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Trend analysis of extreme temperature indices with spatial distribution of temperature extremes over Rajasthan region using CORDEX data

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Abstract: Extreme temperature indices over Rajasthan and its nearby area are evaluated for historical (1970-2005) and twenty-first century (2006-2099) under two emission scenarios RCP4.5 and RCP8.5 using future outputs, daily minimum and maximum temperature of regional climate model CSIRO-CCAM. In this study, non-parametric statistical tests ((Mann-Kendall test, modified Mann-Kendall, Sen's slope estimator and Pettitt t-test) are used for trend analysis. Spatial distribution of mean and extreme temperatures is also analyzed for near future (2006-2040), mid future (2041-2070) and long-term future (2071-2099). The mean minimum and maximum temperature of the study area will increase with 2.20°C (5.61°C) and 1.56°C (4.90°C) under RCP4.5 (RCP8.5) at the end of 21st century. Our results indicate a significant decreasing trend in Frost days (FD) and significant increasing trends in summer days (SD), the annual maximum of maximum temperature (Txx), annual minimum of minimum temperature (Tnn) and annual maximum of minimum temperature (Tnx) under both RCPs. Cold days (CD) and cold nights (CN) have a decreasing trend under the 21st century. A significant reduction in hot days (HD) and hot nights (HN) occurred at the rate of 0.99days/decade and 1.05days/decade under RCP8.5. In historical period annual average SD were 332.38 which will increase to 346.54 and 359.45 in the long-term future period (2071-2099) under RCP4.5 & RCP8.5 respectively. The main intent of this paper is to present spatial distribution of future extreme temperature values relative to historical and long-term trends in extreme temperature indices.

Keywords: CORDEX-SA, Extreme Temperature, Trend Analysis, Rajasthan

1. Introduction

Extreme weather and climate events in recent decades have been a worldwide issue due to their potentially serve impacts on human life, the economy and natural ecosystems (Sun et al., 2016). The 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) revealed that global annual average temperature has shown an increase of 0.85°C (0.65-1.06°C) over the period of 1800-2012(IPCC 2013). In recent decades cold nights, cold days and frost days have become less frequent, while hot nights and hot days have become more frequent over most land areas (IPCC, 2007). Extreme temperatures are changing globally together with changes in the mean temperatures and they are likely to change in the twenty-first century.

Extremes in temperature are characterized by daily temperature level exceeding tolerance limits and their frequency is of great interest in terms of human impacts (Revadekar et al., 2012). Extreme events are relatively rare and unpredictable because they do not commonly occur at a given place and season but they are highly destructive to nature and living world. A set of suitable indices describing the extremes of climate variables can be used in studying climate extremes but the difference in methodologies used limits the scope of direct comparison between studies. The World Meteorological Organization's Expert Team on Climate Change Detection and Indices (ETCCDI) recommended a suite of 27 core indices, which provides a common framework for assessing the frequency, duration, or severity of extreme temperature and precipitation worldwide (Zhang et al., 2011). There are various parametric and non-parametric methods that can be used to detect the trends in such extreme indices. Many researchers have been used various non-parametric statistical tests (Mann-Kendall test, Modified Mann-Kendall test, Sen's slope estimator test and Pettitt Mann-Whitney test) to assess the trends in climatological time series in India (Pingale et al., 2014; Gajbhiye et al., 2015; Taxak et al., 2014; Sonali P. and Kumar DN., 2013; Duhan et al., 2013) and other regions of world (Kousari et al., 2013; Tabari H and Talaee PH, 2011)

Number of studies has been carried out on temperature and its extremes indices across various part of Rajasthan (Pingale et al., 2013; Kundu et al., 2015), India (Jaswal et al., 2015; Pal I and Tabbaa AA, 2010; Dube et al., 2005) and other regions of world (Sun et al., 2016; Dashkhuu et al., 2015; Milanovic et al., 2015; Zhao et al., 2012). Results of some studies from India and other regions of the world are summarized below: -

Spatial distribution of extreme temperature was analyzed over Maharashtra and Karnataka States of India by Dhorde et al. (2016) for the period of 1969-2006. Extreme temperature indices were analyzed using percentiles. The mean temperature of the study area has been increased significantly about 0.44°C. Heat waves and cold wave analysis revealed that 50% stations registered a decrease in cold wave and increase in extremely hot days over the southern part of the study area. Trend analysis of extreme temperature events during post monsoon and winter season over Varanasi, U.P. India were analyzed by Bhatla et al. (2016) for four decades (1971-2010). They found that Cold waves frequency was large during 1971-1990 & 1991-2000 followed by significantly decreasing in the 2001-2010 decade. Jaswal et al. (2015) studied the trends of summer high-temperature days in India during 1969-2013. High-temperature days (maximum temperature >37°C) were increased by 3%, 5% and 18% in north, west and south regions respectively. North-central and east regions of India experienced a decreasing trend by 4% and 9% respectively. Jaipur city of Rajasthan has a steep increase 7.73 days/decade in summer high-temperature days during the period of 1991-2013. Kundu et al. (2015) Studied the spatial and temporal variability of climatic parameters were at Udaipur district of Rajasthan for a period of 1979-2010. Results revealed that insignificant decreasing trend and significant increasing trends were observed in maximum and minimum temperature respectively.

The spatial and temporal trend of extreme temperature and rainfall were analyzed for the 33 urban centers of an arid and semi-arid state of Rajasthan, India by Pingale et al. (2014) from 1971-2005. They found that average temperature significantly increases (at 0.01-0.05°C) for most of the urban centers. A significant increasing trend was observed in extreme annual daily minimum temperature (at 0.03-0.07°C/year) for north-eastern and western regions of Rajasthan. A significant increasing trend in extreme annual daily maximum temperature was observed (at 0.029-0.049°C) in south, east and west of Rajasthan. Punia et al. (2014) studied the temperature variability over North-West part of India for the period of 1970-2000.There was an insignificant increasing trend in maximum temperature ranged from 0.1-0.3°C/decade for four sites, Jaipur, Hisar, Churu, and Mahendragarh. In minimum temperature, significant increasing trends were observed in Jaipur, Hisar, Churu, Mahenderagarh, Shimla and Dehradun, which varied from 0.2-0.7°C/decade. Dash et al. (2007) analyzed that in India the maximum temperature has been increased by 1.2°C in West coast followed by 1°C in the north-east, 0.9°C in the western Himalaya, 0.8°C in north central, 0.6°C in north-west and east coast and the least amount of 0.5°C in the interior peninsula. There was a sharp rise in minimum temperature in last three-four decades of 19th century. Alexander et al. (2006) analyzed the frequencies of cold and hot events and have indicated that cold extremes are decreasing and warm extremes are increasing. Arora et al. (2005) revealed that India has experienced an increase in annual mean temperature by 0.42 °C, rise of 0.92 °C in the annual maximum, and a rise of 0.09 °C in minimum during the last 100 years. Changes in extreme temperature events are likely to continue in the future, and India will experience widespread warming by an increase in intensity and frequency of hot events and also with a decrease in frequency of cold events (Revadekar et al. 2012). Changes in extreme climate are not uniform over the world so to predict the changes in extremes in future, it is essential to understand the characteristics of extremes in recent past decades. Increasingly reliable regional climate change projections are available for many regions of the world due to advances in modeling and understanding of the physical processes of the climate system. Sillmann et al. (2012) analysed the comparison and performance of Coupled Model Intercomparison Project Phase 5 (CMIP5) and CMIP3 models in simulating the extreme climate indices. They found that the CMIP models represent a decreasing trend in cold spell duration over the period 1948-2005 while warm spell duration average increases from about 6 days in 1960 to 20 days at the beginning of 21st century.

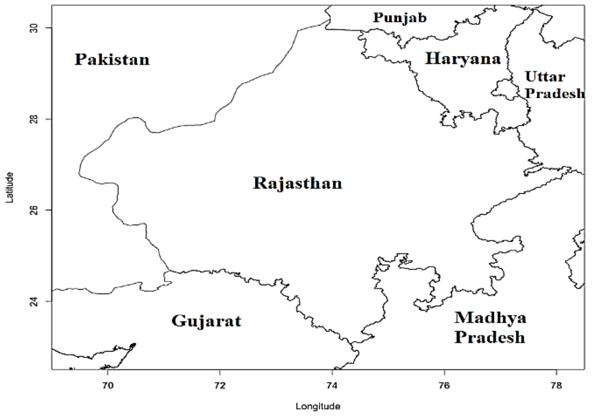
A comprehensive analysis of future projections of extreme temperature indices for Rajasthan and its nearby area still lacking. The purpose of this study was to evaluate changes in Historical and model projections of the extreme temperature indices through the long-term trend in Rajasthan and its nearby areas. Spatial distribution of temperature extreme values for near future (2006-2040), mid future (2041-2070) and long-term future (2071-2099) were also analyzed.

2. Study area and data used

Rajasthan is the largest state of India situated on its western fringe, with an area of 342,000 km2 and its climate varies from arid to semi-arid. Administratively, it is divided into 33 districts. Geographically, it extends from 23° 3.50′ to 30° 14′N latitudes and 69° 27′ to 78° 19′E longitude (Fig. 1). The climate in Rajasthan is characterized by low and erratic rainfall, extremes of diurnal and annual temperatures, low humidity and high wind velocity. There is also the Great Indian Desert (Thar Desert) in the north-western part of Rajasthan, which is covering almost 70% of the state. The study area is mainly focused on Rajasthan with some nearby regions of Madhya Pradesh, Uttar Pradesh, Gujarat, Punjab, Haryana, and Pakistan. The Tropic of Cancer passes through the southern districts of the state resulting in high temperatures during the summer. The summer temperature averages around 26º C to 46 ºC and winter temperatures range from 8 ºC to 28 ºC (Roy A.D., 2015)

Daily gridded maximum temperature (TX) and minimum temperature (TN) for historical (1971-2005) and future (2006-2100) output from regional climate model CSIRO-CCAM were obtained from CORDEX (Coordinated Regional Downscaling Experiment) program. CORDEX was developed by the World Climate Research Program (WCRP) with the aim of developing an international coordinated framework to generate improved regional climate change projections worldwide for input into impact and adaptation studies. Two future emission scenarios RCP4.5 and RCP8.5 were considered over the twenty-first century.

Figure 1. Map of the study area (Mainly focus on Rajasthan)



3. Methodology

3.1 Extreme temperature indices

One of the main concerns while assessing extreme climate events is properly defining extreme indices for climate variables (temperature and precipitation). There are various definitions for extreme indices which vary with different study regions. There are 27 extreme indices recommended by the Expert Team on Climate Change Detection Indices (ETCCDMI) for climate variables. These extreme indices can be classified as relative indices, relative indices and extreme value indices. Absolute indices are defined by an absolute value while Relative indices are defined by higher and lower extreme of climate variables. Extreme value indices are defined by monthly or annually maximum (minimum) of climate variables. However, we examine only temperature extremes and use a set of ten indices to explore possible changes in temperature extremes in the future. All the 10 extreme temperature indices used in this study are summarized in Table 1. Such extreme temperature indices were also used to assess the changes in extreme temperature events in India by Revadekar et al. (2012) and Panda et al. (2014). More detail information of these extreme indices can be found by Alexander et al. (2006) or from http://etccdi.pacificclimate.org/list_27_indices.shtml. SU25 and FD0 respectively defined as the annual summer days (TX≥25° C) and frost days (TN≤0°C). TXN, TNN, TXX, and TNX are the annual lowest maximum temperature, lowest minimum temperature, highest maximum temperature and highest minimum temperature respectively. Tx10thp and Tn10thp are indices representing the percentage of low-temperature days (cold days) and low- temperature nights (cold nights) in a year with daily maximum and minimum temperature lower than the 10th percentile of maximum and minimum temperature, respectively. Tx90thp and Tn90thp indices are the measures of the percentage of high-temperature days (hot days) and nights (hot nights) in a year having daily maximum and minimum temperature greater than the 90th percentile of maximum and minimum temperature, respectively.

Table 1: Definition of extreme temperature indices used in this study

Abbreviation name	Description		Unit
	Absolute indices		
FD	Frost days	TN< 0 °C	Day
SU	Summer Days	TX> 25°C	Day
	Relative indices		
Tx90p	Hot days (HD)	Percentage of days when TX>90th percentile of TX	Day
Tn90p	Hot nights (HN)	Percentage of days when TN>90th percentile of TN	Day
Tx10p	Cold days (CD)	Percentage of days when TX<10th percentile of TX	Day
Tn10p	Cold nights (CN)	Percentage of days when TN<10th percentile of TN	Day
	Extreme value indices		
TXX	Maximum TX	Annual maximum value of TX	°C
TXN	Minimum TX	Annual minimum value of TX	°C
TNN	Minimum TN	Annual minimum value of TN	°C
TNX	Maximum TN	Annual maximum value of TN	°C

3.2 Trend analysis

All chosen indices were calculated on an annual basis. The resulting annual frequency series of these indices were analyzed through non-parametric Mann-Kendall (MK) and Modified Mann-Kendall (MMK) test with Sen's slope estimator to detect the monotonic trends, magnitude, and their statistical significance. The annual Sen's slope of trends was converted into slope per decade. A trend was considered to be statistically significant at the 95% significance level (p-value <0.05) (Mann, 1945; Kendall, 1975; Sen, 1968). Mann-Whitney Pettitt's t-test was used for shift detection in the series. These methods are widely used because they neither assume a specific distribution for the data nor sensitive to the outliers. However, possible autocorrelation in the time series may render the test of statistical significance of a trend unreliable is taken into account by MMK test. Detection of a trend is an indication of non-stationary climate which could have arisen due to change in mean or its variability.

4. Results and discussions

Spatial distribution of mean, low and higher extreme temperature with trends in extreme temperature indices for historical and 21st century are discussed below-

4.1 Spatial distribution of extremes temperature –

Spatial distribution of changes in mean, lower and higher extremes of temperature are analyzed for near future (2006-2040), mid future (2041-2070) and long-term future (2071-2099) periods relative to the historical period (1970-2005) under RCP4.5 and RCP8.5.

4.1.1 Ninetieth percentile of maximum temperature (Tx90thp) -

The spatial distribution of 90th percentile of maximum temperature for the historical period (1970-2005) with changes in Tx90thp for near future, mid future and long-term future of 21st century projected by RCP4.5 and RCP8.5 is shown in figure 2. In historical period Tx90thp was high in North-West of the study area and small in central, South of Rajasthan, western Gujrat, and Madhya Pradesh. The range of Tx90thp temperature was 36.93-47.31°C (average 43.38°C) in the historical period which will increase with 1.28-2.46°C(2.14°C) and 3.75-5.66°C(5.17°C) for RCP4.5 and RCP8.5 at the end of 21st century. Results show that near future, mid future, and long-term futures represent a similar distribution of Tx90thp changes with less increase less in South-West (Gujrat) and higher in North and North-west (Thar Desert) of study area under both RCPs.

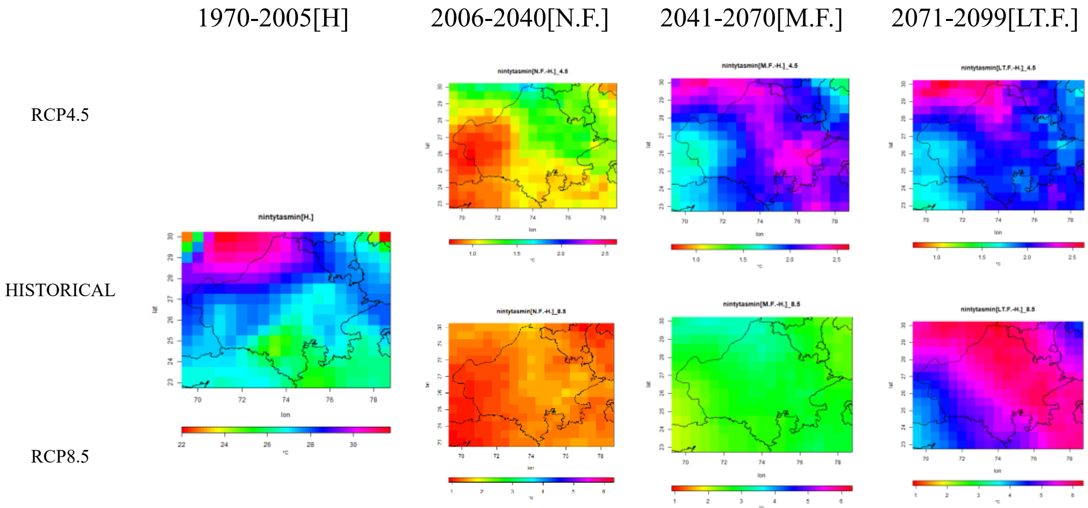


Figure 3. Spatial distribution of Tn90thp for Historical[H], near future[N.F.], mid future[M.F.] and long-term future[LT. F.] period under RCP4.5 and RCP8.5

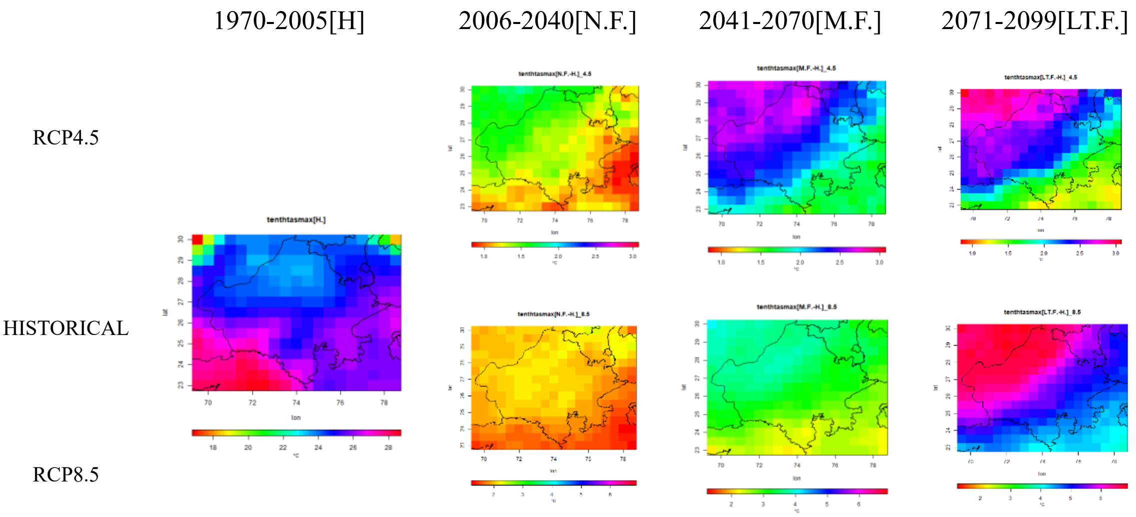


Figure 4. Spatial distribution of Tx10thp for Historical[H], near future[N.F.], mid future[M.F.] and long-term future[LT. F.] period under RCP4.5 and RCP8.5

4.1.2 Ninetieth percentile of minimum temperature (Tn90thp) -

Figure 3 shows the spatial distribution of 90th percentile of daily minimum temperature (Tn90thp) for the historical and 21st century (N.F., M.F., and LT.F.). The distribution of Tn90thp in historical period shows the higher values in the Thar Desert, Punjab and Uttar Pradesh and low values in South –East of Rajasthan, Madhya Pradesh and Gujrat. The Tn90thp in historical period varied between 22.07-31.64°C (27.56°C). It will increase with 1.59-2.61°C (2.00°C) and 3.81-6.28°C (5.38°C) under RCP4.5 and RCP8.5 respectively at the end of 21st century. The distribution of Tn90thp shows that Western Rajasthan and Gujrat will have small change than other areas in all study periods of the 21st century. The average increase in near future and mid future will be 0.98°C (1.37 °C) and 2.16°C (2.67°C) for RCP4.5 (RCP8.5). South- East of Rajasthan have the higher changes in mid future than long-term future period under RCP4.5.

4.1.3 Ninetieth percentile of minimum temperature (Tn90thp) -

The Spatial variation of the 10th percentile of daily maximum temperature for historical and its changes in the 21st century using future projections of RCP4.5 and RCP8.5 are shown in figure 4. The Tx10thp temperature was higher in the south-western region (Gujrat) in the historical period and varied between 16.88-28.62°C (average 25.30°C) in the study area. It will increase with 1.18-3.05°C (2.13°C) and 3.88-6.84°C (5.52°C) for RCP4.5 and RCP8.5 respectively at the end of the 21st century. The average increase of 10th percentile in near future and mid future will be 1.31°C (1.90°C) and 2.20°C (3.13°C) for RCP4.5 (RCP8.5) respectively. The Thar Desert area in North-west of the study area will have a large increase of temperature which will be low towards the south-East of the study area (Madhya Pradesh) in near future, mid future and long-term future period.

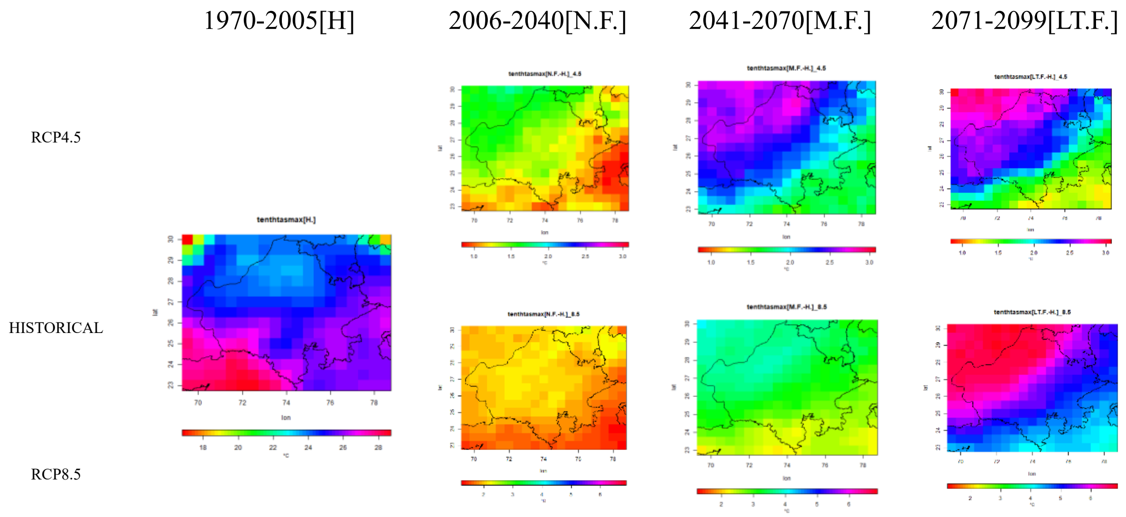


Figure 4. Spatial distribution of Tx10thp for Historical[H], near future[N.F.], mid future[M.F.] and long-term future[LT. F.] period under RCP4.5 and RCP8.5

4.1.4 Tenth percentile of Tn (Tn10thp)

Spatial distribution of 10th percentile of daily minimum temperature for historical and future projections of RCP4.5 and RCP8.5 (near future, mid future and long-term future) is shown in figure 5. The range of 10th percentile temperature in historical period was 1.84-11.72°C (average 7.83°C) and varied as low temperature at the north (Punjab, Haryana, Thar desert and north & central Rajasthan) to higher at the south (Gujrat and M.P.) of the study area. This range of minimum temperature will increase with 2.21-3.56°C (3.08°C) and 5.58-7.95°C (7.20°C) for RCP4.5 and RCP8.5 at the end of 21st Century. The average increase of Tn10thp in near future and mid future will be 1.14°C (1.90°C) and 3.00°C (3.93°C) for RCP4.5 (RCP8.5) respectively. In long-term future of RCP8.5 increase in temperature will be more than two times than RCP4.5. Tn10thp will be higher in the south-east of the study area in all study periods of the 21st century (N.F., M.F. and LT.F.) under both RCPs.

4.1.5 Mean of daily maximum temperature (Txmean)

Spatial distribution of the mean of maximum temperature for historical and future projections of RCP4.5 and RCP 8.5 are represented in figure 6. Txmean was varied between 26.63-37.35°C (average 34.38°C) in the historical period (1970-2005). At the end of the 21st century it will increase to 0.94-2.30°C(1.56°C) and 4.14-5.59°C(4.90°C) under RCP4.5 and RCP8.5 respectively. In historical period it was higher in the north-west and low in the south-east (Madhya Pradesh) of the study area. In near future changes in Txmean will be less in east and North-East (Utter Pradesh, Haryana, east Rajasthan and some area of Madhya Pradesh) of the study area. The magnitude of temperature change will be small in East and South-East (which will higher towards North-West (Thar Desert) of the study area at the end of

21st century. Results show that the temperature change will be higher in mid future than long-term future in whole study area except some North-Western area.

4.1.6 Mean of minimum temperature (Tnmean)

Mean of minimum temperature (Tnmean)- Spatial distribution of the mean of minimum temperature for historical and future projections under two RCPs are shown in figure 7. In historical period Tnmean was 13.25-21.11°C(19.48°C) which will increase with 1.95-2.47°C(2.20°C) and 4.98-6.15°C(5.61°C) under RCP4.5 and RCP8.5 respectively at the end of 21st century. In historical period it was low in central Rajasthan and North-East (Punjab, Haryana and some area of U.P.) and highest in the south-west of study area (Gujrat). But at the end of the 21st century, the mean temperature will be highest in North and North-West of the study area. The average increase in temperature in near future and mid future will be 1.08°C (1.14°C) and 2.12°C (3.01°C) for RCP4.5 and RCP8.5 respectively.

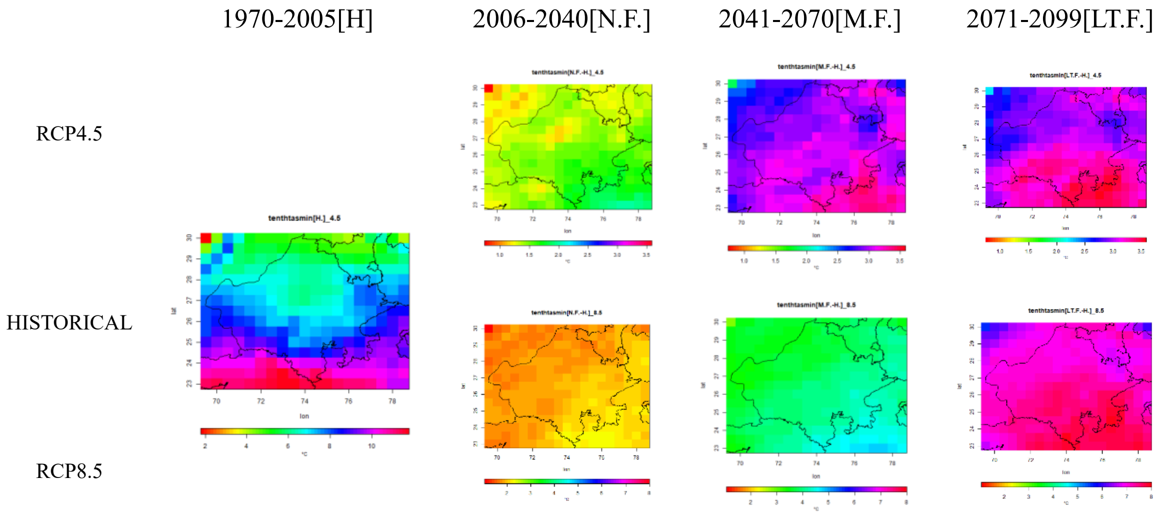


Figure 5. Spatial distribution of Tn10thp for Historical[H], near future[N.F.], mid future[M.F.] and long-term future[LT. F.] period under RCP4.5 and RCP8.5

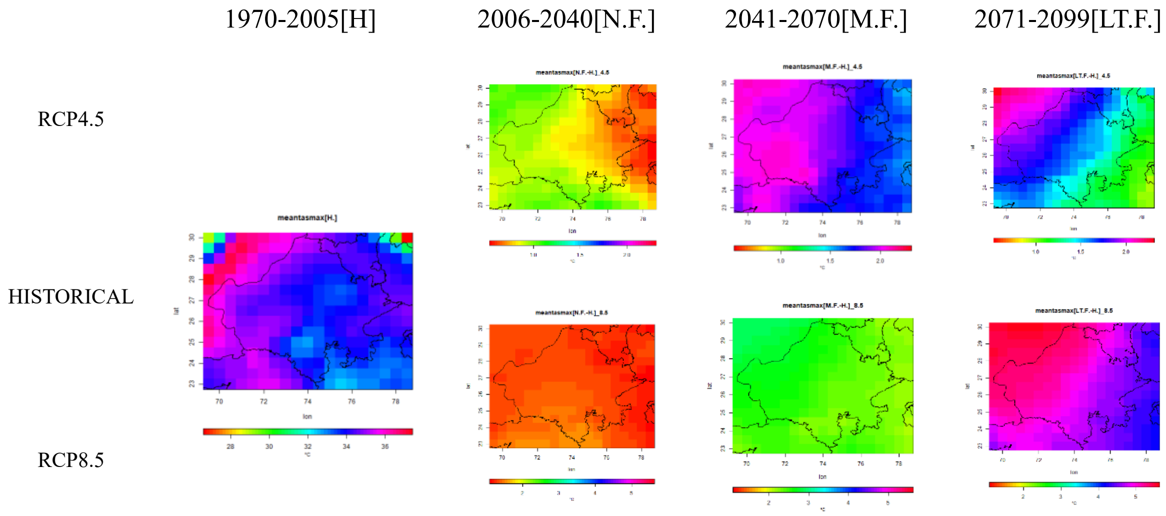


Figure 6. Spatial distribution of Txmean for Historical[H], near future[N.F.], mid future[M.F.] and long-term future[LT. F.] period under RCP4.5 and RCP8.5

4.2 Trend analysis of extreme temperature indices- Trend analysis for annual time series of all extreme temperature indices are carried out using non-parametric tests for Historical (1970-2005) and three different time periods of the 21st century (near future (2006-2040), mid future (2041-2070) & long-term future (2071-2099)) under future projections of RCP4.5 & RCP8.5. The long-term trend of all extreme temperature indices was also analyzed for the period of 2006-2099. The results of MK/MMK test, Sen's slope estimator test and Pettitt t-test for all extreme temperature indices are discussed below-

4.2.1 Absolute indices (FDs and SDs)

Figure 8 (a) and (b) shows the annual time series curves of frost days and summer days for RCP4.5 and RCP8.5 (2006-2099) with historical (1970-2005) period. The straight red, green, blue lines indicate linear trend lines for historical, RCP4.5 and RCP8.5 respectively.

The annual number FD was nearly 2-3 days in study area calculated by the average of the number of FDs on all grids. There is decreasing trend for historical, RCP4.5 and RCP8.5 (2006-2099) determined by MK/MMK test. MK/MMK Z/Zc* values for FD are shown in table no. 2. FDs have significant decreasing trend for both RCPs (2006-2099) but there is an insignificant increasing trend in the long-term future period (2071-2099) under RCP4.5. The Sen's slope was -0.07/decade (-9.06 % change/decade) for historical period (1970-2005) which will change to -0.012/decade (-4.75%) and -0.010/decade (-6.68%) for RCP4.5 & RCP8.5 respectively as shown in table no. 2 and 3. The most probable change point calculated by Pettitt t-test represent the major change point which is 1997, 2043 and 2062 for historical, RCP4.5 and RCP8.5 respectively as shown in table no 5. Time series of FDs represent that there is no FDs after 1962(change point) in RCP8.5.

Summer days (SDs) are the days having daily maximum Temperature (Tx) more than 25°C. The annual time series of SD was created by the average of a number of summer days on all grids of the study area. The MK/MMK test results show (table no. 2) significant increasing trend in SD for the historical period (1970-2005) and both RCPs (2006-2099). RCP4.5 represent an insignificant decreasing trend in SDs for the long-term future (2071-2099) period with the rate of -0.62days/decade. Sen's slope results (table no. 2 & 3) represent that SD has been increased with the rate of 5.07days/decade (1.53%/decade) in the historical period (1970-2005). SDs will increase with the rate of 1days/decade (0.29%/decade) and 2.02/decade (0.57%/decade) in the period of 2006-2099 under RCP4.5 and RCP8.5 respectively. In historical period annual average SDs were 332.38 which will increase to 346.54 and 359.45 under RCP4.5 & RCP8.5 (2006-2099) respectively. The major change point was 1986 in the historical period, 2031 and 2057 for future projections of RCP4.5 and RCP8.5 respectively.

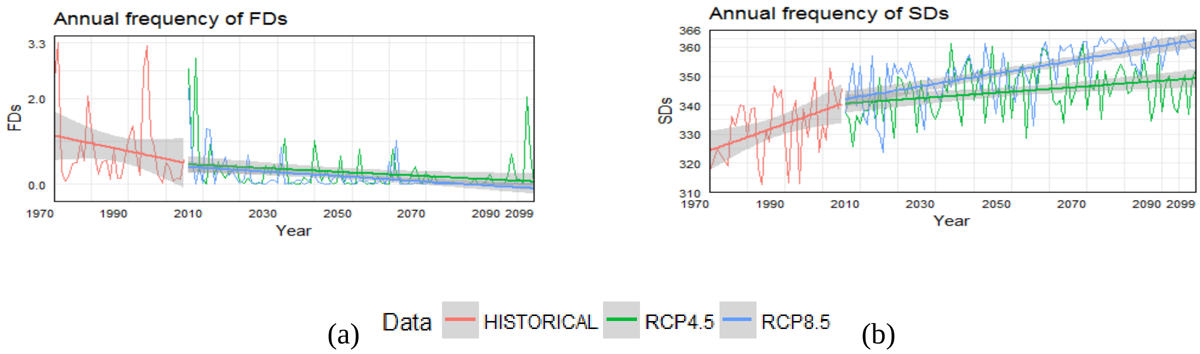


Figure 8: Annual time series curves of frost days (a) and summer days (b) for RCP4.5 and RCP8.5 (2006-2099) with historical (1970-2005) period.

Table no 2- Results of Mann-Kendall/Modified Mann-Kendall* test (Z/Zc* values)

Mann-Kendall/Modified Mann-Kendall Test Z/Zc*										
SN	**Indices**	**Historical**	**RCP4.5**				**RCP8.5**			
		1970-2005 (H.)	**2006-2040 (N.F.)**	**2041-2070 (M.F.)**	**2071-2099 (LT.F.)**	**2006-2099**	**2006-2040 (N.F).**	**2041-2070 (M.F.)**	**2071-2099 (LT.F.)**	**2006-2099**
1	FD	-0.81*	-1.75*	-0.17*	1.06	**-2.86***	**- 2.33**	-1.41	-1.48	**-2.50***
2	SD	**2.65**	**2.73**	0.21	-0.32	**2.99**	1.65*	**3.14**	0.64	**8.50***
3	HD	**4.33***	1.56	**2.32**	0.3*	0.93	**2.70**	**5.93***	**3.51**	**2.29***
4	HN	**2.96**	1.76	**2.18**	0.98*	0.74	**2.07**	**3.14***	**3.55**	**1.97***
5	CD	**-3.17**	**-2.84**	-0.66*	-0.24*	-0.88	**-2.2**	**-3.09***	-1.19*	-1.75*
6	CN	**-2.79**	**-4.11***	**-2.75**	1.03*	-0.95*	**-3.58**	**-3.60***	**-3.71**	**-1.80***
7	TXX	**2.26***	**2.12***	1.05*	1.41	**2.94***	1.65	**5.76***	**4.72***	**9.94***
8	TXN	0.53	0.88	1.07	-1.52	1.80	1.62	1.36	1.78	**5.67***
9	TNN	0.67	**1.93**	0.99*	-0.96	**17.88***	1.65	1.5	1.37	**5.23***
10	TNX	1.19	**4.26***	**2.34***	0.18*	**3.45***	**2.73**	**3.28**	**2.48***	**11.60***

Bold values show the significant trend at 95% level. MMK values with " * " represents the presence of autocorrelation in time series. Positive /negative Z/Zc* value indicates increasing/decreasing trend.

Table no. 3 – Results of Sen's Slope estimator test for all extreme temperature indices (FD, SD, HD, HN, CD & CN in Days/Decade and TXX, TXN, TNN & TNX in °C/Decade)

SN	Indices	Historical	RCP4.5				RCP8.5			
		1970-2005 (H.)	2006-2040 (N.F.)	2041-2070 (M.F.)	2071-2099 (LT.F.)	2006-2099	2006-2040 (N.F).	2041-2070 (M.F.)	2071-2099 (LT.F.)	2006-2099
1	FD	-0.07	-0.1	0	0.01	-0.012	-0.09	-0.01	0	-0.010
2	SD	5.07	3.69	0.48	-0.62	1	2.03	5.05	0.5	2.02
3	HD	4.48	3.7	6.3	0.51	0.40	4.9	11.13	8.78	0.99
4	HN	8.22	3.16	5.31	3.13	0.36	4.5	14.8	12.83	1.05
5	CD	-6.28	-5.07	-1.4	-0.4	-0.4	-3.97	-12.5	-6.12	-1.06
6	CN	-3.9	-3.07	-4.1	3.44	-0.33	-8.45	-8.75	-9.71	-0.90
7	TXX	0.57	0.47	0.14	0.37	0.20	0.38	1.27	0.63	0.66
8	TXN	0.27	0.47	0.75	-1.1	0.20	0.68	0.83	1.34	0.74
9	TNN	0.18	0.47	0.35	-0.48	0.27	0.6	0.61	0.51	0.57
10	TNX	0.26	0.5	0.46	0.04	0.20	0.5	1.27	1	0.74

Table no. 3 – Results of percentage changes in all extreme temperature indices (FD, SD, HD, HN, CD & CN in Days/Decade and TXX, TXN, TNN & TNX in °C/Decade)

SN	Indices	Historical	RCP4.5				RCP8.5			
		1970-2005 (H.)	2006-2040 (N.F.)	2041-2070 (M.F.)	2071-2099 (LT.F.)	2006-2099	2006-2040 (N.F).	2041-2070 (M.F.)	2071-2099 (LT.F.)	2006-2099
1	FD	-9.06	-19.31	0.00	4.43	-4.75	-29.97	-6.55	0.00	-6.68
2	SD	1.53	1.08	0.14	-0.18	0.29	0.59	1.43	0.14	0.57
3	HD	12.08	10.09	17.23	1.41	1.10	13.41	30.48	24.01	2.70
4	HN	21.42	8.64	14.55	8.58	0.99	12.29	40.64	35.14	2.88
5	CD	-17.93	-13.89	-3.81	-1.06	-1.10	-10.88	-34.21	-16.76	-2.91
6	CN	-11.40	-8.61	-11.33	9.51	-0.92	-23.52	-24.11	-26.60	-2.48
7	TXX	1.07	0.87	0.24	0.66	0.37	0.68	2.23	1.06	1.17
8	TXN	3.49	5.05	6.88	-10.37	1.94	7.12	7.13	9.59	6.40
9	TNN	4.26	15.85	21.24	-37.80	13.30	23.63	49.12	43.11	59.17
10	TNX	0.70	1.30	1.18	0.10	0.50	1.29	3.18	2.29	1.85

Table no. 5 Results of Pettitt t-test gives most probable Changepoint (T) for all extreme temperature indices

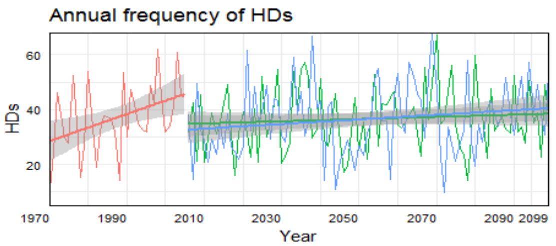
SN	Indices	Historical	RCP4.5				RCP8.5			
		1970-2005 (H.)	2006-2040 (N.F.)	2041-2070 (M.F.)	2071-2099 (LT.F.)	2006-2099	2006-2040 (N.F).	2041-2070 (M.F.)	2071-2099 (LT.F.)	2006-2099
1	FD	1997	2019	2060	2091	2043	2022	2062	2086	2062
2	SD	1986	2019	2060	2086	2031	2016	2057	2084	2057
3	HD	1988	2032	2052	2074	2052	2020	2053	2082	2053
4	HN	1988	2032	2053	2093	2032	2020	2053	2086	2058
5	CD	1986	2019	2055	2086	2019	2016	2057	2086	2057
6	CN	1984	2031	2055	2086	2062	2020	2058	2085	2020
7	TXX	1984	2015	2056	2079	2041	2019	2052	2087	2052
8	TXN	2000	2020	2053	2091	2053	2022	2062	2090	2062
9	TNN	1997	2019	2053	2091	2044	2022	2062	2086	2062
10	TNX	1995	2015	2059	2078	2049	2020	2058	2080	2058

4.2.2 Relative indices (HD, HN, CD and CN)

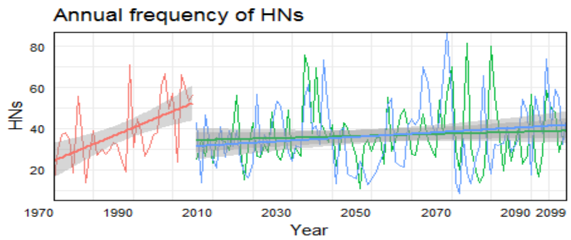
Annual time series of hot days (HD) with linear trend line for the historical and 21st century is shown in figure 9 (a). HD are warm days calculated as the days having the maximum temperature greater than the 90th percentile of daily maximum temperature (Tx). HD time series were calculated by averaging the number of HD on all grids in the study area. MK/MMK test results are shown in table no. 2. HDs have a significant increasing trend in historical (1970-2005) and RCP8.5 (2006-2099) but insignificant under RCP4.5 (2006-2099). RCP8.5 also have significant trends in all three-study period of the 21st century but RCP4.5 have only in 2041-2070 period. The Sen's slope values are 4.48days/decade (12.08%/decade), 0.40days/decade (1.10%/decade) and 0.99days/decade (2.70%/decade) for historical period (1970-2005), RCP4.5 and RCP8.5 (2006-2099) respectively as shown in table no. 3. The rate of change of HDs is higher in mid future (2041-2070) for both RCPs. The change point in historical time series of HDs was 1988. For RCP4.5 and RCP8.5, the most probable change point year will be 2052 and 2053 respectively as shown in table no. 5. The 90th percentile of Tx will increase with 1.63-2.38°C and 4.93-5.64°C at the end of the 21st century for RCP4.5 and RCP8.5 respectively.

HN are warm nights represented by the days have the minimum temperature greater than the 90th percentile of daily minimum temperature (Tn). Figure 9 (b) shows the annual time series of HN with linear trend line for the historical and 21st century under two RCPs. HN appear to have significant increase for historical and RCP8.5 (2006-2099) while RCP4.5 (2006-2099) have insignificant one as shown in table no. 2. The trend is significant in near, mid and long-term future for RCP8.5 but in RCP 4.5 only mid future period have a significant trend. The rate of changes is given in table no. 3 and 4 which are as 8.22days/decade (21.42%/decade), 0.36days/decade (0.99%/decade) and 1.05days/decade (2.88%/decade) for historical, RCP4.5 and RCP8.5 respectively. Major changes in HNs will occur in the mid future with the rate of 5.31days/decade and 14.8days/decade. Major change points for historical, RCP4.5 and RCP8.5 are 1988, 1932 and 1958 shown in table no. 5.

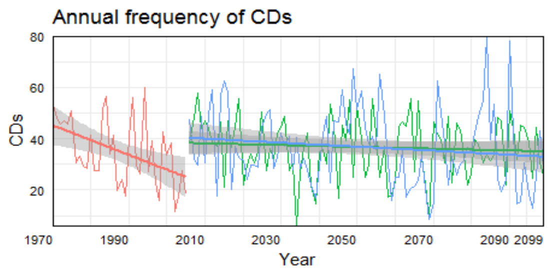
CD annual time series calculated by averaging the CD of all grids in the study area with linear trend line in shown in figure 9 (c). MK/MMK test results represent that there is decreasing trend for the historical period (1970-2005) as well as for both RCPs (2006-2099) as shown in table no. 2. CD decreases with the rate of 6.28days/decade (17.93%/decade), 0.4days/decade (1.10%/decade) and 1.06day/decade (2.91%/decade) for historical, RCP4.8 and RCP8.5 respectively shown in table no. 3 and 4. Sen's Slope is higher in near future for RCP4.5 while in mid future for RCP8.5. The change point (table no 5) for the Historical period was 1986. The RCP4.5 and RCP8.5 have the change point in near future 1919 and mid future 1957.



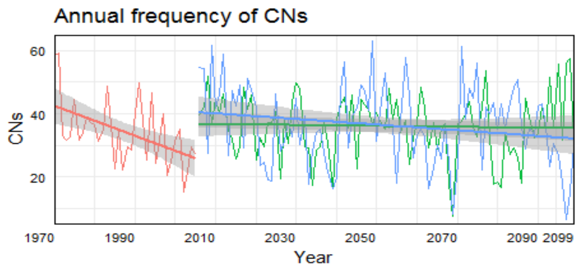
(a)



(b)



(c)



(d)

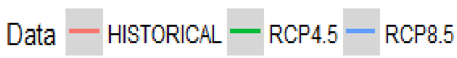


Figure 9: The annual time series curves of hot days (a), hot nights (b), cold days (c) and cold nights (d) for RCP4.5 and RCP8.5 (2006-2099) with historical (1970-2005) period.

CN are also appeared to decrease in the future projection of RCP4.5 and RCP8.5 similar to the historical period. CN have significant decreasing trend for the historical period (1970-2005) and RCP8.5 (2006-2099) as shown in figure 9 (d). MK/MMK test results Z/Zc* values are shown in table no. 2. Near future, mid future and long-term future period also have significant decreasing trend for both RCPs except long-term future for RCP4.5 with an insignificant increasing trend. Sen's slope test results table no 3 represents the rate of change per decade. The rate of change is -3.90days/decade for historical, -0.33 days/decade for RCP4.5 and -0.90 days/decade for RCP8.5. Sen's slope percentage changes are shown in table no. 4. Pettitt t-test shows the most probable change points for historical and both RCPs in table no 5. The major change points are 1984, 1962 and 1920 for historical, RCP4.5 and RCP8.5 respectively.

4.2.3 Extreme value indices (TXX, TXN, TNX and TNN)

TXX is the annual maximum of maximum temperature. It is calculated as the annual maximum of maximum temperature at all the grids of the study area. It has a significant increasing trend for the historical period (1970-2005) and both RCPs (2006-2099) as shown in figure 10 (a). MK/MMK Z/Zc values are shown in table no. 1. Near future of RCP4.5, mid future and long-term future of RCP8.5 also have significant increasing trends. In historical period (1970-2005), it was increased by 0.57°C/decade (1.07%/decade) (0.029-0.049°C/year according to Pingale et al., 2014) as shown in table number 3. The rate of change appeared to be 0.20°C/decade (0.37%/decade) and 0.66°C/decade (1.17%/decade) for RCP4.5 and RCP8.5 respectively. The rate of change is higher in near future (0.47°C/decade) for RCP4.5 and in mid future (1.27°C/decade) for RCP8.5. Major changes in historical period occurred after the year of 1984 shown in table no. 5. Major change points of TXX will be 2041 and 2052 for RCP4.5 and RCP8.5 (2006-2099).

TXN is the annual minimum of maximum temperature and the annual time series for the study area is calculated as the annual minimum of maximum temperature of all grids of the study area. Annual time series trend plot of TXN is shown in figure 10 (b). MK.MMK test results Z/Zc* values are shown in table 2. There was an increasing trend in the historical period and it will continue to increase in 21st century except for long term future period of RCP4.5 shows an insignificant decreasing trend. A significant increasing trend was found only for RCP8.5. TXN have been increased with the rate of 0.27°C/decade (3.49%/decade) in the historical period and it will continue to increase with 0.20°C/decade (1.94%/decade), 0.74°C/decade (6.40%/decade) for RCP4.5 and RCP8.5 as shown in table 3 & 4. The long-term future period shows larger percentage change as compared to near future and mid future for both RCPs. The most probable change points shown in table 5, will be 2053 and 2062 for RCP4.5 and RCP8.5.

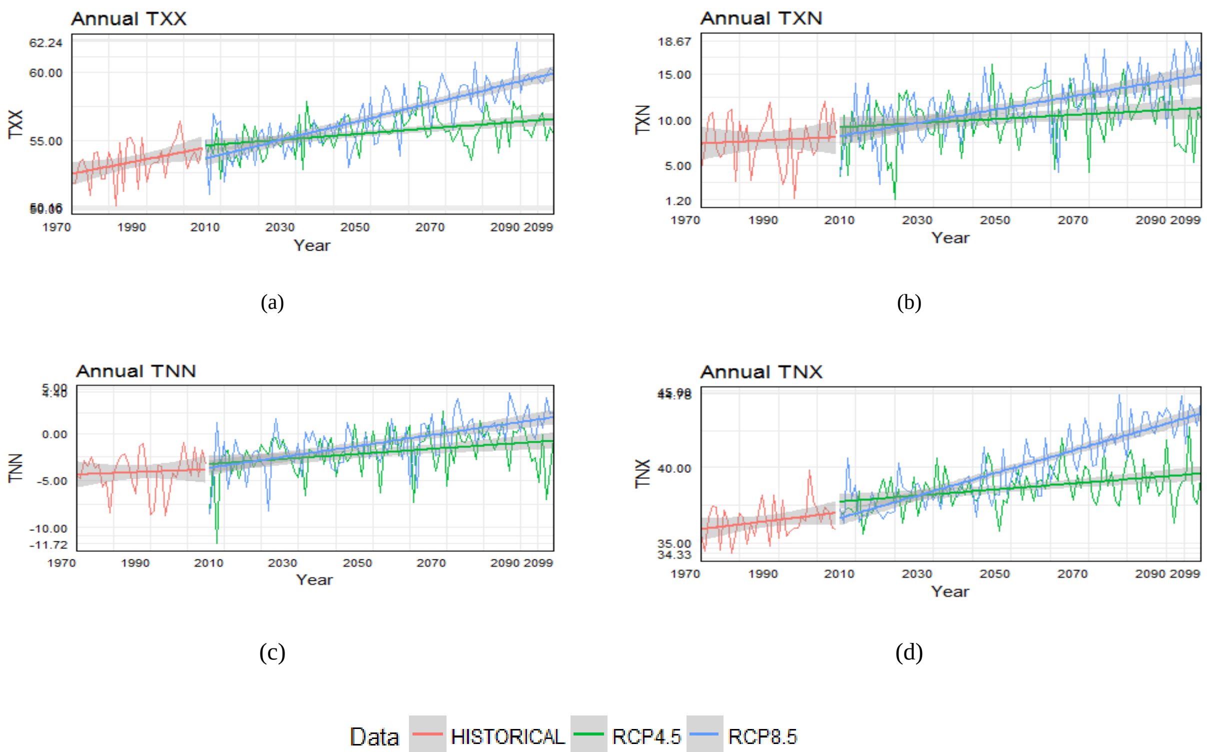


Figure 10: the annual time series curves of TXX (a), TXN (b), TNN (c) and TNX (d) for RCP4.5 and RCP8.5 (2006-2099) with historical (1970-2005) period.

TNN is the annual minimum of minimum temperature and its time series is calculated as the annual minimum of minimum temperature among all grids in the study area as shown in figure 10 (c). MK/MMK Z/Zc* values are shown in table no. 2. It has an insignificant increasing trend for historical period and appeared to significantly increase in the 21st century for both RCPs (2006-2099). The long-term future period has an insignificant decreasing trend. The Sen's slope values and percentage changes are shown in table no. 3 and 4 respectively. The rate of change increases from 0.18°C/decade (4.26%/decade) in historical period to 0.27°C/decade (13.30%/decade) and 0.57°C/decade (59.17%/decade) for RCP4.5 and RCP8.5 respectively. Pettitt t-test results (table no. 5) revealed that the most of the changes in historical period occurred after 1997. Major change points for 21st Century will be 2044 and 2062 for RCP4.5 and RCP8.5 respectively.

TNX is the annual maximum of minimum temperature calculated by annually maximum of minimum temperature among all grids in the study area. Time series plot of TNX is shown in figure 10 (d) with linear trend lines for the historical and 21st century under RCP4.5 and RCP8.5. It has an increasing trend for historical and both RCPs. Except for historical and long-term future period of RCP4.5 trends were significant for all study periods. Sen's slope was very high with 0.74°C/decade (1.85%/decade) for RCP8.5 as compared to 0.20°C/decade (0.50%/decade) and 0.26°C/decade (0.70%/decade) for RCP4.5 and historical period respectively as shown in table no. 3 and 4. Most probably change points in TNX time series in the 21st century will be 2049 and 2058 under RCP4.5 and RCP8.5 (2006-2099) respectively. Pettitt t-test results show in table no. 5 the most probable change point was 1995 in the historical period.

5. Conclusion

In this study, 10 extreme temperature indices over Rajasthan and its nearby area were analysed to detect the trends and its magnitude for historical (1970-2005) and 21st century under RCP4.5 and RCP8.5. Spatial distribution of change in mean, high (90th percentile) and low (10th percentile) temperature extremes for near future (2006-2040), mid future (2041-2070) and long-term future (2071-2099) periods relative to historical period (1970-2005) are also analysed. Spatial distribution of mean and extreme temperature shows warming over study area for the 21st century. Positive trends were observed on SD, HN, HD, TXX, TXN, TNN and TNX whereas negative trend was found FD, CD and CN indices. The following conclusions were drawn: -

1. The mean of daily minimum (Tnmean) and maximum (Txmean) temperature shows an increasing trend over entire study area and the average increase at the end of the 21st century will be 2.20°C (5.61°C) and 1.56°C (4.90°C) respectively under RCP4.5 (RCP8.5) relative to historical temperature. In historical period Tnmean was highest in the south-west of study area (Gujrat) but at the end of the 21st century, it will be highest in North and North-West of the study area. The magnitude of Txmean change will be small in East and South-East which will higher towards North-West (Thar Desert) of the study area at the end of 21st century.
2. The ninetieth percentile of daily maximum temperature (Tx90thp) varied as 36.93-47.31°C(average 43.38°C) in the historical period which will increase with 1.28-2.46°C(2.14°C) and 3.75-5.66°C(5.17°C) for RCP4.5 and RCP8.5 at the end of 21st century. Near future, mid future and long-term futures results represent a similar distribution of Tx90thp changes with less increase in South-West (Gujrat) and higher in North and North-west (Thar Desert) of study area under both RCPs. The ninetieth percentile of minimum temperature (Tn90thp) in historical period varied between 22.07-31.64°C (27.56°C) and it will increase with 1.59-2.61°C(2.00°C) and 3.81-6.28°C(5.38°C) under RCP4.5 and RCP8.5 respectively at the end of 21st century. The distribution of Tn90thp shows that Western Rajasthan and Gujrat will have small change than other areas in all study periods of the 21st century. The average increase in near future and mid future will be 0.98°C (1.37 °C) and 2.16°C (2.67°C) for RCP4.5 (RCP8.5). South- East of Rajasthan have the higher changes in mid future than long-term future period under RCP4.5.
3. The tenth percentile of maximum temperature (Tx10thp) in historical period varied between 16.88-28.62°C (average 25.30°C) in the study area. The average increase in Tx10thp in near future, mid future and long-term future will be 1.31°C (1.90°C), 2.20°C (3.13°C) and 2.13°C(5.52°C) for RCP4.5 (RCP8.5) respectively. The Thar Desert area in North-west of the study area will have a large increase of temperature which will be low towards the south-East of the study area (Madhya Pradesh) in near future, mid future and long-term future period. The range of the tenth percentile of minimum temperature (Tn10thp) in historical period was 1.84-11.72°C (average 7.83°C) and varied as low temperature at the north (Punjab, Haryana, Thar desert and north & central Rajasthan) to higher at the south (Gujrat and M.P.) of the study area. The average increase of Tn10thp in near future, mid future and long-term future will be 1.14°C (1.90°C) 3.00°C (3.93°C) and 3.08°C(7.20°C) for RCP4.5 (RCP8.5) respectively. In long-term future of RCP8.5 increase in temperature will be more than two times than RCP4.5. Tn10thp will be higher in the south-east of the study area in all study periods of the 21st century (N.F., M.F. and LT.F.) under both RCPs.

4. FDs have significant decreasing trend under both RCPs (2006-2099) but there is an insignificant increasing trend in the long-term future period (2071-2099) under RCP4.5. FDs in future will decrease with the rate of 0.012/decade (4.75%) and 0.010/decade (6.68%) under RCP4.5 & RCP8.5 respectively. Time series of FDs represent that there is no FDs after 1962(change point) in RCP8.5. In the historical period number of annual average SD were 332.38 which will increase to 346.54 and 359.45 in the long-term future period (2071-2099) under RCP4.5 & RCP8.5 respectively. Overall, the SDs will have an increasing trend except in long–term future has a decreasing trend with the rate of -0.62days/decade under RCP4.5. The most probable change points in SDs are 1986, 2031 and 2057 for historical and future projections of RCP4.5 and RCP8.5 respectively.
5. Hot days have increasing trend and the rate of increase are 4.48days/decade (12.08%/decade), 0.40days/decade (1.10%/decade) and 0.99days/decade (2.70%/decade) for historical period (1970-2005), RCP4.5 and RCP8.5 (2006-2099) respectively. The most probable change point in historical time series of HDs was 1988.HN are found to significantly increase for historical and RCP8.5 (2006-2099) while RCP4.5 (2006-2099) have an insignificant increasing trend. The rate of changes is as 8.22days/decade (21.42%/decade), 0.36days/decade (0.99%/decade) and 1.05days/decade (2.88%/decade) for historical, RCP4.5 and RCP8.5 respectively. Major changes in HNs will occur in the mid future with the rate of 5.31days/decade and 14.8days/decade.
6. CDs are found to decreases with the rate of 6.28days/decade (17.93%/decade), 0.4days/decade (1.10%/decade) and 1.06day/decade (2.91%/decade) for historical, RCP4.8 and RCP8.5 respectively. The significant reduction of Cold days and cold nights occurred after the year of 1986 and 1984.CN have a significant decreasing trend in near future, mid future and long-term future period under both RCPs except long-term future for RCP4.5 with an insignificant increasing trend. The rate of change are -3.90days/decade for historical, -0.33 days/decade for RCP4.5 and -0.90 days/decade for RCP8.5 (2006-2099). The major change points were 1984, 1962 and 1920 for historical, RCP4.5 and RCP8.5 (2006-2099) respectively.
7. TXX significantly increased in the historical period and it will increase significantly continue in the 21st century under both RCPs. The rate of change appeared to be 0.20°C/decade and 0.66°C/decade in the 21st century under RCP4.5 and RCP8.5 respectively. TXN has an increasing trend in historical and 21st century except in long term future period of RCP4.5 it shows an insignificant decreasing trend. The significant increasing trend was found only for RCP8.5. The rate of change was 0.27°C/decade in the historical period and it will continue to increase with 0.20°C/decade 0.74°C/decade for RCP4.5 and RCP8.5 (2006-2099).
8. TNN is found to increase in the 21st century but in the long-term future period (2071-2099) it has an insignificant decreasing trend. The Sen's slope was 0.18°C/decade in the historical period which will increase 0.27°C/decade and 0.57°C/decade) for RCP4.5 and RCP8.5 (2006-2099) respectively. TNX has a significant increasing trend for both RCPs. The sen's slope was very high with 0.74°C/decade for RCP8.5 as compared to 0.20°C/decade and 0.26°C/decade for RCP4.5 and historical period respectively. The most probable change point was 1995 in the historical period.

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