



# Abrupt changes in mean temperature over India during 1901–2010

R BHATLA<sup>1,2,\*</sup>, SHRUTI VERMA<sup>1</sup>, SOUMIK GHOSH<sup>1,3</sup> and ANKITA GUPTA<sup>4</sup>

<sup>1</sup>Department of Geophysics, Institute of Science, Banaras Hindu University, Varanasi, India.

<sup>2</sup>DST-Mahamana Centre of Excellence in Climate Change Research, Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi, India.

<sup>3</sup>Scripps Institution of Oceanography, University of California, San Diego, La Jolla, USA.

<sup>4</sup>Department of Botany (Section: Environmental Science), Banaras Hindu University, Varanasi, India.

\*Corresponding author. e-mail: rbhatla@bhu.ac.in

MS received 24 July 2019; revised 20 February 2020; accepted 16 April 2020

Since eternity, the Earth's temperature has varied or fluctuated; it has its cooling and hot timing dependency on its orbital position as well as the isolation received from the Sun. The global climate continues to change rapidly compared to the speed of the natural variations in climate. Therefore, the spatially complete representations of surface climate are required for many purposes in applied sciences. But in recent centuries, the main matter of concern is that Earth's normal temperature fluctuation is being influenced by some external factors such as enhanced greenhouse gases because of extreme uses of fossil fuels, severe industrialization, advance urbanization, etc. This study presents a comprehensive surface temperature dataset of Climatic Research Unit (CRU) available since 1901 for India, which is used to document significant changes in Indian temperature over ten decades, during winter season (January and February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–December) to examine the patterns and possible effects of global warming. A strong increasing pattern is observed with the fast growing of the development after 1950 which has shown nearly doubled in the last 50 yrs. The mean temperature during winter for the 2000s shows a consistent pattern of warming over the Himalayan region, northwestern and southern India, and a pattern of the warming observed over northeastern India and extending southwestward across central India during post-monsoon.

**Keywords.** Seasonal temperature; decadal; industrialization; temperature; CRU.

## 1. Introduction

The variations in temperature can be linked to several atmospheric circulation features predominantly with rainfall. Day-to-day increasing population and urbanization results in the increase in greenhouse gases (GHGs) emission (Roser and Ortiz-Ospina 2018). Along with this critical factor, aerosol loading is supposed to affect the day- and

night-time temperature. The approximate reason behind the changes in temperature is directly linked with enhanced GHGs emission and the aerosol loading in the atmosphere. Although, it is very difficult to establish a direct relationship between two such factors with temperature, numerous studies have been carried out on the long-term temperature variations along with the daily and extreme temperature changes. Some of

them have tried to demonstrate the daily and extreme temperature variation from one region to other. Mearns *et al.* (1984) have established the relationship between changes in temperature with the corresponding changes in probabilities of extreme temperature events which are quite nonlinear.

According to IPCC (2007) report, the temperature over the world has increased by 0.7°C and for Indian region the critical value of increase is 0.5°C. In the recent study of Kjellstrom *et al.* (2009) have shown that the abrupt and frequent temperature changes may give rise to more diseases especially acute for vector-borne diseases. Small changes in temperature adversely affect the crop growth and agricultural products to a large extent (Attri and Rathore 2003; Peng *et al.* 2004). Xia *et al.* (2014) described the temporal and spatial changes in the annual and seasonal temperatures in a typical basin of Qiantang river based on the time series of daily temperature from 14 meteorological stations and found that the considerable warming trend in cold events on annual as well as seasonal basis. They also concluded that the regional factors have influenced their observation in addition to a large-scale circulation because of climate change in the studied region. Dash and Mamgain (2011) have observed the remarkable change in frequency of cold nights during the winter season and hot days during summer over different homogenous regions of India. Bhatla *et al.* (2016) have analyzed the temporal changes in the monthly and seasonal temperature over Varanasi district based on 40 yrs of time series of daily temperature. The country-wide mean maximum temperature has increased by 0.6°C and mean minimum temperature decreased by 0.1°C and concluded that the most of the increases in mean surface air temperature over India are due to the increased daytime temperature (Rupa Kumar *et al.* 1994). The climate is an essential factor for sustainable development of any country such as India, where economy is based 60% on agriculture. The extreme temperature variation in India and the observations were derived from 1970 to 2002 and found that the number of hot days is maximum over central parts and minimum along the west coast of India during summer season (Kothawale and Rupa Kumar 2005). Frequency of occurrence of summer time maximum temperature is found more than 35°C and has a decreasing trend over northern India and an increasing trend over southern India. During winter time, minimum temperature is less than 10°C and has an increasing

trend in northern Indian cities based on the effect of urbanization (Prakasa Rao *et al.* 2004). Padma Kumari *et al.* (2007) observed that decreased solar radiation in India from the period of 1981–2004 (due to anthropogenic aerosol emission) caused an increase in the maximum and minimum surface temperature. The aim of the present study is to analyze the variation of mean temperature over India and Himalayan region during the winter season (January and February), pre-monsoon season (March–May), monsoon season (June–September) and post-monsoon season (October–December) for the period of 1901–2010.

## 2. Data and methodology

For this study, gridded monthly temperature data has been obtained from the Climate Research Unit (CRU) time series data CRUTSv.3.21 from 1901 to 2010 was used. The available CRU dataset covers the global land surface with a very fine spatial resolution of 0.5° × 0.5° latitude and longitude grid cells (Harris *et al.* 2014) which are based on monthly average daily maximum and minimum temperatures provided by more than 4000 weather stations distributed around the world. These datasets have been developed by the CRU at the University of East Anglia in conjunction with the Hadley Centre (UK Met Office) at 0.5° × 0.5° resolution.

This experiment set-up has been carried out with monthly CRU temperature for 110 yrs period (1901–2010) over India and the Himalayan region. To observe the seasonal variation, the season has been categorized into four sections: winter (January and February), pre-monsoon (March–April–May), monsoon (June–July–August–September) and post-monsoon (October–November–December). The deviation from the mean annual temperature has been calculated using standard anomaly and plotted seasonally during 1901–2010. The standardized anomaly ( $z$ ) of CRU time series data has been done by dividing anomaly by its corresponding standard deviation ( $\sigma$ ). It is given by the formula:

$$z = \frac{x - \bar{x}}{\sigma}. \quad (1)$$

Here,  $x - \bar{x}$  is called as anomaly, which is the difference between data value from its mean;  $\bar{x}$  is mean of time series data;  $\sigma$  standard deviation of the time series. The non-parametric statistical

methods Mann–Kendall statistics is used to identify the trend of temperature variation with the 90% significance level. The study also include the decadal (for 10 yrs) and tricadal (for 30 yrs) spatio-temporal variability of mean temperature on the basis of average anomaly difference over Indian subcontinent of during 1901–2010 with respect to the season.

### 3. Results and discussion

The temperature variation for 110 yrs for meteorological season, *viz.*, winter, pre-monsoon, monsoon and post-monsoon season has been depicted in figure 1(a–d). The seasonal temperature variation during winter is considered in figure 1(a) which represents the increasing trend of temperature. The trend of temperature variation is  $0.008^{\circ}\text{C}$  per year. The mean temperature variation pattern during pre-monsoon season is shown in figure 1(b). Unlike to winter season, the temperature increasing rate is slightly lower ( $0.0075^{\circ}\text{C}$  per year) in the pre-monsoon season. During this season, the lowest temperature has been found in the early 1900s

(1900–1950) and the lowest and highest temperature was recorded in 1907 and 2010 which were  $27.8^{\circ}\text{C}$  and  $30.9^{\circ}\text{C}$  per year, respectively. The noticeable temperature variation for this season can be found from 1916 to 1935 and from 1930 to 1958, later on from 1968 to 1973. Also, the highest temperature variation occurred during 2009–2010. The lowest temperature increasing rate is about  $0.0046^{\circ}\text{C}$  per year is observed in the monsoon period (figure 1c) during the last 110 yrs. The temperature fluctuations were also there but the fluctuation rate was lower compared to the other three seasons. The maximum fluctuations could be observed from 1968 to 2002. Also, the temperature variation pattern shows a decreasing trend during 1959–1965. Figure 1(d) illustrates the post-monsoonal temperature variation for the past 110 yrs where the temperature increasing rate was maximum ( $0.01^{\circ}\text{C}$  per year) with less fluctuation. The maximum temperature started occurring after 1950 and it was minimum in the year of 1910 and maximum in the year 2008. Further, the temperature variation has an increasing trend which can be easily explained by the temperature difference between the first decade (1901–1910) and last decade (2001–2010).

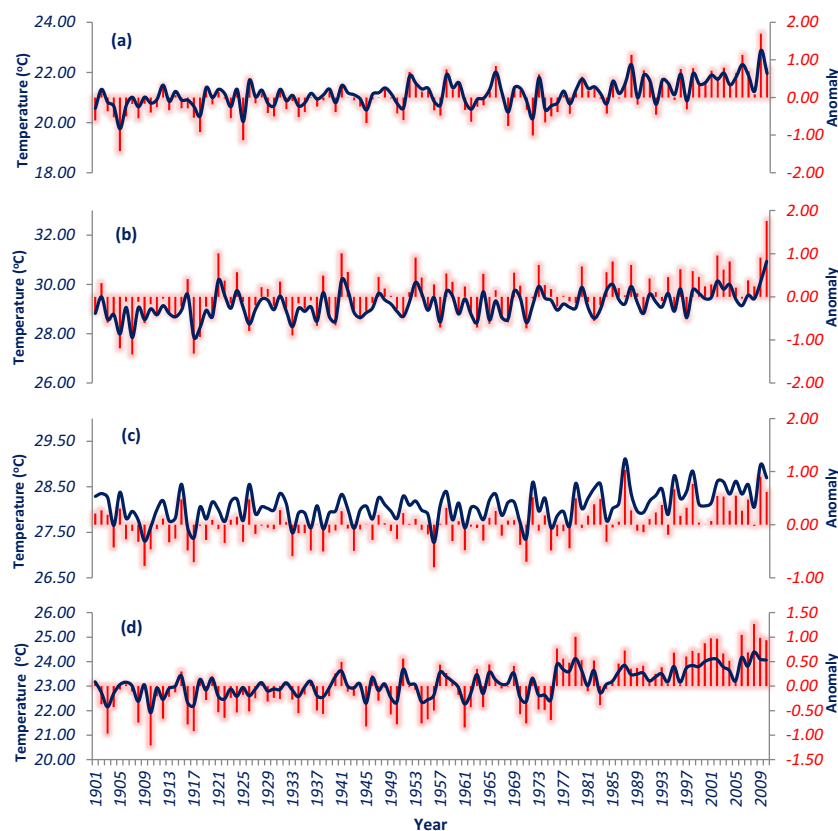


Figure 1. Variation of temperature during (a) winter season, (b) pre-monsoon season, (c) monsoon season, and (d) post-monsoon season over India for the period of 1901–2010.

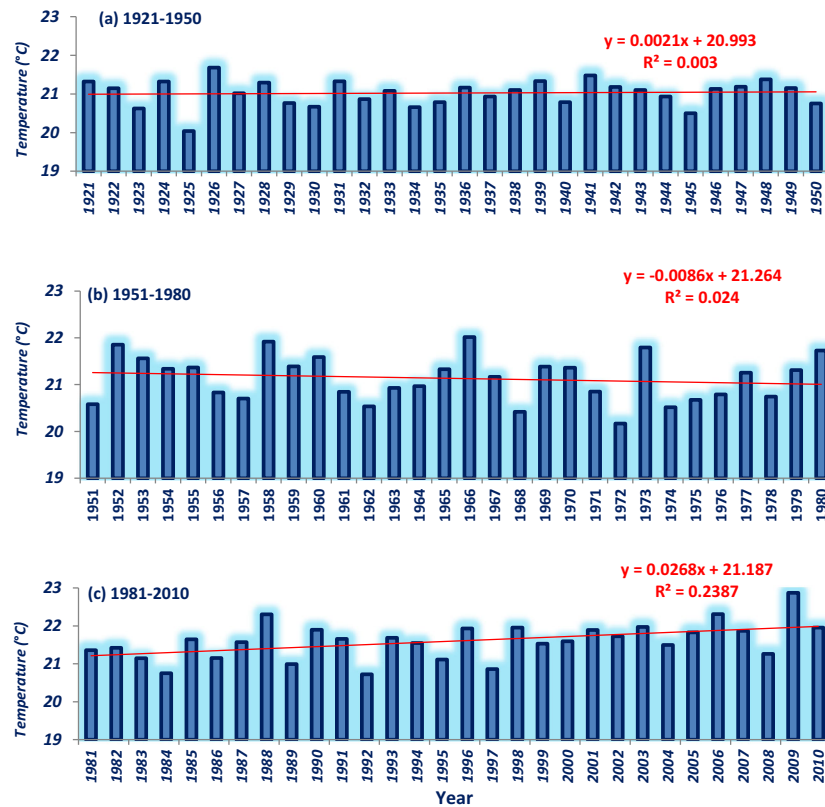


Figure 2. Variation of temperature during winter season over India for different tricades (a) 1921–1950, (b) 1951–1980, and (c) 1981–2010.

The tricadal variation (for 30 yrs) of temperature for the winter season is shown in figure 2. For tricadal distribution, 110 yrs span is divided into three tricades (30-year period), i.e., 1921–1950, 1951–1980 and 1981–2010 which shows the variation of temperature trend more precisely in table 1. Figure 2(a) represents the tricadal temperature variation for 1921–1950 which represents a linear and very low variation rate ( $0.0021^{\circ}\text{C}$  per year), although, there are not many fluctuations in temperature. The temperature variation for the next tricade (1951–1980) has been shown in figure 2(b), surprisingly, it shows a decreasing trend of  $-0.0086^{\circ}\text{C}$  per year. Highest fluctuations can be observed during the years 1951–1952, 1957–1958, 1966–1968 and 1972–1973 where the fluctuation is huge, of almost  $2^{\circ}\text{C}$  per year (figure 2b). A linear increasing trend is observed during recent tricade (i.e., 1981–2010) (figure 2c). Most of the temperature fluctuations could be noticed during 1982–1998 and 2004–2010. From 1999 to 2003, the temperature variation was almost linear which means low fluctuation during this period. A gradual increasing pattern in temperature can cause ultimate alarming global warming condition. The tricadal temperature variation for

pre-monsoon season has been shown in figure 3. The evaluation of distribution of temperature variation during the tricade of 1921–1950 shows a trivial decreasing trend with decreasing rate of  $-0.0073^{\circ}\text{C}$  per year (table 1), but the temperature fluctuations during these years were high. The highest fluctuation in temperature could be observed during the period of 1940–1941 and 1941–1943. During the second tricade of 1951–1980 (figure 3b), the temperature variation trend was positive with a slope of  $0.0015^{\circ}\text{C}$  per year and the highest fluctuations during 1951–1973 and lowest during 1974–1979. The temperature changing rate for the recent tricade of 1981–2010 is observed higher in comparison to early two tricades and the rate was  $0.0256^{\circ}\text{C}$  per year, but here the fluctuations were low except during 2008–2009. Thus, for winter as well as in pre-monsoon season, the temperature has increased steadily.

During the monsoon season, the temperature has increased in recent tricade (1981–2010), which is shown in figure 4. First two tricades, i.e., 1921–1950 and 1951–1980 depict a decreasing pattern with less fluctuation, whereas the first tricade shows a downward trend with slope  $-0.0033^{\circ}\text{C}$  per year (table 1). Further, the temperature variation rate

Table 1. Trends of temperature variation in different seasons.

Decade	Winter			Pre-monsoon			Monsoon			Post-monsoon		
2001–2010 I (0.04)	1991–2000 I (0.03)	1981–1990 I (0.06)	I (0.03)	1971–1980 I (0.07)	1961–1970 I (0.06)	1951–1960 I (0.03)	1941–1950 D (−0.03)	1931–1940 D (−0.001)	1921–1930 D (−0.03)	1911–1920 D (−0.03)	1901–1910 I (0.005)	
I (0.08)												
I (0.06)	I (0.013)	I (0.03)	I (0.04)	I (0.03)	D (−0.01)	D (−0.06)	D (−0.03)	D (−0.008)	D (−0.04)	D (−0.02)		
I (0.07)												
I (0.03)	I (0.004)	D (−0.02)	I (0.02)	I (0.02)	I (0.02)	D (−0.02)	D (−0.01)	D (−0.03)	I (0.007)	D (−0.01)	D (−0.09)	
I (0.04)												
I (0.03)	I (0.08)	I (0.06)	I (0.16)	I (0.05)	D (−0.003)	D (−0.08)	I (0.01)	I (0.04)	I (0.02)	D (−0.04)		
I (0.1)												

\*I = increase, D = decrease.

as well as the fluctuations in temperature was very low for the second tritade. Here, the temperature decreasing rate was very low, i.e.,  $-0.0006^{\circ}\text{C}$  per year and two reasonable fluctuations could be observed in 1955–1957 and 1971–1975. But for the recent tritade of 1981–2010, the temperature variation has a large increase rate of  $0.0113^{\circ}\text{C}$  per year relative to the previous two tritades. The glance on

tritadal temperature variation for post-monsoon season shows that not only the temperature increase rate, but also the fluctuations are quite higher than all other seasons over the tritades (table 1 and figure 5). For the first tritade (1921–1950), the increase rate is  $0.0048^{\circ}\text{C}$  per year and some noticeable fluctuations can be observed during the period of 1937–1942 and 1944–1947. For

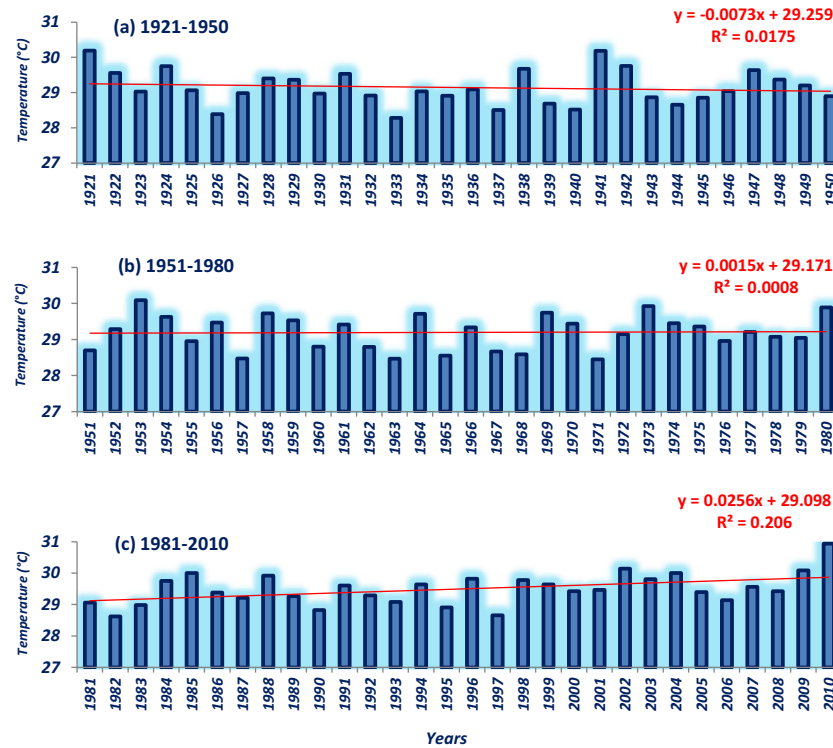


Figure 3. Variation of temperature during pre-monsoon season over India for different tricades (a) 1921–1950, (b) 1951–1980, and (c) 1981–2010.

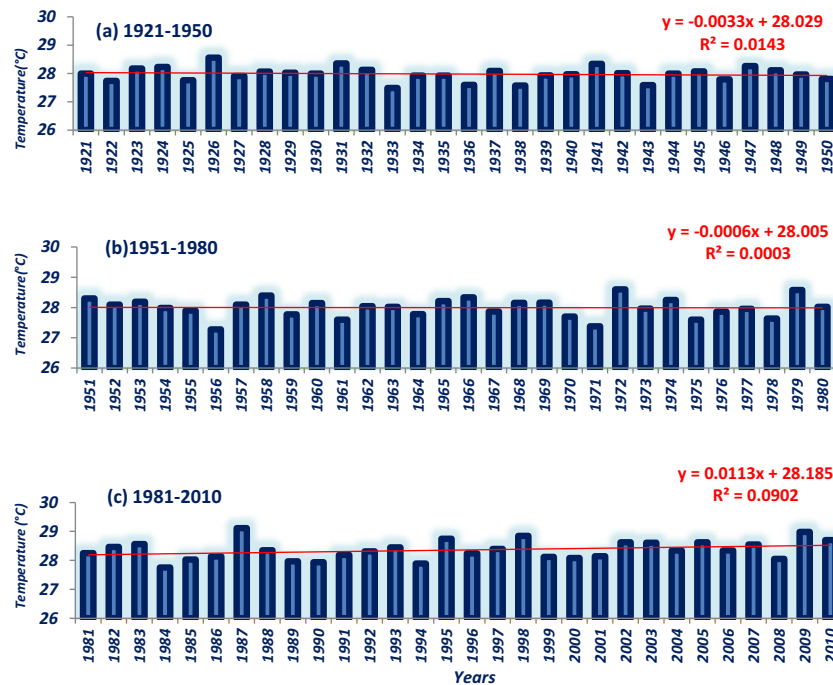


Figure 4. Variation of mean temperature during monsoon season over India for different tricades (a) 1921–1950, (b) 1951–1980, and (c) 1981–2010.

the second tricade (1951–1980), the increase rate is more  $0.0163^{\circ}\text{C}$  per year than the previous one indicating clearly that the temperature is increasing with time. The high fluctuations in temperature

may be observed during 1951–1966 and 1969–1980. During the recent tricade of 1981–2010, the variation rate along with fluctuation was alarming. The lowest temperature of this season is in the year of



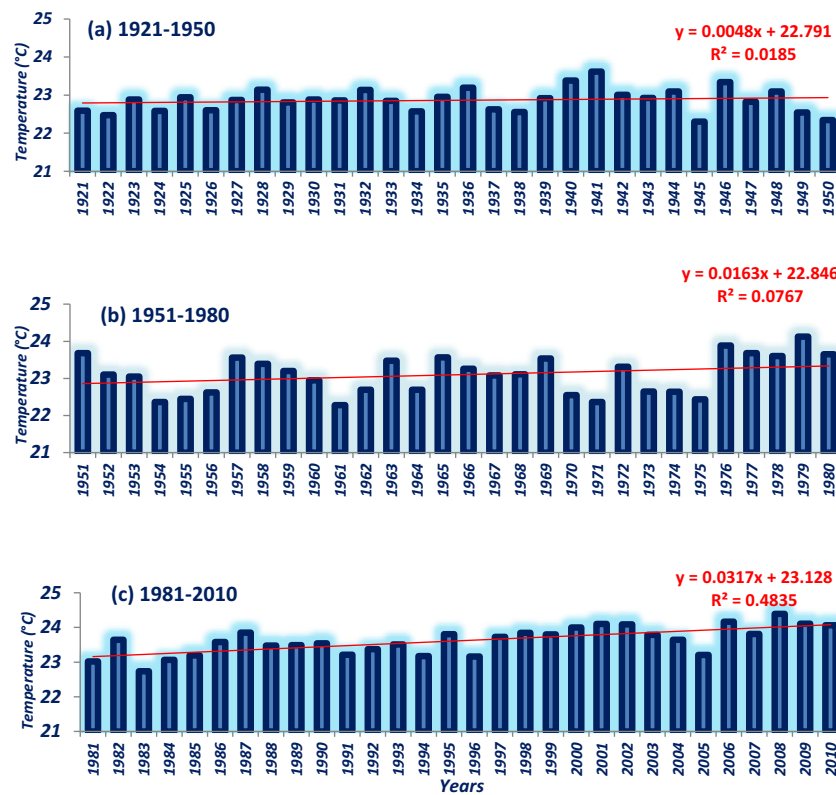


Figure 5. Variation of mean temperature during post-monsoon season over India for different tricades, (a) 1921–1950, (b) 1951–1980, and (c) 1981–2010.

1983 (22.7°C per year) and highest for this season is in 2008 (24.4°C per year). During the periods of 1981–1987 and 1999–2009, the temperature fluctuations are frequent. In other words, the temperature is soaring day-by-day and becoming a major concern in all aspects as most of the climatic variables are dependent on temperature.

Further, the temperature anomaly that is the temperature difference between the first tricade (T1: 1951–1980) and next tricade (T2: 1981–2010) is being analyzed. The spatial temperature anomaly has been shown over the Indian region to understand the changing trend more precisely and elaborately. Figure 6(a) represents the temperature anomaly during the winter season (January–February) of two tricades, which shows that the maximum temperature changes of 0.5°–1.3°C have occurred predominantly over Himalayan regions and southern peninsular of India. The study of Verma and Ghosh (2019) shows the close agreement of CRU with the observed dataset of National Institute of Himalaya data and validate the use of CRU temperature time series to study climatic variation for hilly terrain of Himalayas. Again, the positive temperature anomaly is observed in the range of 0.3°–0.9°C over the northeastern part of

India and northwest India. The temperature is insignificant over central India and small parts of southern India; even in some parts, temperature has decreased by  $-0.5^{\circ}$  to  $-0.1^{\circ}$ C per year. During the pre-monsoon season, the change in temperature is observed all over India and its adjoining sub-continent shown in figure 6(b). Here, the decreasing trend in temperature is observed over eastern peninsular India and extending up to the Indo-Gangetic Plain of India. Whereas, the increasing trend of temperature in the range of 0.5–1.0°C have been seen over the Himalayan region, Pakistan and southern India region. During the monsoon period, the temperature has decreased by  $-0.5^{\circ}$ C over the regional scales around  $27^{\circ}$ – $34^{\circ}$ N and  $65^{\circ}$ – $75^{\circ}$ E including the region of Pakistan, northern India and some part of central India (figure 6c). The spatial variation of tricadal anomaly (T2–T1) during monsoon season is showing positive temperature anomaly in the range of 0.5–0.9°C over southern and northeast parts of India. During post-monsoon period, spatial tricadal anomaly change depicts the dominated positive anomaly over the most parts of India which is clearly indicating the recent tricade warming, i.e., 1981–2010. It shows the increasing pattern in temperature in most parts

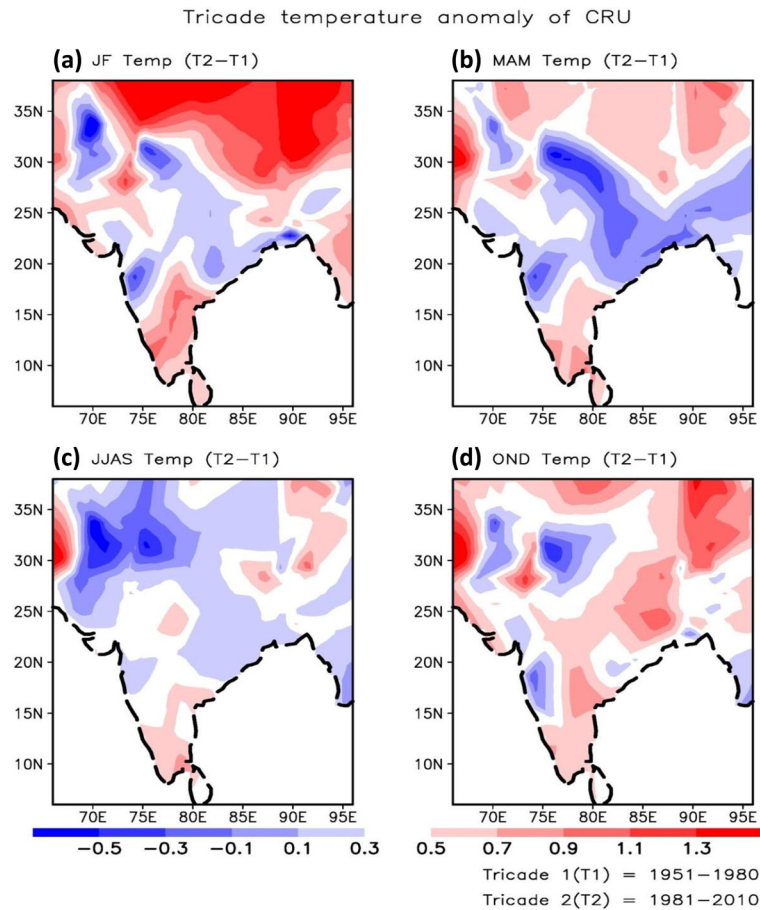


Figure 6. (a–d) Spatial variation of temperature during different seasons over India for the last two tricades.

of India except some regions of western peninsular, north region and northeast region of India (figure 6d). During post-monsoon period, tricadal changes observed mainly over northeast India, stretching southwestward across central India. Overall, this decadal anomaly (T2–T1) represents the warming/cooling trend over the Indian and Himalayan regions. The warming and cooling effects with respect to seasons are showing considerable changes which was also well explained in the study of Ross *et al.* (2018). The analysis of positive anomaly (warming) is a question of concern during the winter and post-monsoon, whereas the cold bias or cooling temperature trend is seen during the pre-monsoon period. During the monsoon, regionalized low in temperature was observed over the northwest India and western Indo-Gangetic Plains (IGP) region.

The decadal variation and trend of temperature during the time period 1981–2010 where the time span is divided into three recent decades: D1 (1981–1990), D2 (1991–2000), D3 (2001–2010) is

analyzed and represented in figure 7. Further, the spatial anomaly of temperature variation has been calculated by subtracting the recent one from the past decade, i.e., D2–D1 and D3–D2 and has been plotted spatially for four seasons as shown in figure 7(a–h). From the figure, it can be observed that the increasing tendency of temperature anomaly is prominent in D3–D2 is more than the D2–D1. This clearly shows the impact of global warming over India and the Himalayan region in the recent decade. During winter (January–February), the comparison between the two decadal anomalies showing the contrast temperature changes are observed over India and adjoining regions, i.e., D3–D2 shows positive anomaly of 0.5°–1.3°C and D2–D1 shows negative anomaly of –0.1° to –0.5°C (figure 7a–b). It also depicts the significant increasing trend in temperature observed during the winter over Himalayan regions. While analyzing the decadal variation of temperature anomaly for pre-monsoon season (figure 7c–d), could be seen that the impact of



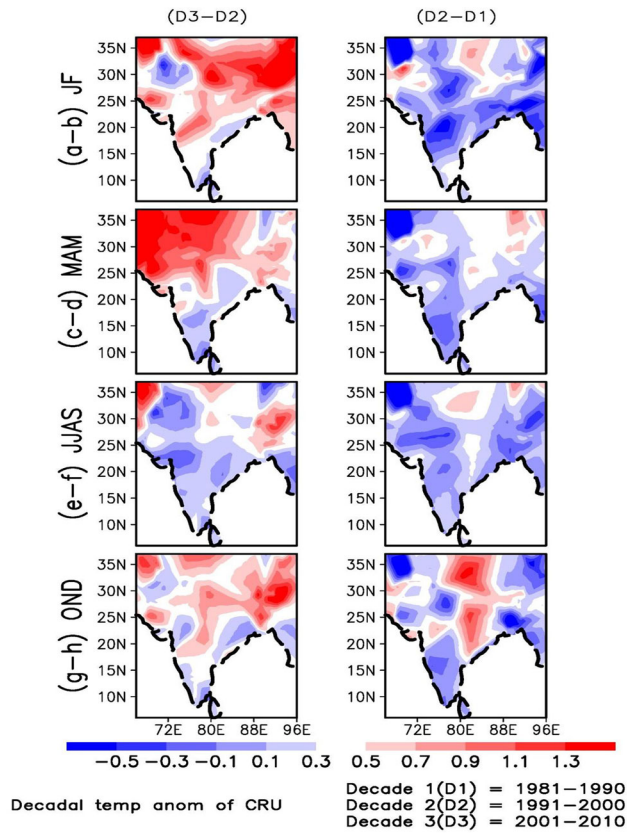


Figure 7. (a–h) Spatial representation of decadal variations of mean temperature over India during different seasons.

increased temperature found over the northwest part of India and Pakistan. The decadal change in temperature in figure 7(d) shows that the spatial negative temperature change ( $-0.1$  to  $-0.3^{\circ}\text{C}$ ) is dominated all over India and Himalayan regions and are quite consistent in temperature change but the recent changes during D3–D2 is alarming because it shows (figure 7c) warming over the northwestern side of the domain in the range of  $0.3$ – $1.3^{\circ}\text{C}$ . The increased warming condition has been observed during the recent decadal change are set alarming condition for the more frequent extreme weather events in near future (figure 7a and c). But during the monsoon, the decadal anomaly temperature changes show cold biasness in nature for both the decadal anomalies (figure 7e–f). Also, heating/warming over extreme northwest part and north eastern part of India has been observed (figure 7e). The decadal temperature anomaly for CRU temperature data represents in figure 7(g–h) for post monsoon season. In figure 7(g), the maximum zones including central India, northeast India and IGP regions are showing an increase in temperature in post-monsoon season;

on another side, the decadal change D2–D1 shows cooling or negative decadal anomaly over most parts of the India. But eastern peninsular India and middle range of Himalaya are showing an increase of  $1.3^{\circ}\text{C}$  in mean temperature. It is notable from the analysis that the decadal mean temperature pattern manifested the impact of global warming over the parts of India, Pakistan, Nepal, Bhutan and most importantly over the Himalayan region. The maximum change in temperatures was observed during the winter and pre-monsoon period, which was significant particularly in recent decades. The warming trend is mainly observed over northwest India, Pakistan, Afghanistan, northeast India and Himalayan regions.

Figure 8 shows the decadal temperature variation from 1901 to 2010 by dividing the 110 yrs period into 11 decades. There are significant increases found in the trend of the mean temperature of CRU along with the increase in the anomaly during all seasons over India. Hence it proves that the significant/insignificant change in the monthly and yearly mean temperature eventually leads to the alarming decadal changes in the mean temperature change in 110 yrs period of time. For all the seasons, trend is positively increasing which shows the fact that temperature is increasing with time; among all the plots, maximum slope of trend can be observed during post-monsoon season and minimum slope of trend can be observed during monsoon season. The lowest mean temperature of all the seasons is seen in first decade 1901–1910 and maximum mean temperature can be observed in 2001–2010 except in post-monsoon season where the minimum temperature is attended in the decade 1931–1940. The decadal anomaly represents above/below changes in mean temperature from the normal temperature of a decade. The maximum rise in the positive anomaly of mean temperature has been observed in the last decade (2000–2010) during winter, post-monsoon and pre-monsoon, i.e.,  $0.8^{\circ}$ ,  $0.7^{\circ}$  and  $0.6^{\circ}\text{C}$ , respectively, though the increasing temperature trend is of concern during winter and post-monsoon season. Thus, by comparing the first and the last decade changes in the mean surface temperature over India, one can interpret that the temperature increase was more than double as compared to first to last decade. This study presents a comparable platform for other studies related to long-term change in surface temperature (Kothawale and Rupa Kumar 2005; Kothawale *et al.* 2010; Ross *et al.* 2018). The spatially complete representations

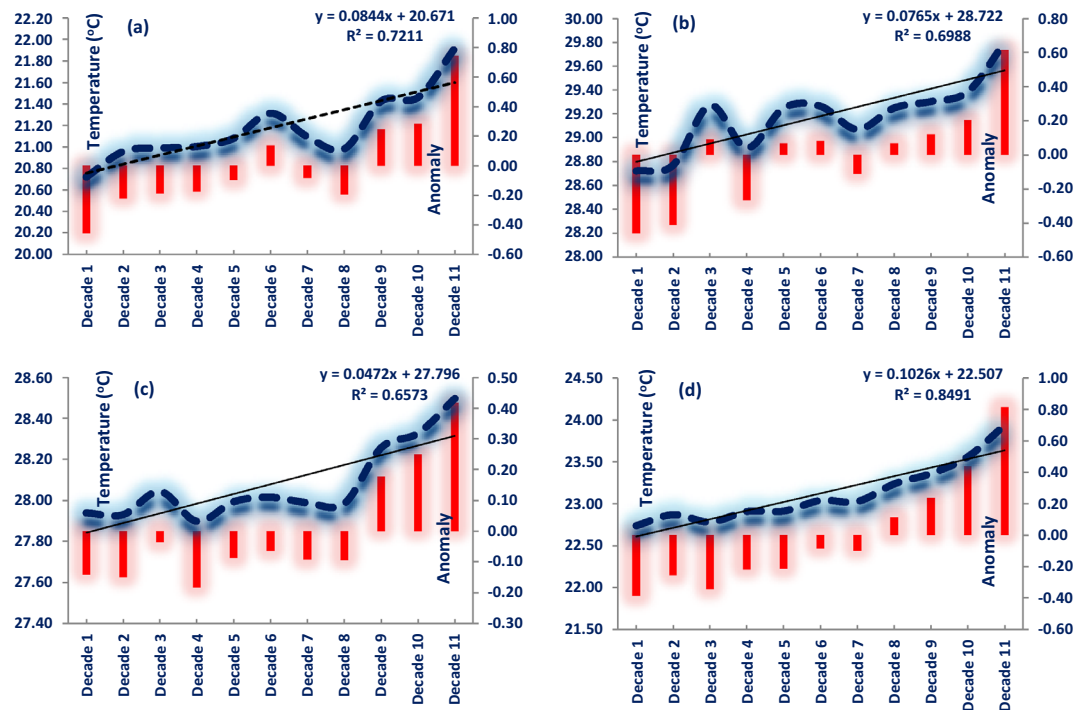


Figure 8. Decadal variation of temperature during (a) winter season, (b) pre-monsoon season, (c) monsoon season, and (d) post-monsoon season.

of surface climate particularly the mean changes in the state of temperature over a century are required for many purposes in applied sciences. These multi-decadal patterns of mean temperature change will help in the policy and planning for the effects of climate change in India, particularly in assessing the impacts of climate change on the agricultural and health system of the country.

#### 4. Conclusions

The study easily expounds the temperature annual, decadal and tricadal anomaly over India and Himalayan region during the last century. Despite fluctuations in temperature, it is easily visible from the analysis that there is an increasing pattern from the mid-century (1950s) to recent years. The multi-decadal change in temperature mainly occurred after 1950, when civilization revolutionised rapidly, causing unplanned urbanization and severe industrialization which later geared up cutting of trees vastly resulting in less absorption of greenhouse gases. The rate of temperature increase has nearly doubled in the last 50 years and if situation continues like present, then the temperature will increase further and that is certain. Also, in the warmer atmosphere, probability of extreme rainfall event get enhanced. The important finding of this study also

shows the importance to compare long term changes in Indian surface temperatures to other studies like aerosol pollution, health, agriculture production, etc., over India and its regional levels.

#### Acknowledgements

This work is a part of an R&D project funded by Department of Science and Technology (DST) PURSE grant. The authors wish to thank to Climate Research Unit (CRU) for providing the necessary data.

#### References

- Attri S D and Rathore L S 2003 Simulation of impact of projected climate change on wheat in India; *Int. J. Climatol.* **23** 693–705.
- Bhatla R, Tripathi A and Singh R S 2016 Study of trend analysis and extreme events of temperature over Varanasi During Summer monsoon season; *Mausam* **67**(2) 463–474.
- Dash S K and Mangain Ashu 2011 Changes in the frequency of different categories of temperature extremes in India; *J. Appl. Meteorol. Climatol.* **50**(9) 1842–1858.
- Harris I, Jones P D, Osborn T J and Lister D H 2014 Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset; *Int. J. Climatol.* **34** 623–642.
- Intergovernmental Panel on Climate Change (IPCC) 2007 Climate Change 2007: The Fourth Assessment Report of the IPCC; Cambridge University Press: Cambridge, UK.

- Kjellstrom T, Holmer I and Lemke B 2009 Workplace heat stress, health and productivity; *Global Health Action* **2** 1–6.
- Kothawale D R and Rupa Kumar K 2005 On the recent changes in surface temperature trends over India; *Geophys. Res. Lett.* **32** L18714.
- Kothawale D R, Revadekar J V and Rupa Kumar K 2010 Recent trends in pre-monsoon daily temperature extremes over India; *J. Earth Syst. Sci.* **109** 51–65.
- Mearns L O, Katz R W and Schneider S H 1984 Extreme high-temperature events: Changes in their probabilities with changes in mean temperature; *Am. Meteorol. Soc.* **23**(12) 1601–1613.
- Padma Kumari B, Londhe A L, Daniel S and Jadhav D B 2007 Observational evidence of solar dimming: Offsetting surface warming over India; *Geophys. Res. Lett.* **34** L21810.
- Peng S *et al.* 2004 Rice yield decline with higher night temperature from global warming; *Proc. Natl. Acad. Sci. USA* **101**(27) 9971–9975.
- Prakasa Rao G S, Jaswal A K and Kumar M S 2004 Effect of urbanization on meteorological parameter; *Mausam* **55**(3) 429–440.
- Roser M and Ortiz-Ospina E 2018 World Population Growth; <https://ourworldindata.org/world-population-growth>.
- Ross R S, Krishnamurti T N, Pattnaik S and Pai D S 2018 Decadal surface temperature trends in India based on a new high resolution data set; *Nat. Sci. Rep.* **8** 7452.
- Rupa Kumar K, Krishan Kumar K and Pant G B 1994 Diurnal asymmetry of surface temperature trends over India; *Geophys. Res. Lett.* **21** 677–680.
- Verma P and Ghosh S K 2019 Trend analysis of climatic research unit temperature dataset for Gangotri glacier, India; *Dyn. Atmos. Oceans* **85** 83–97.
- Xia F, Liu X, Xu J, Wang Z, Huang J and Brookes P C 2014 Trends in the daily and extreme temperatures in the Qiantang River Basin, China; *Int. J. Climatol.* **35**(1) 57–68.

Corresponding editor: A K SAHAI