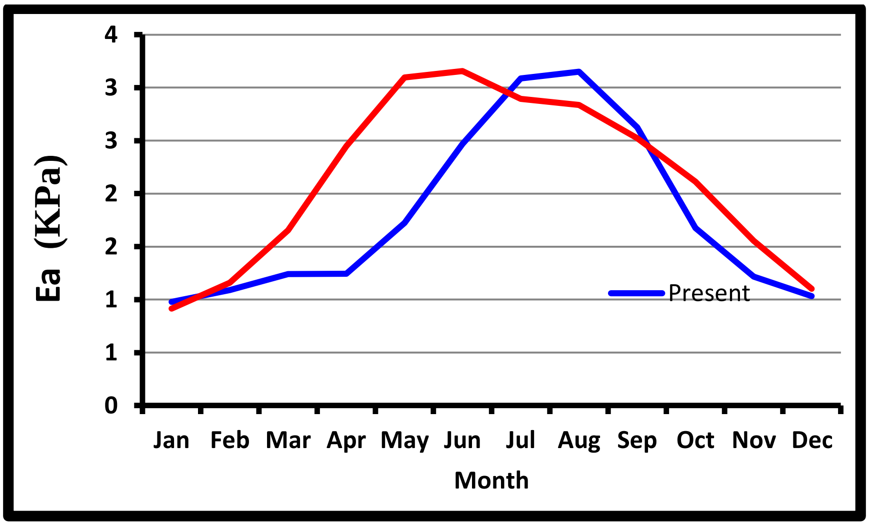
(a) Tmax



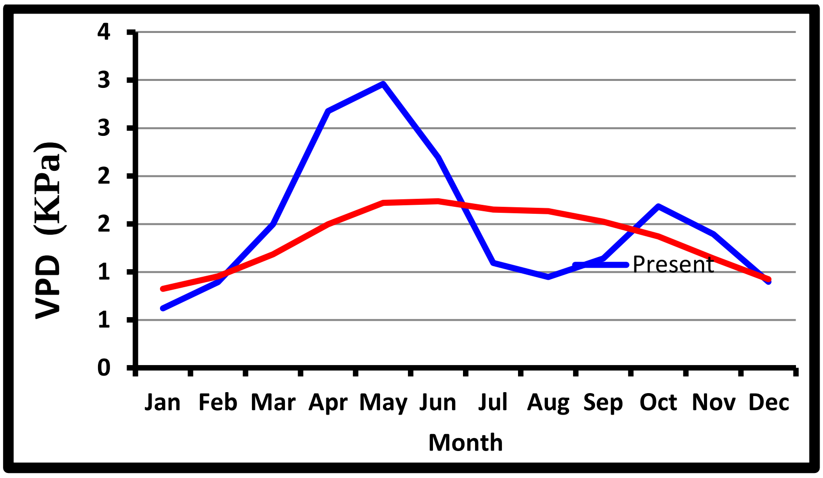
(b) Tmin



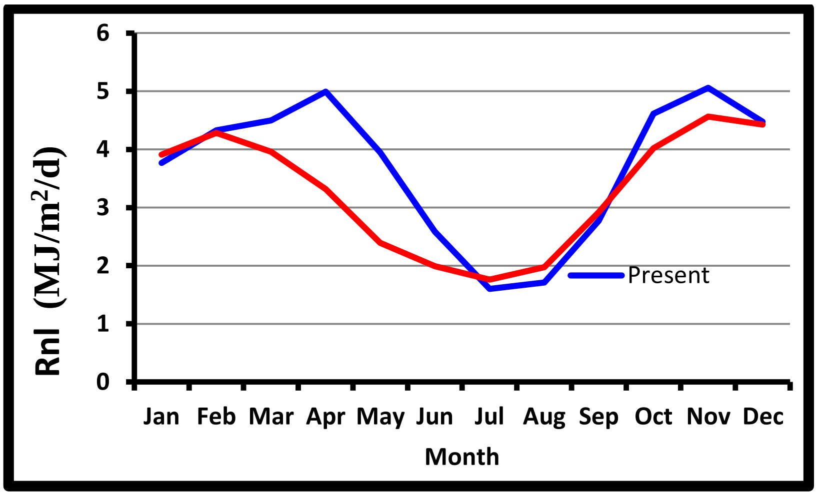
(c) Es



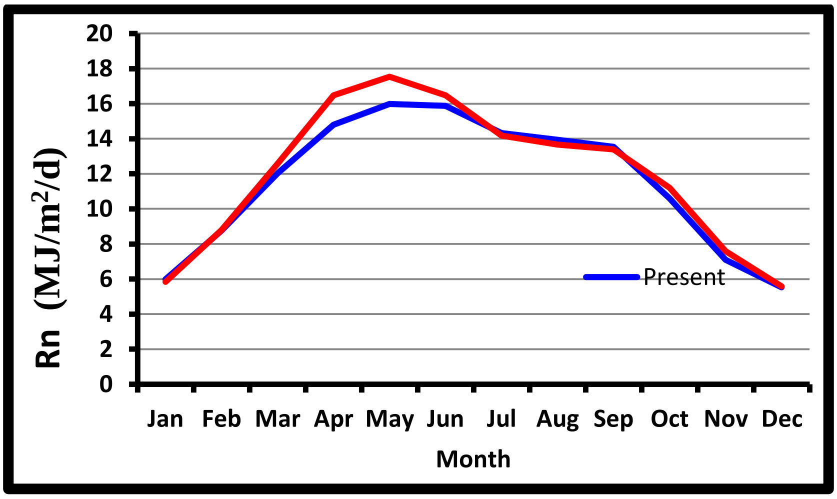
(d) Ea



(e) VPD



(f) Rnl



(g) Rn

Fig. 6: Projected variations in temperature dependent parameters at Chandigarh

It can be observed from Fig. 6 (a) to (g) that with one degree rise in mean temperature, maximum temperature is expected to vary within the range of 21.5 to 337.6^0 C from the present range of 19.8 to 37 ^{0}C. The variation rise is expected to be within the range of -1.4 to 3.2 ^{0C} (-3.8 to 9.8 respectively), with decrease (-3.8 %) in the month of April and increase (9.8%) in August respectively.

Minimum temperature is expected to vary within the range of 25.19 to 31.55 ^{0} C from the present range of 19.49 to 27.28 ^{0}C showing a significance variation within a range of 10.93 to 29.24 %. The minimum temperature is likely to rise by 2.79 ^{0}C (10.93%) for the month of July to 6.07 ^{0}C (29%) in the month of December, from its present values.

Due to change in temperature parameters, the saturation vapour pressure (es) is also likely to change. It is expected o vary within a range of 3.9 to 5.07 compared to the present range o 3.31 to 4.47 Kpa. Thus, increase is expected to be within a range of 0.42 to 0.76 KPa (11.18 to 19.48 %) for the months of July and January respectively.

Changes in temperature parameters would cause change in evaporation regime which is expected to cause a change in humidity regime. This change will induce change in the vapour pressure regime of the region thereby causing change in the actual vapour pressure, ea. It is likely to vary in a range of 3.27 to 4.57 KPa from the present range of 2.20 to 3.35 KPa showing a significant change of 17.68 to 48.61 %. While lower increase is expected for the month of July, significant increase of 48.61% is expected for the month of January.

As a consequence of changes in actual vapour pressure and saturated vapour pressure, the vapor pressure deficit (VPD) is also likely to change significantly. It is expected to change to the range of 0.31 to 0.77 KPa from the present range of 0.47 to 1.25, showing a significant decrease ranging from 0.15 to 0.75 KPa (32.06 to 59.86 % decrease). This is expected to significantly impact the evaporation rates for the region. The decrease is expected to be more significant for the warmer months of March to June. Highest decrease (59.86 %) is likely for the month of May while a 32.06 % decrease in VPD values is expected for the month of August.

One degree change in mean temperature is also likely to cause change in the radiation parameters. The net long-wave radiation is expected to change to a new range of 0.63 to 2.55 MJ/sq.m/d from the present range of 0.82 to 3.72 MJ/sq.m/d. Thus it is likely to decrease by 22 to 53%. Highest decrease is expected in the month of May while the lowest is expected in the month of August. Due t changes in net long wave radiation the net radiation is also expected to change. This is expected to cause a change in net radiation, by 1.03 to 6.18%.

It has been observed that actual vapour pressure is expected to vary from present range of 0.98 to 3.15 Kpa to a new range of 0.91 to 3.16 Kpa. The change is expected to vary within a range of -9.9 % in September to 97.07 % in April. A very significant change is expected during the summer months. Similarly, the saturation vapour pressure is expected to vary by 0.69 to 9.17%. As a result of change in regime of vapour pressure, both actual and saturated, a significant variation (-44.06 % to +72.68) is expected for Vapour pressure deficit. An absolute variation of -39.37% to +15.45 % % is projected for net long-wave radiation also. This is expected to cause a change in net radiation, by -2.39 to 11.32%.

Based on the expected change in various temperature dependent parameters, impact on evaporation rates has been studied. Results indicate that 1^{0}C increase in temperature can cause a significant change in evaporation regime during different months, particularly in summer and monsoon (Figs. 7 & 8). While the normal range of evaporation from open water surface at Chandigarh is 3.20 (Jan) to 10.98 (May) it is expected to shift to a range of 3.45 (Dec) to 9.01 (May). Evaporation is expected to increase during the monsoon months of July, August and September by 11.53%, 13.47% and 7.38 % respectively. However, contrary to the common perception, evaporation is projected to actually decrease during the summer months of March, April, May and June by 9.31%, 19.26%, 17.95, and 7.19 % respectively.

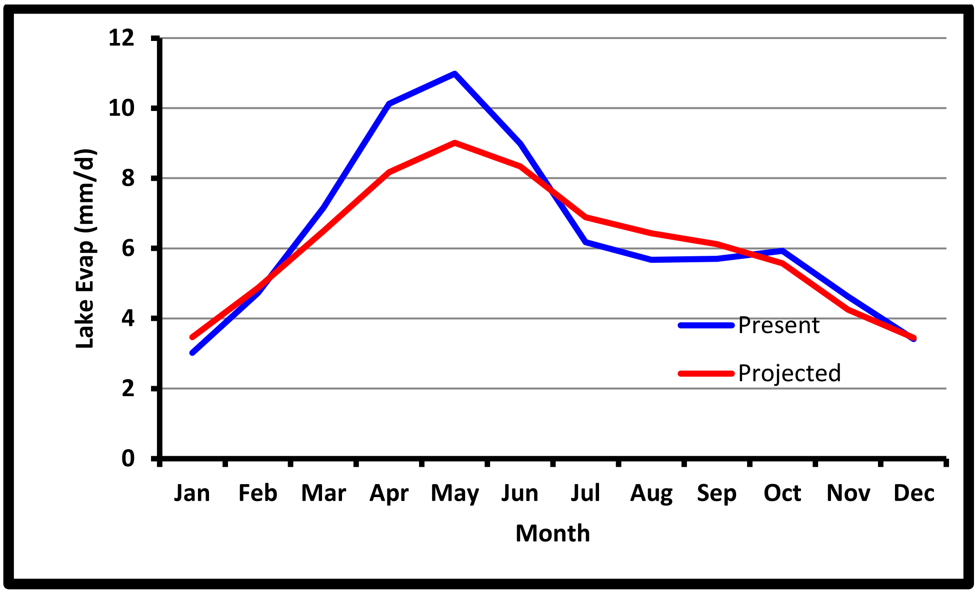


Fig. 7: Present versus projected evaporation for Chandigarh region

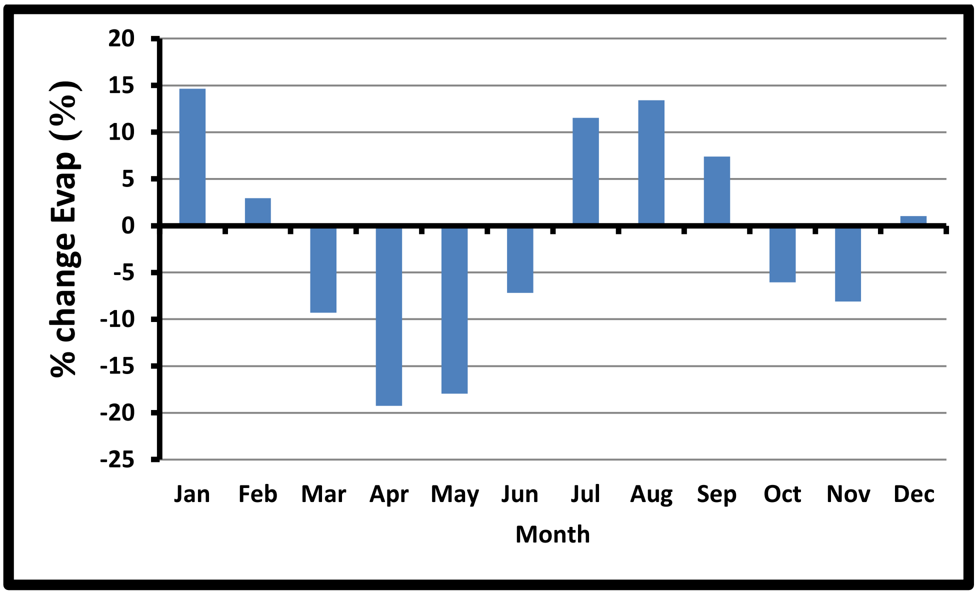


Fig. 8: Expected change in evaporation during different months for Chandigarh

7.3 RESULTS FOR MUMBAI REGION

To predict the future values of minimum and maximum temperature from the increased (future) values of mean temperature, linear regression equations between maximum temperature (T_{max}) and minimum temperature (T_{min}) with mean temperatures (T_{mean}) were developed based on present day correlation. Following linear equations were developed between T_{min} and T_{mean} with an R^2 value of 0.82.

$$T_{min} = 1.3041\ T_{mean} - 12.424$$

However, correlation analysis carried out between Tmax and Tmean using total data showed a poor linear correlation (R^2). Therefroe correlation anlyssis was carried out on monthly basis. It was observed that on monthly basis the correlation is high (Table below).

Month	**R^2**
January	0.94
February	0.92
March	0.93
April	0.95
May	0.98
June	0.97
July	0.98
August	0.95
September	0.99
October	0.95
November	0.90
December	0.95

Therefore, regression was carried out on monthly data. The results are shown in following table.

Month	**Regression equation**	**R^2**
January	$T_{max} = 1.2768\ T_{mean} - 1.3528$	0.90
February	$T_{max} = 0.9345 T_{mean} + 6.6044$	0.85
March	$T_{max} = 1.218\ T_{mean} - 1.6538$	0.87

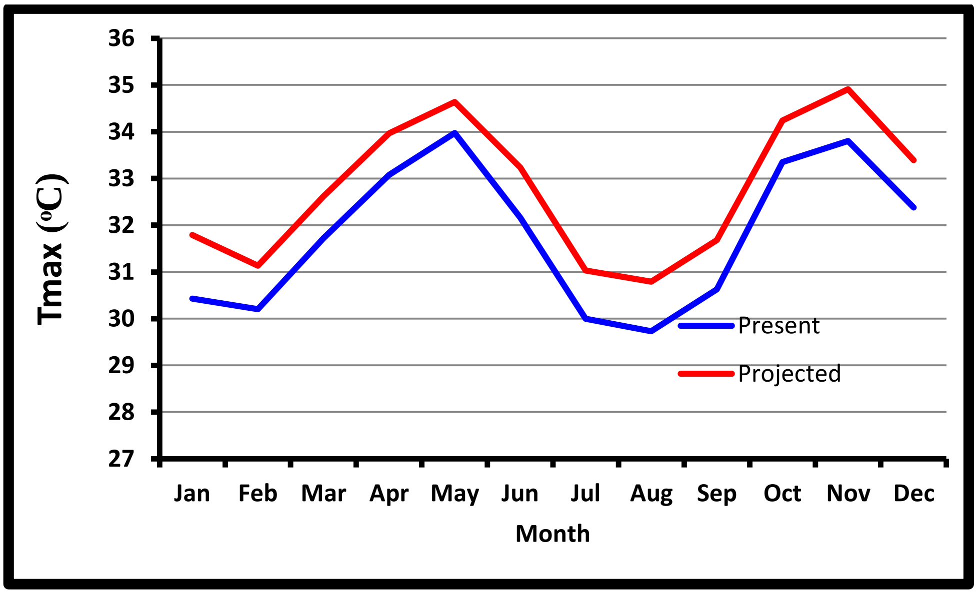
April	$T_{max} = 0.0528T_{mean} + 2.0976$	0.91
May	$T_{max} = 0.7971T_{mean} + 9.4278$	0.96
June	$T_{max} = 1.0763\ T_{mean} +0.6029$	0.94
July	$T_{max} = 1.0292\ T_{mean} +1.4086$	0.95
August	$T_{max} = 1.0596\ T_{mean} +0.6702$	0.90
September	$T_{max} = 1.1917\ T_{mean} - 2.7393$	0.98
October	$T_{max} = 0.9865\ T_{mean} +4.5049$	0.90
November	$T_{max} = 1.3963\ T_{mean} - 6.4364$	0.82
December	$T_{max} = 1.0463\ T_{mean} + 4.3461$	0.90

To predict the projected values of dry bulb and wet bulb temperatures from air temperature data, following simple linear regression equations have been developed:

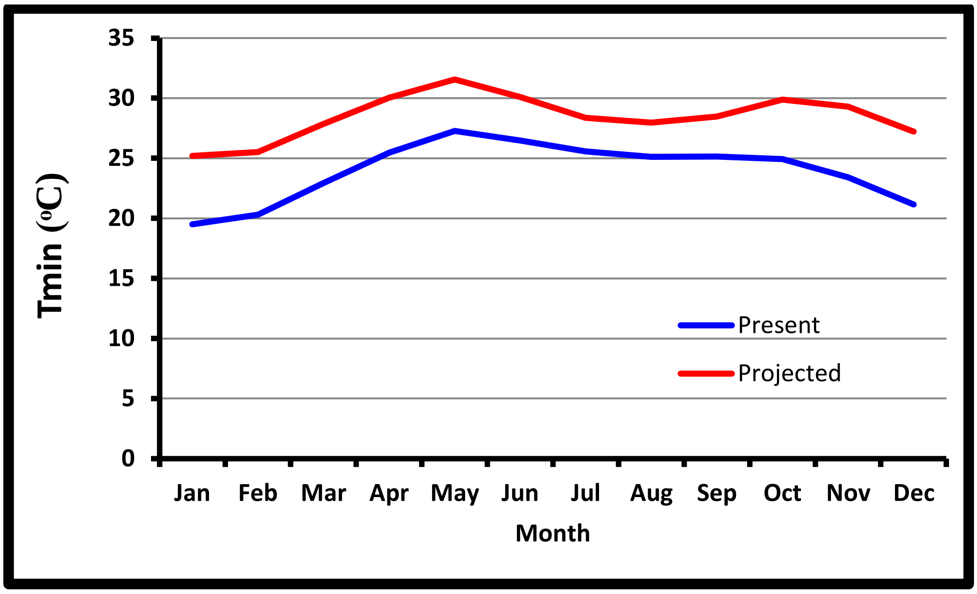
$$T_{dry\ bulb} = 1.1227*T_{mean} - 3.9572 \quad (r^2 = 0.91)$$

$$T_{wet\ bulb} = 0.93572*T_{min} + 1.8427 \quad (r^2 = 0.92)$$

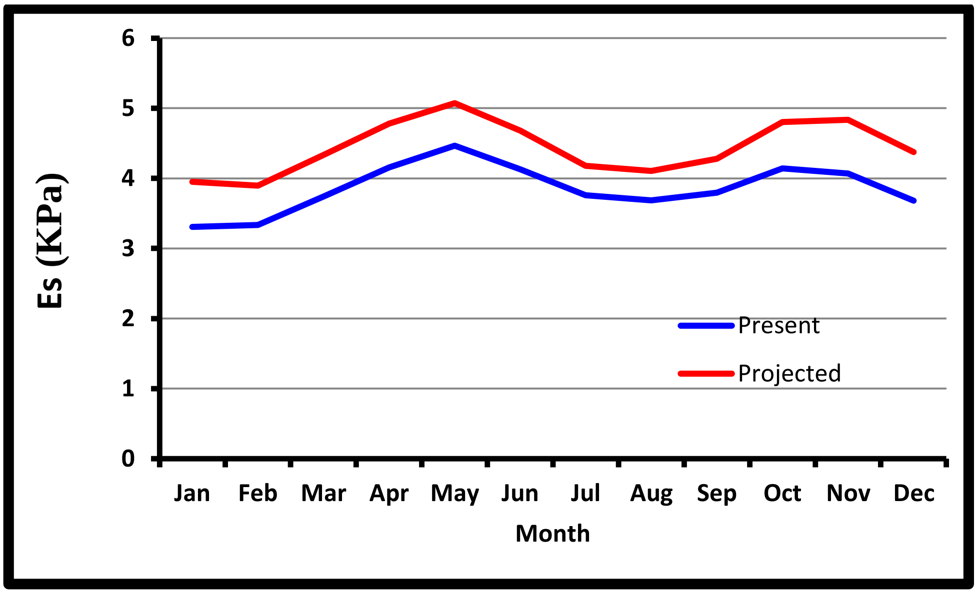
Induced variation in various temperature dependent parameters has been estimated and it shown in Fig. 7.



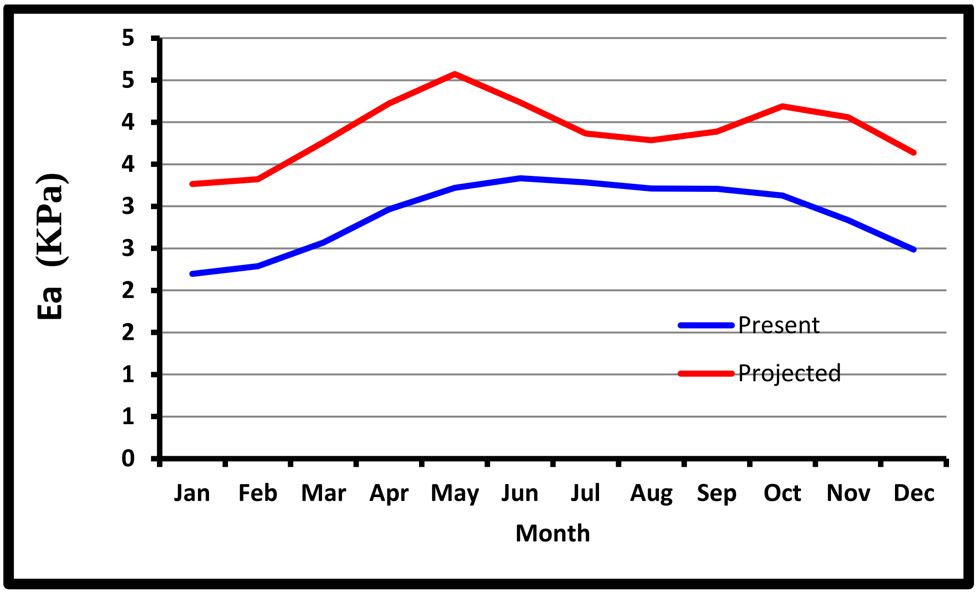
(a) T_{max}


Tmin (ºC)
35
30
25
20
15
10
5
0
Present
Projected
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

(b) T_{min}

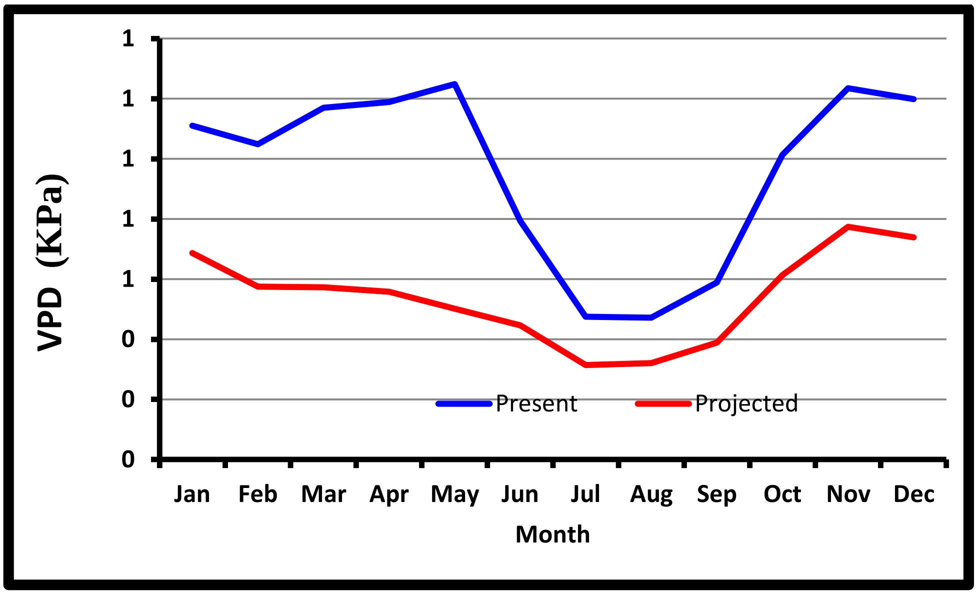

Es (KPa)
6
5
4
3
2
1
0
Present
Projected
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

(c) E_s



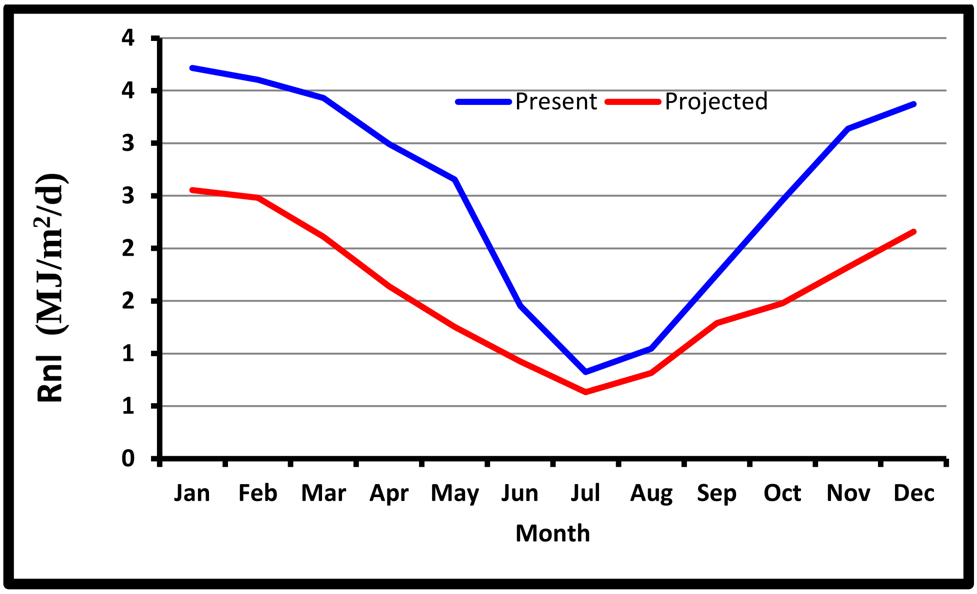
Ea (KPa)
5
5
4
4
3
3
2
2
1
1
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month
Present
Projected

(d) E_a

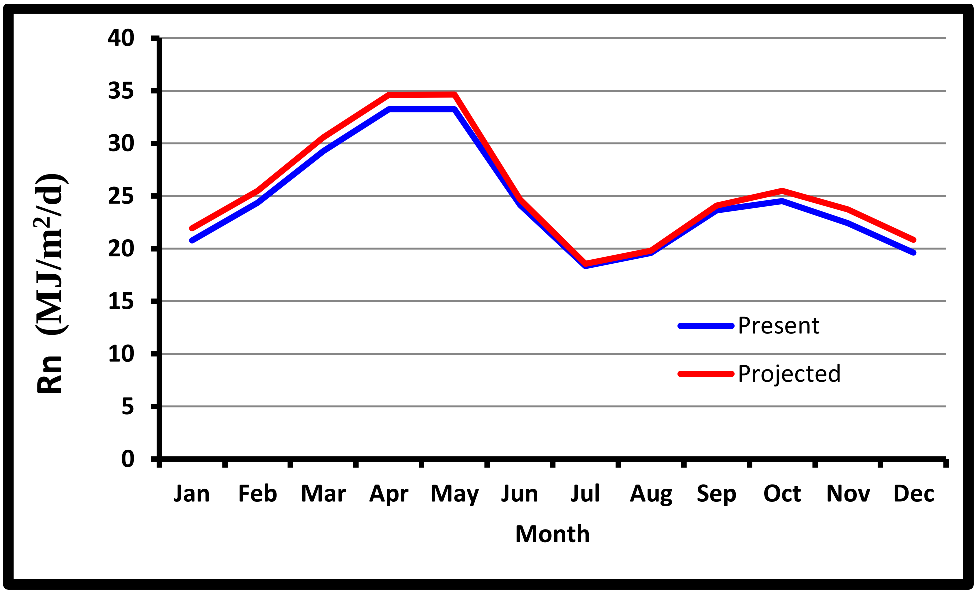


VPD (KPa)
1
1
1
1
1
0
0
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month
Present
Projected

(e) VPD



(f) R_{nl}



(g) R_n

Fig. 7: Expected variation in various temperature dependent parameters for Chandigarh region

It can be observed from Fig. 7 (a) to (g) that with one degree rise in temperature maximum temperature is expected to vary within the range of 30.79 to 34.91^0 C from the present range of 29.73 to 33.97 ^{0}C. The rise is expected to be within the range of 0.67 to

1.36 ^{0}C (1.96 to 4.48 % respectively), with low (1.96 %) in the month of May and high (4.48%) in January respectively.

Minimum temperature is expected to vary within the range of 25.19 to 31.55 ^{0} C from the present range of 19.49 to 27.28 ^{0}C showing a significance variation within a range of 10.93 to 29.24 %. The minimum temperature is likely to rise by 2.79 ^{0}C (10.93%) for the month of July to 6.07 ^{0}C (29%) in the month of December, from its present values.

Due to change in temperature parameters, the saturation vapour pressure (es) is also likely to change. It is expected o vary within a range of 3.9 to 5.07 compared to the present range o 3.31 to 4.47 Kpa. Thus, increase is expected to be within a range of 0.42 to 0.76 KPa (11.18 to 19.48 %) for the months of July and January respectively.

Changes in temperature parameters would cause change in evaporation regime which is expected to cause a change in humidity regime. This change will induce change in the vapour pressure regime of the region thereby causing change in the actual vapour pressure, ea. It is likely to vary in a range of 3.27 to 4.57 KPa from the present range of 2.20 to 3.35 KPa showing a significant change of 17.68 to 48.61 %. While lower increase is expected for the month of July, significant increase of 48.61% is expected for the month of January.

As a consequence of changes in actual vapour pressure and saturated vapour pressure, the vapor pressure deficit (VPD) is also likely to change significantly. It is expected to change to the range of 0.31 to 0.77 KPa from the present range of 0.47 to 1.25, showing a significant decrease ranging from 0.15 to 0.75 KPa (32.06 to 59.86 % decrease). This is expected to significantly impact the evaporation rates for the region. The decrease is expected to be more significant for the warmer months of March to June. Highest decrease (59.86 %) is likely for the month of May while a 32.06 % decrease in VPD values is expected for the month of August.

One degree change in mean temperature is also likely to cause change in the radiation parameters. The net long-wave radiation is expected to change to a new range of 0.63 to 2.55 MJ/sq.m/d from the present range of 0.82 to 3.72 MJ/sq.m/d. Thus it is likely to decrease by 22 to 53%. Highest decrease is expected in the month of May while the lowest is expected in the month of August. Due t changes in net long wave radiation the net radiation is also expected to change. This is expected to cause a change in net radiation, by 1.03 to 6.18%.

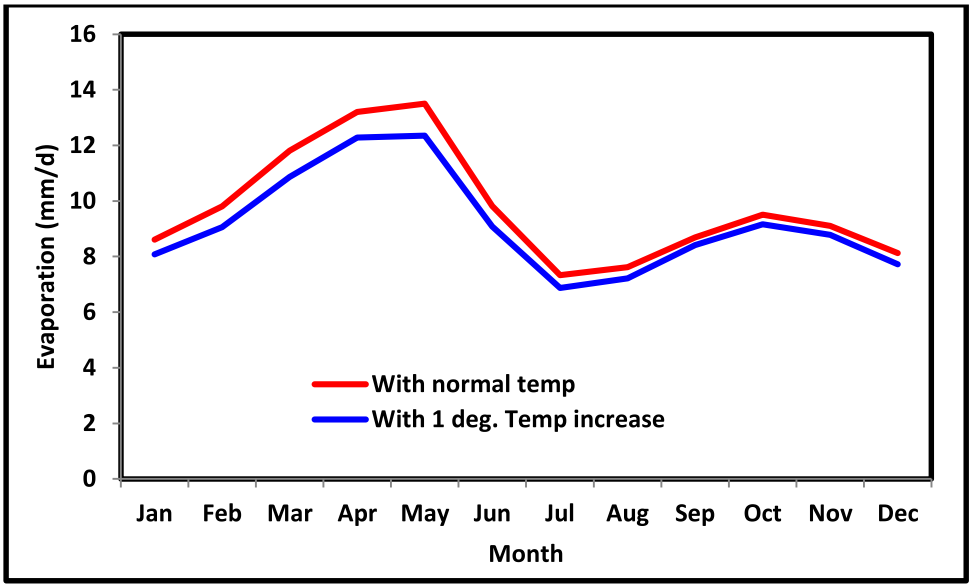


Fig. 7: Present versus projected evaporation for Chandigarh region

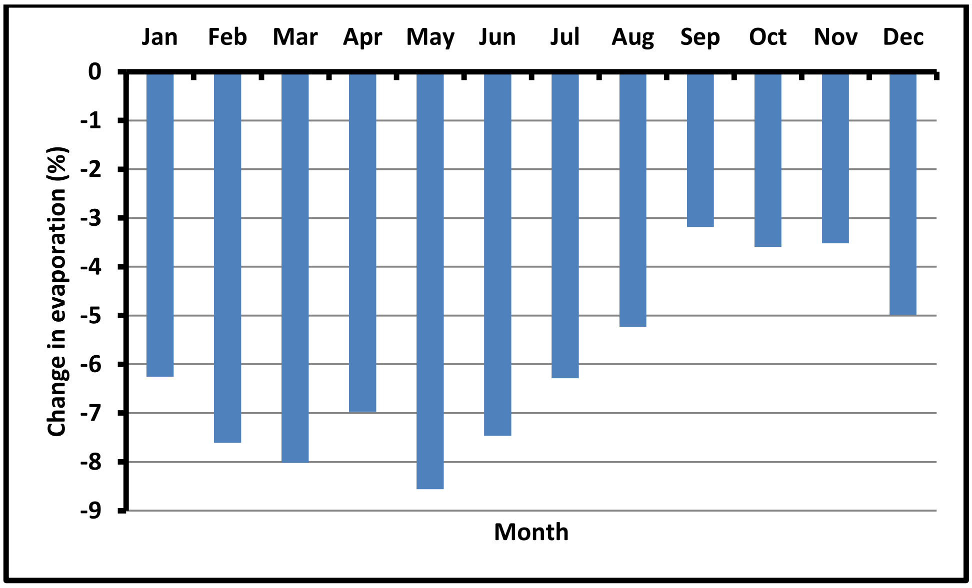
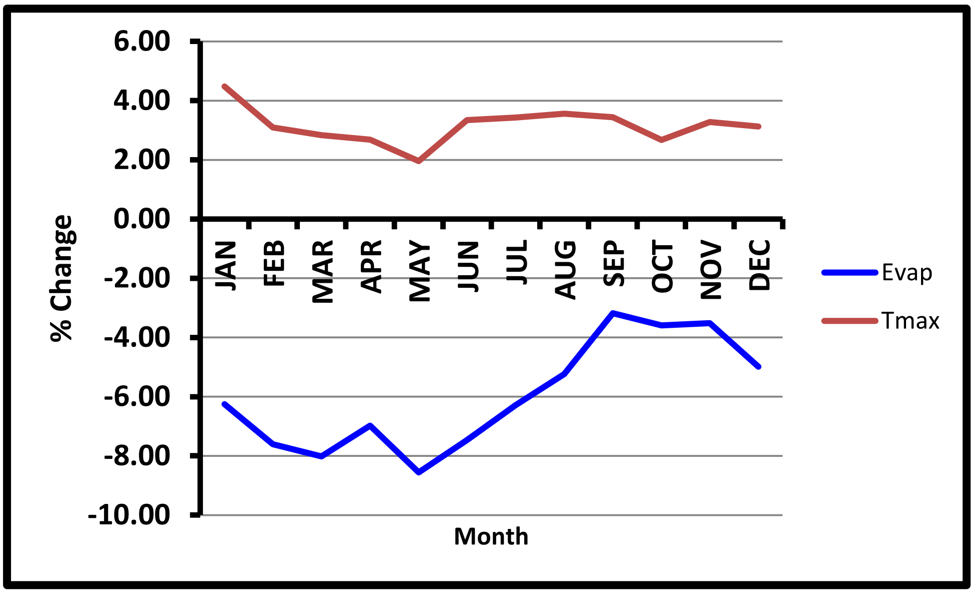
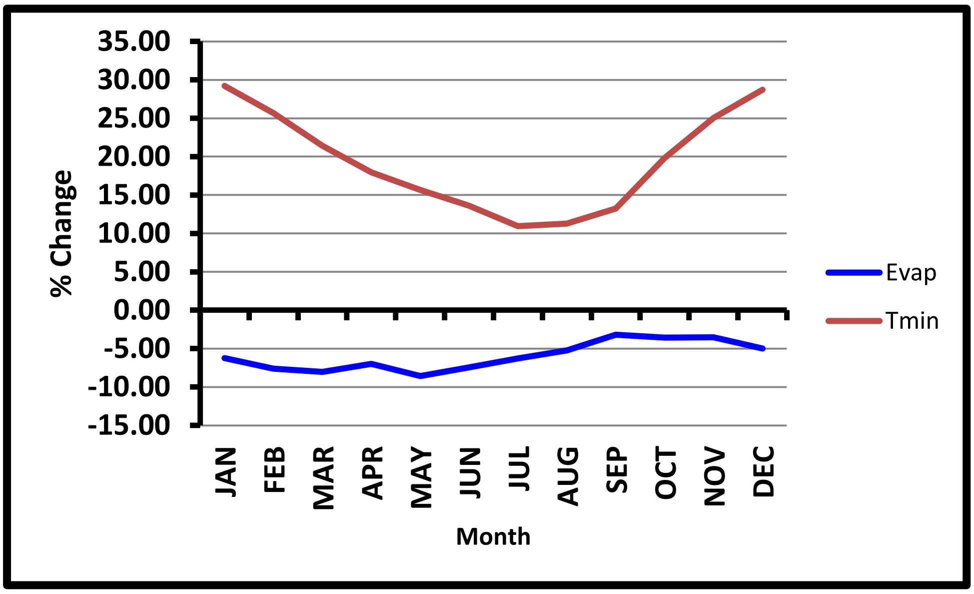
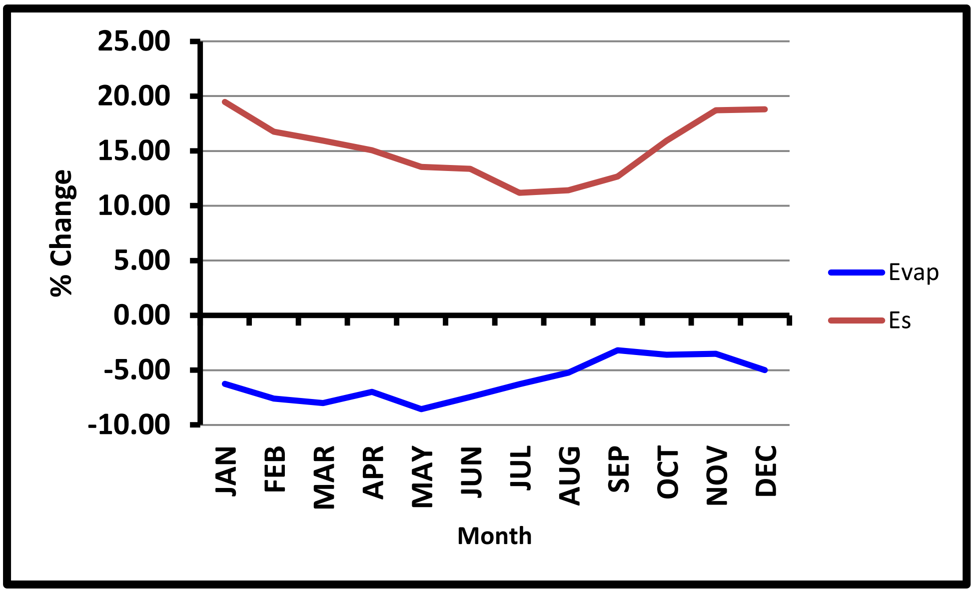


Fig. 8: Expected change in evaporation during different months for Mumbai


6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
% Change
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Month
Evap
Tmax


35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
% Change
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Month
Evap
Tmin



25.00
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
% Change
JAN
FEB
MAR
APR
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JUL
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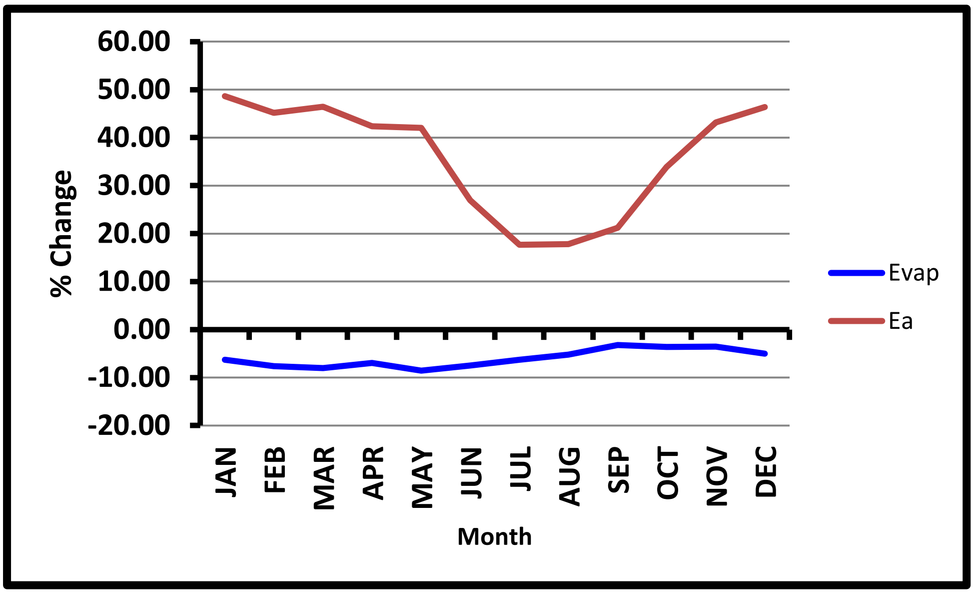
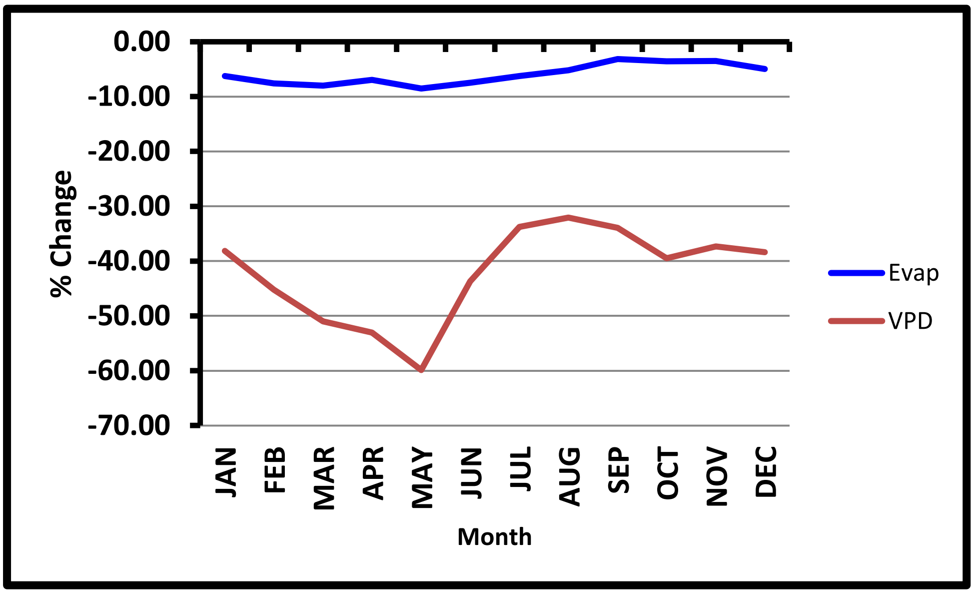
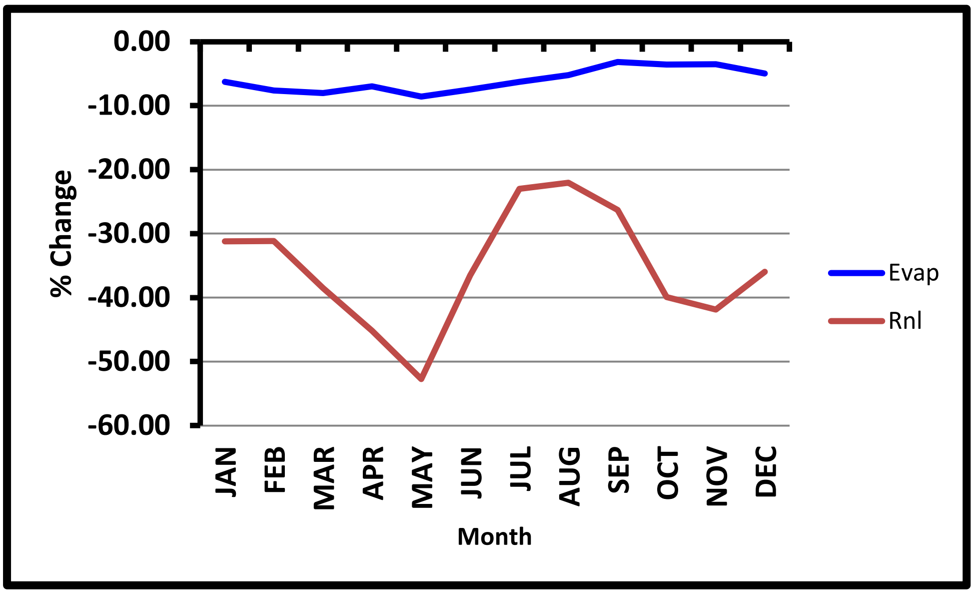
SEP
OCT
NOV
DEC
Month
Evap
Es

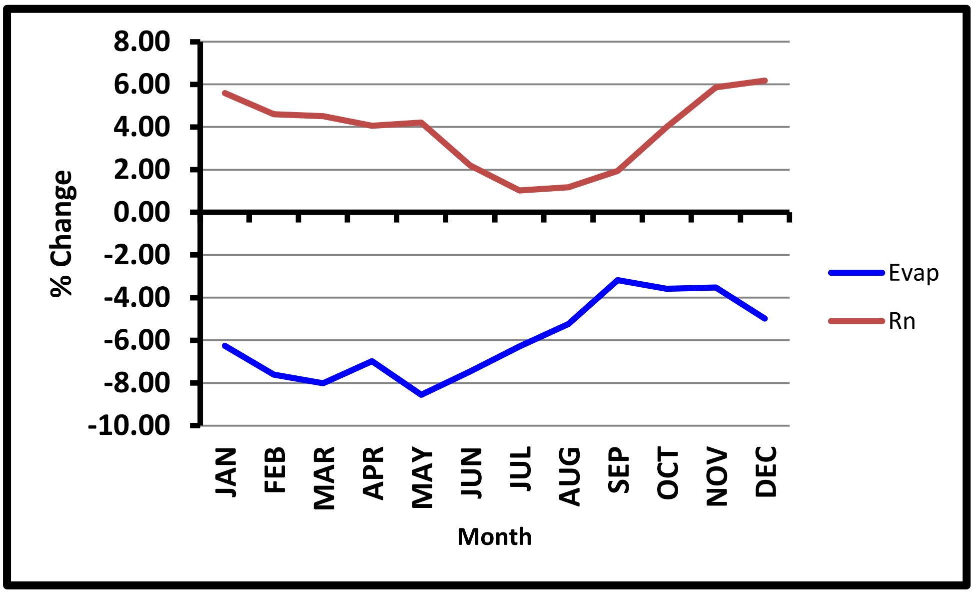


60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
% Change
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Month
Evap
Ea



0.00
-10.00
-20.00
-30.00
-40.00
-50.00
-60.00
-70.00
% Change
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Month
Evap
VPD





7.4 RESULTS FOR TEHRI REGION

7.5 COMPARISION OF RESULTS

Fig. 10. shows a comparison of change in open water surface evaporation at Udaipur and Chandigarh due to assumed 1^0 C hypothetical increase in normal temperature at these locations. It can be observed that there is a variation in the pattern of expected change at the two stations. Thus, while there is an expected increase in evaporation at Chandigarh

during February, a decrease is expected at Udaipur in this month. During June and October, a reverse situation is expected. Thus, increase is expected in evaporation at Udaipur and decrease is expected at Chandigarh during these months. The pattern of change in evaporation is same for the remaining months. Thus, there is a projected decrease in evaporation during the summer months of March, April and June as well as during the November, at both the stations. Similarly, evaporation is expected to increase during the monsoon months at both the stations.

Further, it has been observed that there is a quantitative difference in the expected variation at the two stations (Fig. 10). At Udaipur, the expected change in evaporation is much smaller during the warmer months of March, April and May. The changes are 3.12%, 3.9% and 2.19 % respectively for these months. Comparatively, the changes are much more pronounced at Chandigarh. The respective changes at Chandigarh are 9.87%, 19.72% and 18.24%. Both the stations show significant variations during the monsoon months of July to September, but changes at the semi arid station of Udaipur are much higher compared to humid Chandigarh. The expected change for the months of July, August and September are respectively 15.41%, 23.57% and 13.15% at Udaipur and respectively 11.07%, 12.7% and 6.35 % at Chandigarh. The changes at both the stations are due to expected variation in the vapour pressure deficit regime.

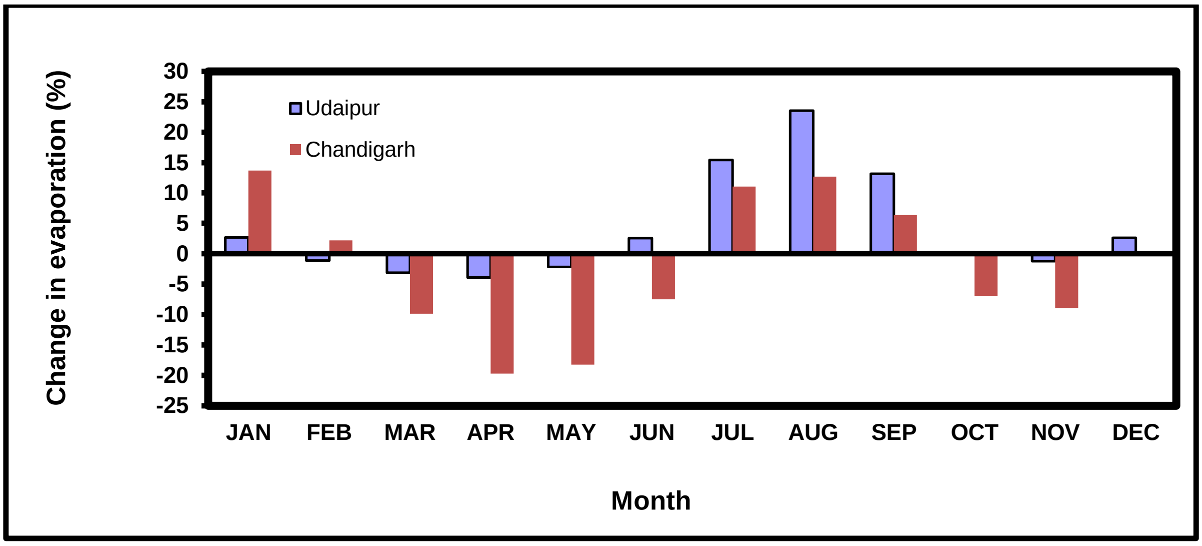


Fig 10.: Comparison of projected change in evaporation at Udaipur and Chandigarh

Table 2: Comparison of possible Impacts at Udaipur and Chandigarh

	Present range (mm/d)	Projected range (mm/d)	Range of % change
Chandigarh	**3.0 -11.0**	**3.4 - 9.0**	**-19.3 to +14.7**
Udaipur	**2.3-10.77**	**2.5-10.57**	**-3.9 to 23.6**

Table 3. R^2 between change in evaporation and change in parameters

Station	T_{max}	T_{min}	e_a	e_s	**VPD**	R_{nl}	R_n
Udaipur	**0.90**	**0.66**	**0.65**	**0.81**	**0.94**	**0.86**	**0.68**
Chandigarh	**0.94**	**0.50**	**0.87**	**0.94**	**0.91**	**0.89**	**0.94**

8.0 CONCLUDING REMARKS

In the present study, impact of global warming on future evaporation rates for Udaipur and Chandigarh region have been studied using a simple climatic variability approach wherein a hypothetical increase of 1^0C in daily mean temperature has been assumed. As a results of the projected changes in regimes of various meteorological parameters due to 1 ^0C rise in temperature, daily evaporation rates for both the study areas are expected to change. For Udaipur region evaporation is expected to rise significantly (upto 30%) during the monsoon and to some extent (upto 8%) during the winter. However, they are expected to fall by about 5% during the summer. Further, it has been observed that the changes in evaporation regime would be influenced most by the changes in the regime of VPD, followed by T_{max} and radiation regime. For Chandigarh region evaporation rates are expected to rise significantly (upto 15%) during the monsoon and winter. However, they are expected to fall by upto about 20% during the summer. Further, it has been observed that the changes in evaporation regime at Chandigarh would be influenced most by the changes in the regime of VPD.

9.0 FUTURE PALNS

The study is to be carried out for few more regions of India and the various results would be compared. At present 1 ^{0}C increase in temperature has been assumed. It is proposed to carry out the analys for 0.5 ^{0}C increase also and the results would be compared for all the regions as well as for two different assumed rates of temperatures. .

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ANNEXURE-1

APPROVED ACTIVITY SCHEDULE OF THE STUDY

S.N.	Activities	QUARTERS							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1.0	**PREPARATORY WORK**								
1.1	Selection of study area	√							
1.2	Review of Literature	√	√	√	√				
1.3	Identification of data requirement	√							
1.4	Collection and compilation of all data	√	√						
2.0	**DATA INTERPRETATION AND ANALYSIS**								
2.1	Impact of temperature rise on various meteorological parameters in different climatic settings			√	√				
2.2	Impact of temperature rise on evaporation in different climatic settings					√	√		
2.3	Comparison of variation in impact of temperature rise on evaporation of different climatic regions						√	√	
3.0	**PROJECT REPORT**								√