

Trends in Diurnal Temperature Range over India (1961-2010) and Their Relationship with Low Cloud Cover and Rainy Days

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Abstract: A study has been carried out to analyze the annual and seasonal spatial patterns of trends in mean maximum temperature (MMAX), mean minimum temperature (MMIN) and diurnal temperature range (DTR = MMAX-MMIN) in India during 1961-2010. Additionally, we analyzed the spatial dependence of DTR trends on the low cloud cover (LCC) and number of rainy days (NRD). The study has revealed uneven changes in DTR across regions and time of the year in India. All India averaged annual MMAX and MMIN are increasing at the rate of 0.05 °C/decade but there is no trend in annual DTR. Seasonal averaged MMAX and MMIN are increasing for all seasons except MMIN in monsoon. But country averaged seasonal DTR is decreasing for winter and post monsoon mainly due to higher increases in MMIN or lesser decreases in MMAX, increasing for monsoon mainly due to higher increases in MMAX or lesser decreases in MMIN and showing no trend for summer during the period of study.

Spatially, both MMAX and MMIN have increased all over India with the exception of northeastern region. However, DTR trends show a distinct contrast between northern and southern half of India. The amplitude of increase of MMIN compared to MMAX is high over north causing significant decrease in DTR. However, the amplitude of increase in MMAX compared to MMIN is high enough to cause significant increase in DTR in southern half of India. Stations in Western Himalayas show significant increase in DTR in all seasons except monsoon. MMAX trends in the Indo-Gangetic plains are significantly decreasing. The correlation analysis reveals that LCC and NRD are responsible for explaining much of the variance in DTR over India during the study period. Furthermore, local factors like land-use change, deforestation, urbanization, anthropogenic aerosols may also have contributed to the overall trends in DTR.

Keywords: Climate change, Maximum temperature, Minimum temperature, Diurnal temperature range, Low cloud cover, Rainy days, Trends, Correlation.

Introduction

The rising surface temperature is one of the major concerns all over the world because main manifestation of global warming is attributed to the maximum and minimum temperatures due to their association with other climatic parameters. Studies conducted in

many parts of the world have confirmed that global surface warming is taking place at the rate of 0.74 ± 0.18 °C over 1906-2005 (IPCC, 2007). Braganza et al. (2004) proposed that changes in daily maximum and minimum temperatures provide more information than the mean temperature alone because trends in mean surface temperature can be due to changes in either

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maximum or minimum temperature, or relative changes in both. The temperature difference between maximum and minimum temperatures is known as the diurnal temperature range (DTR), which is a meteorological indicator independent of internal climate variation and, therefore, considered as a signature of observed climate change (Karl et al., 2004). However, the change in maximum and minimum temperatures is not uniform across the world. This asymmetry between maximum and minimum temperatures causes increase or decrease in DTR. Therefore, DTR is useful in defining a signature of observed climate change that is less likely to show a common response to different radiative forcing mechanisms. Considered as an important index of climate change, DTR is receiving considerable attention in various regions of the globe in recent times (Karl et al., 1993; Plummer et al., 1995; Kaas and Frich, 1995; Razuvaev et al., 1995; Easterling et al., 1997; Price et al., 1999; Roy and Balling, 2005; Englehart and Douglas, 2005; Makowski et al., 2008; Jhajharia and Singh, 2011; Rai et al., 2012; Sang, 2012; Qu et al., 2014).

Worldwide, DTR has decreased since the mid-twentieth century (Karl et al., 1991, 1993; Kukla and Karl, 1993; Easterling et al., 1997; IPCC, 2001), with exceptions reported in only a few regions (Weber et al., 1994). Karl et al. (1993) detected increases in maximum temperature and minimum temperature over a large portion of the earth's surface area and attributed the decrease in DTR to the possible increase in cloud cover. Turkes et al. (1996) have shown significant decreases in DTR in Turkey which was attributed to significant increases in minimum temperature. Significant decreasing trends in DTR were also reported in the Jordan Valley (Cohen and Stanhill, 1996), Israel (Ben-Gai et al., 1999), and Cyprus (Price et al., 1999). Vose et al. (2005) and Dai et al. (2006) have reported weakening of DTR trend during the last 20 years. Shahid et al. (2012) have found significant increase in mean minimum and maximum temperatures but a non-significant change in DTR in Bangladesh. Qu et al. (2014) have found steady decrease in annual DTR with spatial and seasonal patterns in the amplitude of trend over the continental United States. The reduction in DTR is mainly attributed to increase in cloud cover, precipitation and soil moisture (Karl et al., 1993; Dai et al., 1997, 1999). Other factors responsible for reduction in DTR are decrease in solar irradiance (Liu et al., 2004), the increase in atmospheric aerosols and greenhouse gases (Hansen et al., 1995; Dai et al., 1997).

Investigation by number of researchers have revealed

spatial pattern of increasing and decreasing DTR in Indian subcontinent (Rupa Kumar et al., 1994; Yadav et al., 2004; Roy and Balling, 2005; Fowler and Archer, 2006; Bhutiyaani et al., 2007; Jhajharia et al., 2009, 2012; Jhajharia and Singh, 2011; Rai et al., 2012). Rupa Kumar et al. (1994) reported an increase in daily maximum temperature and no change in minimum temperature and consequently, an increase in DTR over the Indian subcontinent. Yadav et al. (2004) reported an increase in DTR due to a relatively high decrease in minimum temperature and an increase in maximum temperature in the western Himalayas. Kothawale and Rupa Kumar (2005) have reported increase in all India mean annual temperature at the rate of 0.05 °C/decade over 1901–2003, mostly contributed by the rise of maximum temperature (0.07 °C/decade) rather than by the rise of minimum temperature (0.02 °C/decade). Roy and Balling (2005) have found non-significant trends in DTR over India and a decrease over Northwest Kashmir in summer. Fowler and Archer (2006) reported large increases in DTR in all the seasons over the Karakoram and Hindu Kush Mountains of the Upper Indus basin during the period 1961–2000. Bhutiyaani et al. (2007) observed increasing trends in DTR in northwestern Himalayan region. Jhajharia and Singh (2011) found a decrease in DTR in northeast India. Analyzing $0.5^\circ \times 0.5^\circ$ gridded dataset of India for 19101–2003, Rai et al. (2012) have found increase in annual DTR and detectable changes in seasonal DTR with fastest increase in winter and slowest increase in post monsoon season.

From the available literature, it is clear that regional basis of DTR studies assume special importance in context of global warming because its pattern is not uniform across the globe. In this paper we analyze annual and seasonal variability and trends in DTR over India based upon 215 surface meteorological stations for the time period 1961–2010. The relationship between DTR and other variables viz. low cloud cover and number of rainy days was also explored to understand the observed variability of DTR over the country.

Data and Methodology

Data Used

We have obtained data from National Data Centre (NDC) of India Meteorological Department (IMD). All climatological data are archived at NDC where series of robust quality control methods at data keying centres and NDC are implemented before archiving the data (Jaswal et al., 2014). After filtering stations with more than 10% missing data, 215 surface meteorological

stations under network of India Meteorological Department (IMD) are selected for analyzing changes in diurnal temperature range over India during 1961-2010. Geographical locations of these 215 stations are shown in Figure 1. Monthly mean maximum temperature and minimum temperature data for these 215 stations were taken from the archives of IMD. The DTR is calculated as the difference between the mean monthly maximum (MMAX) and minimum temperatures (MMIN). In addition to monthly temperature data, mean low cloud amount and total number of rainy days data of the same stations are taken for investigating the reasons for changes in DTR. Low cloud amount refers to the portion of the sky in eights (okta) covered by low clouds at any height. Daytime mean low cloud amount is calculated from low cloud amount recorded at main synoptic hours 0300 and 1200 UTC which represent morning and evening time sky conditions respectively. The mean low cloud amount is converted to low cloud cover (LCC) in % by dividing cloud amount in okta by 8 and multiplying by 100. IMD defined the rainy day as a day when total precipitation is 2.5 mm or more, such count represents the number of rainy days (NRD) in a month. From monthly values, time series of mean annual (January-December), winter (December, January, February), summer (March-May), monsoon (June-September) and post monsoon (October-November) DTR, MMAX, MMIN, LCC and NRD were prepared

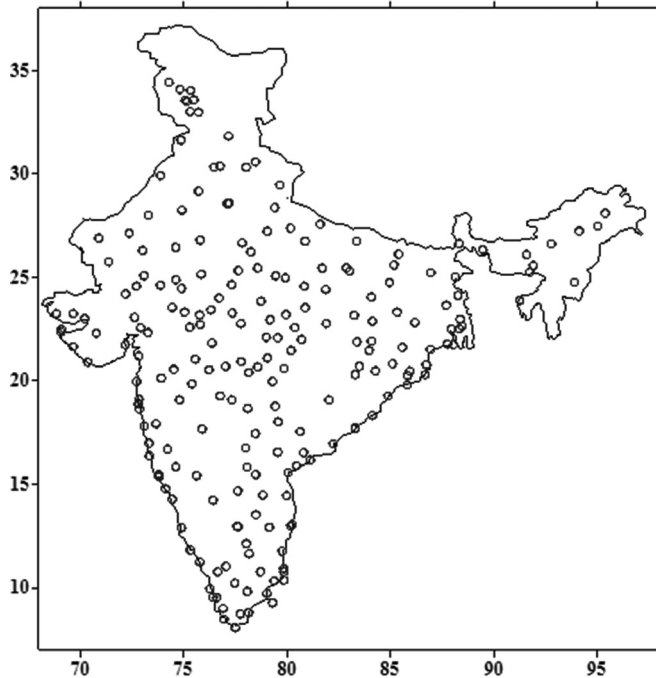


Figure 1: Geographical locations of 215 meteorological stations used for study.

for the period 1961-2010. All India averaged time series for annual and seasonal MMAX, MMIN, DTR, LCC and NRD were prepared by averaging all 215 stations.

Trends Evaluation

Trends are determined using a non-parametric Mann-Kendall test to assess the probability that there is a trend statistically different from zero and evaluate increasing or decreasing slope of trends in the time series of temperature and rainfall by using Sen's method (Sen, 1968). The Mann-Kendall test consists of comparing each value of the time-series with the others remaining, always in sequential order. The number of times that the remaining terms are greater than that under analysis is counted. The Mann-Kendall statistic is given by:

$$S = \sum_{i=2}^n \sum_{j=1}^{i-1} \text{sign}(x_i - x_j) \quad (1)$$

where n is the length of the data set, x_i and x_j are two generic sequential data values. The function $\text{sign}(x_i - x_j)$ assumes the following values:

$$\text{sign}(x_i - x_j) = \begin{cases} +1, & \text{if } (x_i - x_j) > 0 \\ 0, & \text{if } (x_i - x_j) = 0 \\ -1, & \text{if } (x_i - x_j) < 0 \end{cases} \quad (2)$$

Under the hypothesis of independent and randomly distributed variables when $n > 10$, the statistic S is approximately normally distributed (Helsel and Hirsch, 1992) with zero mean and the variance $\text{Var}(S)$ as follows:

$$\text{Var}(S) = \frac{1}{18} [n(n-1)(2n+5)] \quad (3)$$

where n is the length of the time-series. The standardized test statistic Z is then computed as given by Hirsch et al. (1993):

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0. \end{cases} \quad (4)$$

The presence of a statistically significant trend is evaluated using the Z value. This statistic is used to test the null hypothesis (H_0) such that no trend exists. A positive Z indicates an increasing trend in the time-series, while a negative Z indicates a decreasing trend. In this study, if $Z > +1.96$ or $Z < -1.96$, the null

hypothesis (H_0) is rejected at the 95% significance level. The estimate for the magnitude of the slope of trend b is calculated using non-parametric Sen's method, which is the median of slopes of all data value pairs.

$$b = \text{median} \left[\frac{(X_j - X_i)}{(j - i)} \right], \text{ for all } i < j \quad (5)$$

where b is the slope between data points X_j and X_i measured at times j and i respectively. Annual and seasonal trends in DTR, MMAX and MMIN over India are calculated for all 215 stations and tested for significance by Mann-Kendall and Sen's methods.

All India averaged monthly values of MMAX, MMIN, DTR, LCC and NRD are calculated and their variability is shown in Figure 2. Temporal variations in all India averaged annual and seasonal time series of MMAX, MMIN, DTR, LCC and NRD during 1961-2010 are shown in Figures 3 and 4 respectively. Annual and seasonal climatology of DTR is prepared where spatial patterns of contours of mean DTR are shaded in colour. Long-term variability of DTR, MMAX and MMIN was estimated by using the least square method to fit linear trend to annual and seasonal time series. The significance of the calculated trend was estimated using the Student's t-test with 5% significance level. Number of stations showing increasing/decreasing trends in DTR, MMAX and MMIN are given in Tables 1-3. Spatial distributions of annual and seasonal trends in DTR, MMAX and MMIN are shown in by marking trends significant at 95% level by an outer circle in black. Further, we have linearly detrended the time series of DTR, LCC and NRD for all 215 stations before calculating correlations. Annual and seasonal patterns of DTR climatology and DTR, MMAX and MMIN trends are shown in Figures 5 to 9. Scatter plot

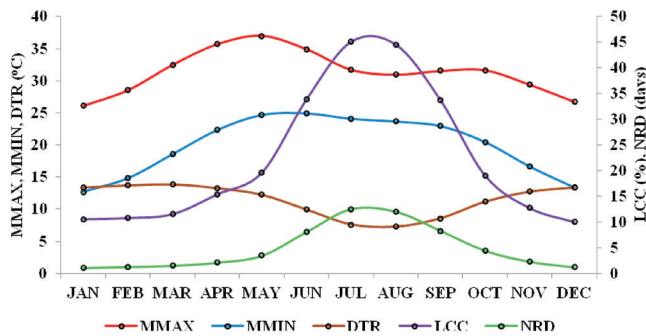


Figure 2: Monthly variations in all India mean maximum temperature (MMAX), mean minimum temperature (MMIN), diurnal temperature range (DTR), low cloud cover (LCC) and number of rainy days (NRD) based upon 215 stations for 1961-2010.

of India averaged detrended DTR against LCC and NRD are shown in Figures 10 and 12, respectively. Spatial patterns of correlation coefficients between detrended DTR and LCC & NRD are shown in Figures 11 and 13, respectively where regions of correlation coefficient less than -0.4 and more than $+0.4$ are shaded. Number of stations having positive/negative correlations between DTR & LCC and DTR & NRD are given in Table 4.

Results and Discussion

Monthly Variations in MMAX, MMIN, DTR, LCC and NRD

Climatologically, India has four distinct seasons: winter (cold weather) season (December-February), summer (hot weather) season (March-May), monsoon (rainy) season (June-September) and the post monsoon (retreating monsoon) season (October-November). Figure 2 shows monthly variability of climatic parameters MMAX, MMIN, DTR, LCC and NRD over India. All India averaged MMAX is highest in summer month May (37.0°C) and lowest (26.1°C) is in winter month January, while MMIN is highest in summer month June (25.0°C) and lowest (12.7°C) in winter month January. Country averaged highest monthly DTR is 13.9°C in March when day and night temperatures have large difference and lowest is 7.3°C in August when the entire country is under the grip of cool monsoon winds. Highest monthly LCC is 45.1% in July which is peak monsoon rainfall month and lowest is 10.0% in December where entire country is under the influence of cold dry winds. Similarly, highest NRD is in July (12.5 days) and lowest in January (1.1 days). However, annual variability of DTR is consistent with variations in cloud cover (LCC) and precipitation (NRD).

Temporal Variations in MMAX, MMIN and DTR

Figure 3 shows temporal variations in all India averaged mean annual MMAX, MMIN and DTR during 1961-2010. Both MMAX and MMIN showed non-significant increasing trends ($+0.05^{\circ}\text{C/decade}$ each), while DTR showed no trend. DTR is difference of maximum and minimum temperature and increasing annual MMAX and MMIN has contributed to no change in country averaged DTR (Figure 3a). All India averaged MMAX and MMIN trends obtained here for 1961-2010 period are consistent with earlier reported by Kothawale and Rupa Kumar (2005) but contrary to reported DTR trends. However, a closer look at Figures 3(b) and 3(c) indicates a steep rise in both MMAX and MMIN

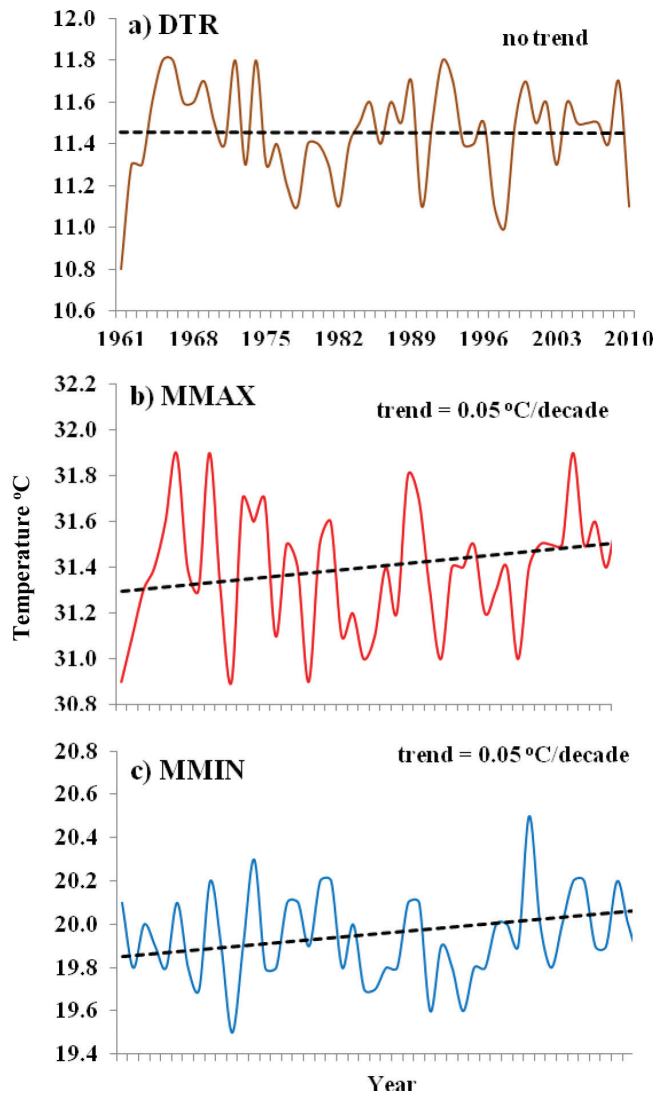


Figure 3: Temporal variations in all India averaged annual (a) diurnal temperature range (DTR), (b) mean maximum temperature (MMAX) and (c) mean minimum temperature (MMIN) during 1961-2010.

in last two decades which peaked to 32.1 °C in 2009 and 20.7 °C in 2010, respectively. During 1991-2010, the rate of increase in MMAX and MMIN is +0.21 °C/decade and +0.19 °C/decade which is significant at 95% level of confidence. Temporal variations in seasonal MMAX, MMIN and DTR for the period 1961-2010 are shown in Figure 4. Seasonally averaged DTR (Figure 4a) is showing non-significant decrease for winter and post monsoon (−0.03 °C/decade and −0.02 °C/decade, respectively) and increase for monsoon (+0.06 °C/decade) while there is no trend for summer. All India averaged MMAX is increasing by +0.05 °C/decade, +0.02 °C/decade, +0.05 °C/decade, +0.04 °C/decade for winter, summer, monsoon and post monsoon seasons, respectively but not significantly as shown in Figure

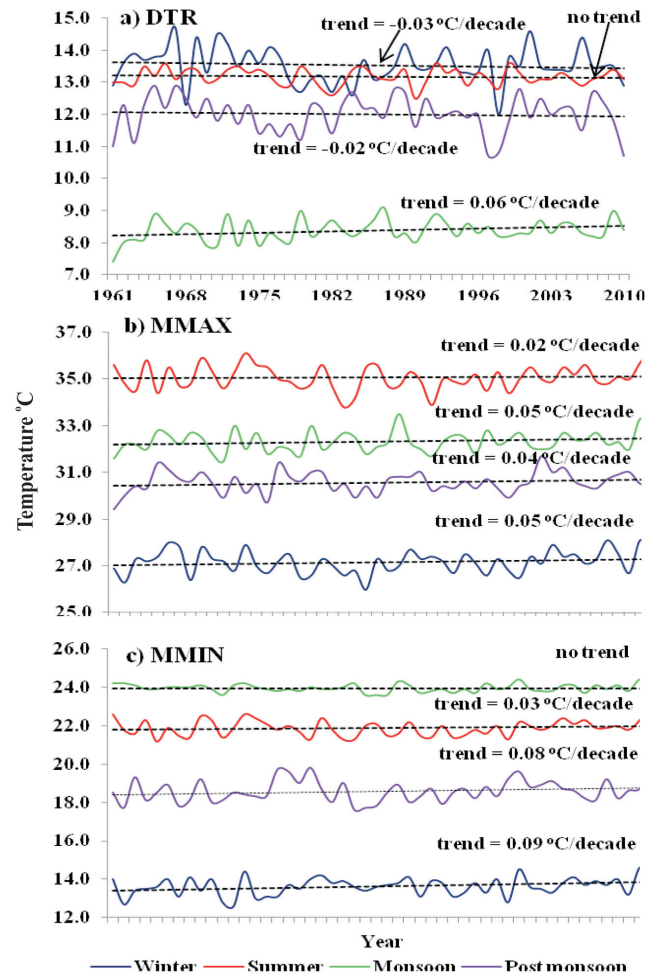


Figure 4: Temporal variations in all India averaged seasonal (a) mean maximum temperature (MMAX), (b) mean minimum temperature (MMIN) and (c) diurnal temperature range (DTR) for winter, summer, monsoon and post monsoon during 1961-2010.

4(b). Temporal variations in averaged seasonal MMIN indicate non-significant increasing trends except for monsoon season. The MMIN trend values are +0.09 °C/decade, +0.03 °C/decade and +0.08 °C/decade for winter, summer and post monsoon season, respectively as shown in Figure 4(c). However, seasonal MMAX and MMIN are significantly increasing during 1991-2010 for winter (+0.34 °C/decade and +0.36 °C/decade, respectively) and summer (+0.35 °C/decade and +0.42 °C/decade, respectively).

Climatology of DTR and Trends in DTR, MMAX and MMIN

Annual

Spatial distribution of long-term annual mean DTR over India based upon 1961-2010 period is shown in Figure 5(a). The patterns of annual mean DTR indicate

region of highest temperature over Western Himalayas, northwest and west central parts of the country where temperatures are above 14 °C. Coastal regions and northeast India have lowest temperature range with annual mean DTR below 10 °C.

Figure 5(b) shows spatial patterns of trends in annual DTR over India. Out of 215 stations selected for study, number of stations exhibiting decrease and increase in DTR are almost same as shown in Table 1. Sixty-six stations are showing significant decrease, while 65 are showing significant increase in annual DTR. However, spatial patterns of DTR trends present a distinct geographical divide over India with some pockets of exceptions. While northern half of the country except Western Himalayas is exhibiting decrease in annual DTR, southern half is having increase in DTR. Many stations in Western Himalayas and coastal areas are particularly having significant increasing trends in the range +0.4 to +0.8 °C/decade. Stations showing significant decrease in annual mean DTR are spatially more coherent in Indo-Gangetic plains, Gujarat region and northeast India where many stations are having decreasing trends in the range -1.3 to -0.8 °C/decade. Stations in Western Himalayas are exhibiting significant increasing trends in DTR in the range +0.23 to +0.35 °C/decade which are consistent with the results reported by Rupa Kumar et al. (1994), Yadav et al., (2004), Fowler and Archer (2006), Bhutiyani et al. (2007), Singh et al. (2008) and Jaswal (2010).

Spatial patterns of annual MMAX are shown in Figure 5(c) which presents a picture of general increase over the country except pockets over Indo-Gangetic plains where a few stations are showing decreasing trends. Out of 215 stations, 167 stations are exhibiting increase in annual MMAX out of which trends are significant for 127 stations as given in Table 2. The significant increasing trends in annual MMAX are spatially coherent over Western Himalayas, central, western, eastern, southeastern peninsula and along both coasts of India where many stations are having trends in the range +0.4 to +0.7 °C/decade. Rising trends in MMAX over Western Himalayas and central India obtained here are consistent with results reported by Dash et al. (2007). Figure 5(d) presents spatial patterns of annual MMIN suggesting a general increase over all over the country except a few stations showing decreasing trends. Out of 215 stations, 164 stations are exhibiting increase in annual MMIN out of which trends are significant for 128 stations as given in Table 3. The significant increasing trends in annual MMIN are spatially coherent over Western Himalayas, northwest,

central, west, northeast and along east coast of India where many stations are having trends in the range +0.6 to +0.9 °C/decade. The increasing trends in MMAX and MMIN over seasonally dry and tropical regions of India may affect crop yields (Kalra et al., 2008), since crop productivity is projected to decrease for even small local temperature increase (IPCC, 2007).

Winter

Climatological patterns long term mean DTR for winter season over India based upon 1961-2010 period is shown in Figure 6(a). With large difference in day and night temperatures, DTR is largest in this season at most of the stations in India. The region of higher DTR is over northwest, west, central and eastern parts of the country where temperatures are above 15 °C. Western Himalayas and coastal regions particularly along east coast have lowest temperature range with DTR below 10 °C in this season.

Winter season DTR trends are shown in Figure 6(b). Out of 215 stations selected for study, numbers of stations exhibiting increase in DTR are 112 while 103 are having decrease in DTR as given in Table 1. While 65 stations are showing significant increase, 58 are showing significant decrease in winter season DTR. Similar to annual trends, spatial patterns of winter DTR trends also present a clear picture of contrasting trends over India with some exceptions. While northern half of the country except Western Himalayas is exhibiting decrease in DTR, southern half is having increase in winter DTR. Stations in Western Himalayas and coastal areas are particularly having significant increasing trends in the range +0.8 to +1.4 °C/decade in this season. Stations showing significant decrease in DTR are spatially more coherent in Indo-Gangetic plains, northwest, west, east and northeast India where many stations are having trends in the range -1.3 to -0.8 °C/decade. The increasing DTR trend over Western Himalayas obtained for 1961-2010 in this study is consistent with Yadav et al. (2004), Fowler and Archer (2006) and Bhutiyani et al. (2007) but contrary to Roy and Balling (2005).

Spatial patterns of winter MMAX are shown in Figure 6(c) which indicates a general increase of mean temperature over the country except over Indo-Gangetic plains where stations are showing decreasing trends. Out of 215 stations, 160 stations are exhibiting increase in winter MMAX out of which trends are significant for 122 stations as given in Table 2. The significant increasing trends in winter MMAX are spatially coherent over Western Himalayas, west, central, northeast, south peninsula and along both coasts of India

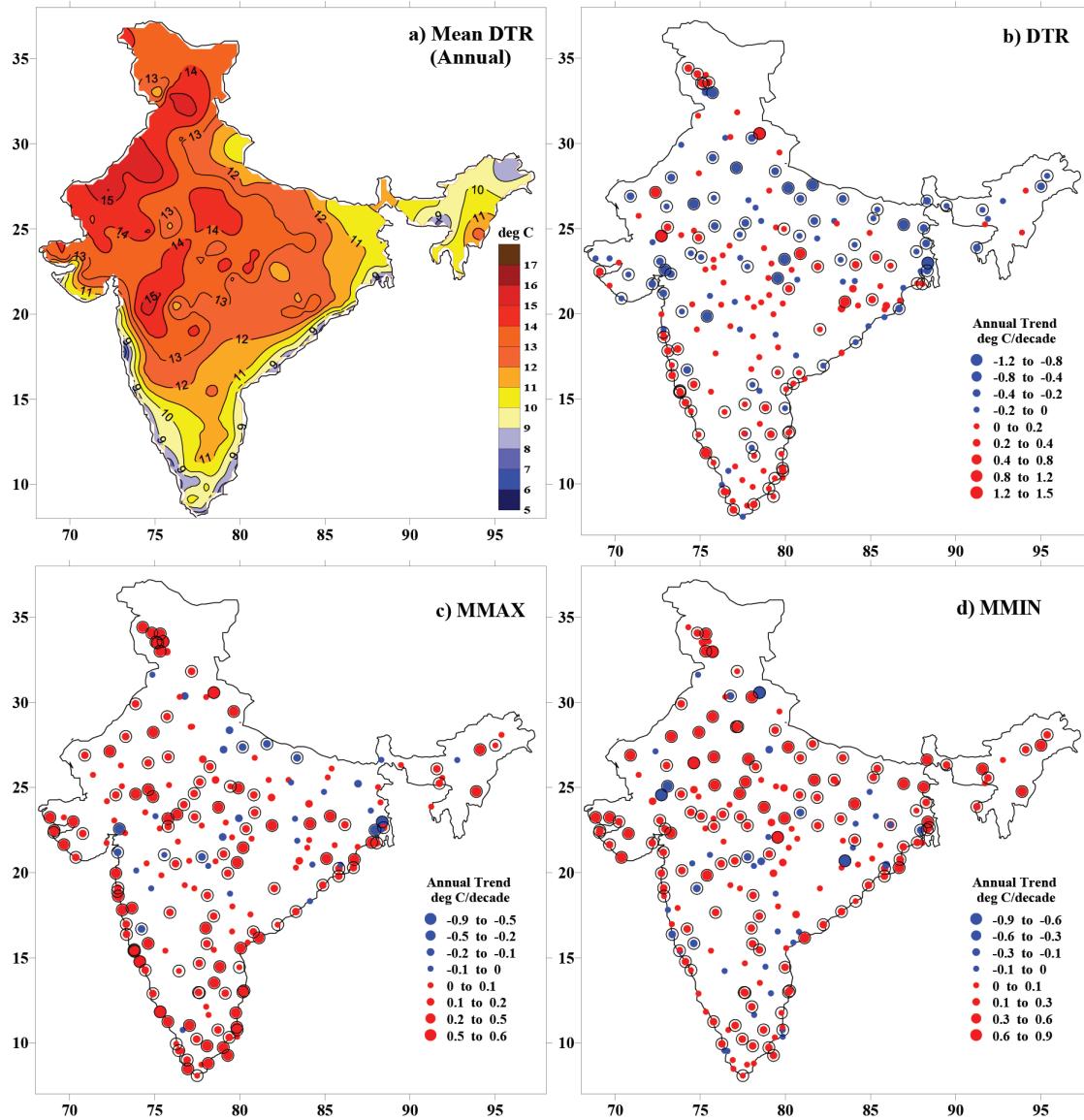


Figure 5: Spatial patterns of annual (a) climatology of diurnal temperature range (DTR), (b) trends in DTR, (c) trends in mean maximum temperature (MMAX) and (d) trends in mean minimum temperature (MMIN) during 1961-2010. Trends statistically significant at 95% level are marked by an outer circle.

Table 1: Number of stations having decreasing/increasing trends of diurnal temperature range (DTR) during 1961-2010 for annual, winter, summer, monsoon and post monsoon

	Number of stations				
	Annual	Winter	Summer	Monsoon	Post monsoon
Decreasing	90	94	88	90	97
Significantly decreasing	57	51	52	35	38
Increasing	125	121	127	125	118
Significantly increasing	58	59	54	43	35

where many stations are having trends in the range +0.8 to +1.1 °C/decade. Figure 6(d) shows spatial patterns of winter season MMIN which suggests a general

increase of mean temperature over the country except a few pockets in south peninsula where some stations are showing decreasing trends. Out of 215 stations, 161

stations are exhibiting increase in winter MMIN out of which trends are significant for 111 stations as given in Table 3. The significant increasing trends in winter MMIN are spatially coherent over Western Himalayas, northwest, central, west and northeast India where many stations are having trends in the range $+0.6$ to $+1.1$ °C/decade. The increasing trends in MMAX and MMIN are consistent with Rupa Kumar et al. (1994), Yadav et al. (2004), Roy and Balling (2005) and Kothawale and Rupa Kumar (2005).

Summer

Climatological patterns long term summer mean DTR over India based upon 1961-2010 period is shown in

Figure 7(a). Almost all regions of the country except coastal and extreme northeast are having higher DTR in this season. Northwest, west and central regions of India have many pockets of DTR above 17 °C. Coastal regions and northeast India have lowest temperature range with DTR below 10 °C in this season.

Spatial patterns of summer season DTR trends are shown in Figure 7(b). Out of 215 stations, numbers of stations exhibiting increase in DTR are 112 while 103 are having decrease in summer DTR as given in Table 1. While 64 stations are showing significant decrease, 58 are showing significant increase in DTR in this season. Spatial patterns of summer DTR trends also

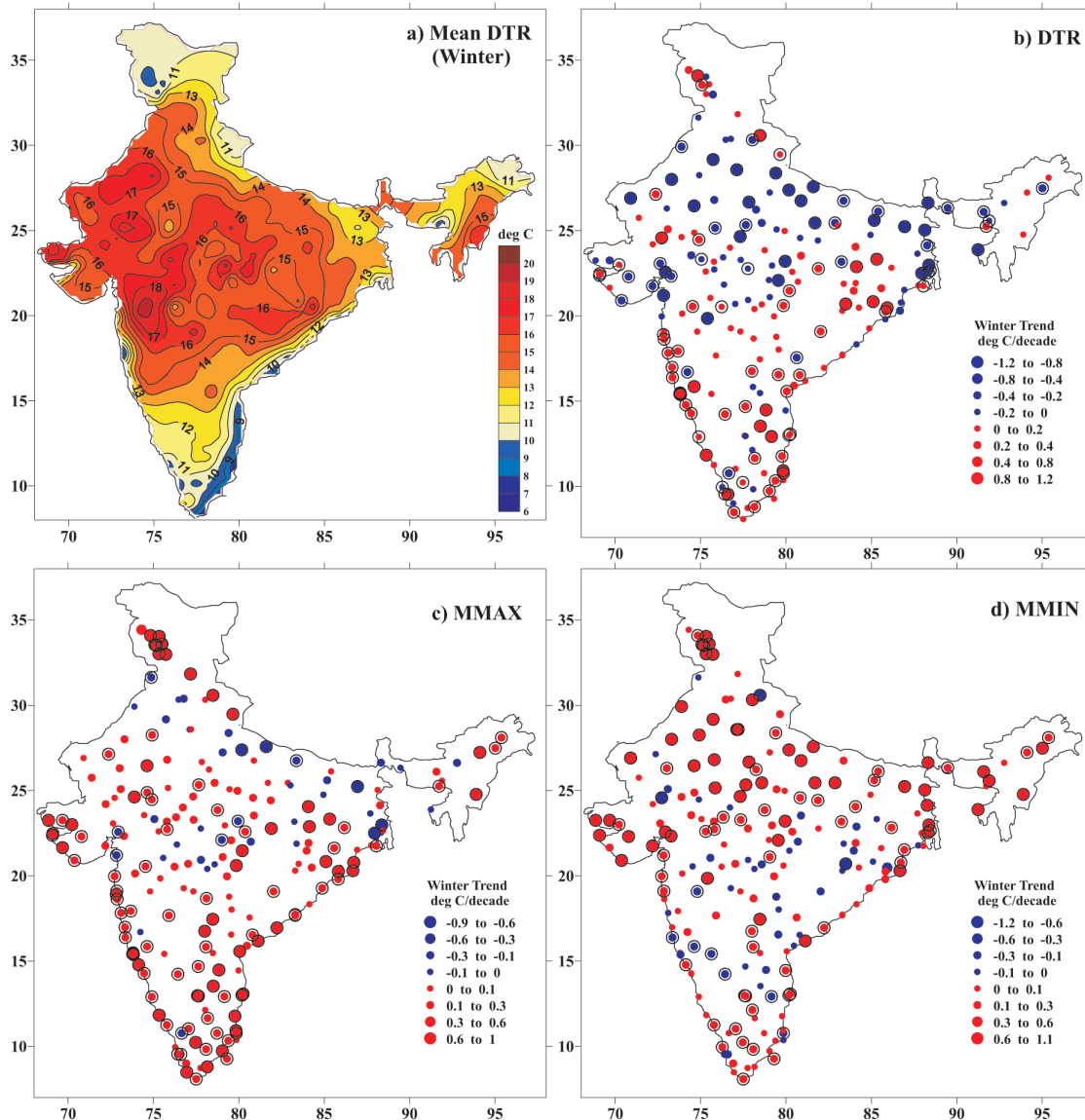


Figure 6: Spatial patterns of winter (a) climatology of diurnal temperature range (DTR), (b) trends in DTR, (c) trends in mean maximum temperature (MMAX) and (d) trends in mean minimum temperature (MMIN) during 1961-2010. Trends statistically significant at 95% level are marked by an outer circle.

Table 2: Number of stations having decreasing/increasing trends of mean maximum temperature (MMAX) during 1961-2010 for annual, winter, summer, monsoon and post monsoon

	<i>Number of stations</i>				
	<i>Annual</i>	<i>Winter</i>	<i>Summer</i>	<i>Monsoon</i>	<i>Post monsoon</i>
Decreasing	34	39	41	39	31
Significantly decreasing	10	12	10	6	7
Increasing	181	176	174	176	184
Significantly increasing	120	104	82	71	81

Table 3: Number of stations having decreasing/increasing trends of mean minimum temperature (MMIN) during 1961-2010 for annual, winter, summer, monsoon and post monsoon

	<i>Number of stations</i>				
	<i>Annual</i>	<i>Winter</i>	<i>Summer</i>	<i>Monsoon</i>	<i>Post monsoon</i>
Decreasing	39	46	50	35	32
Significantly decreasing	12	10	14	14	6
Increasing	176	169	165	180	163
Significantly increasing	121	95	98	107	98

present a general increase in northern half and decrease in southern half of the country with some exceptions. Stations in Western Himalayas and coastal areas are particularly having significant increasing trends in the range +0.8 to +1.5 °C/decade in this season. The increasing summer DTR trends over Kashmir obtained in this study are in contrast to the decreasing summer DTR trends over northwest Kashmir reported by Roy and Balling (2005). The significant increase in DTR obtained here is in contrast to the reported stations showing significant decrease in summer. DTR are spatially more coherent in Indo-Gangetic plains, west, east and northeast India where many stations are having trends in the range –1.4 to –0.8 °C/decade.

Figure 7(c) presents spatial patterns of summer MMAX trends which shows a general increase in mean maximum temperature over the country except over eastern half of the Indo-Gangetic plains where stations are showing decreasing trends. Out of 215 stations, 161 stations are showing increase in summer MMAX out of which trends are significant for 102 stations as given in Table 2. The significant increasing trends in summer MMAX are spatially coherent over Western Himalayas, west, central, south peninsula and along both coasts of India where many stations are having trends in the range +0.4 to +1.0 °C/decade. Summer season trends in MMIN are shown in Figure 7(d) which suggests a strong increase over northern half and mild increase/decrease over southern half of the country. Out of 215 stations, 155 stations are exhibiting increase in summer MMIN out of which trends are significant for 108 stations as

given in Table 3. Most of the stations having significant increasing trends in summer MMIN are spatially coherent over Western Himalayas, northwest, central, west and northeast India with trends in the range +0.5 to +1.0 °C/decade.

Monsoon

Spatial distribution of long-term climatological mean DTR for monsoon season over India is shown in Figure 8(a). The patterns of monsoon mean DTR indicate general lower temperature values (<10 °C) except over Western Himalayas and northwest where temperatures are above 10 °C. West coast and northeast India have lowest temperature range with DTR even below 5 °C in this season.

Figure 8(b) shows spatial patterns of trends in monsoon season DTR over India. Out of 215 stations selected for study, numbers of stations exhibiting decrease and increase in DTR are almost same as given in Table 1. While 54 stations are showing significant increase, 47 are showing significant decrease in monsoon DTR. However, spatial patterns of DTR trends are mixed with regions of both decrease and increase in both halves of the country. Many stations in Western Himalayas, the Indo-Gangetic plains, south central and east coast of India are having significant decreasing trends in the range –1.2 to –0.8 °C/decade. Stations showing significant increase in monsoon season DTR are spatially more coherent in north central and along west coast of India where trends are in the range +0.8 to +2.1 °C/decade.

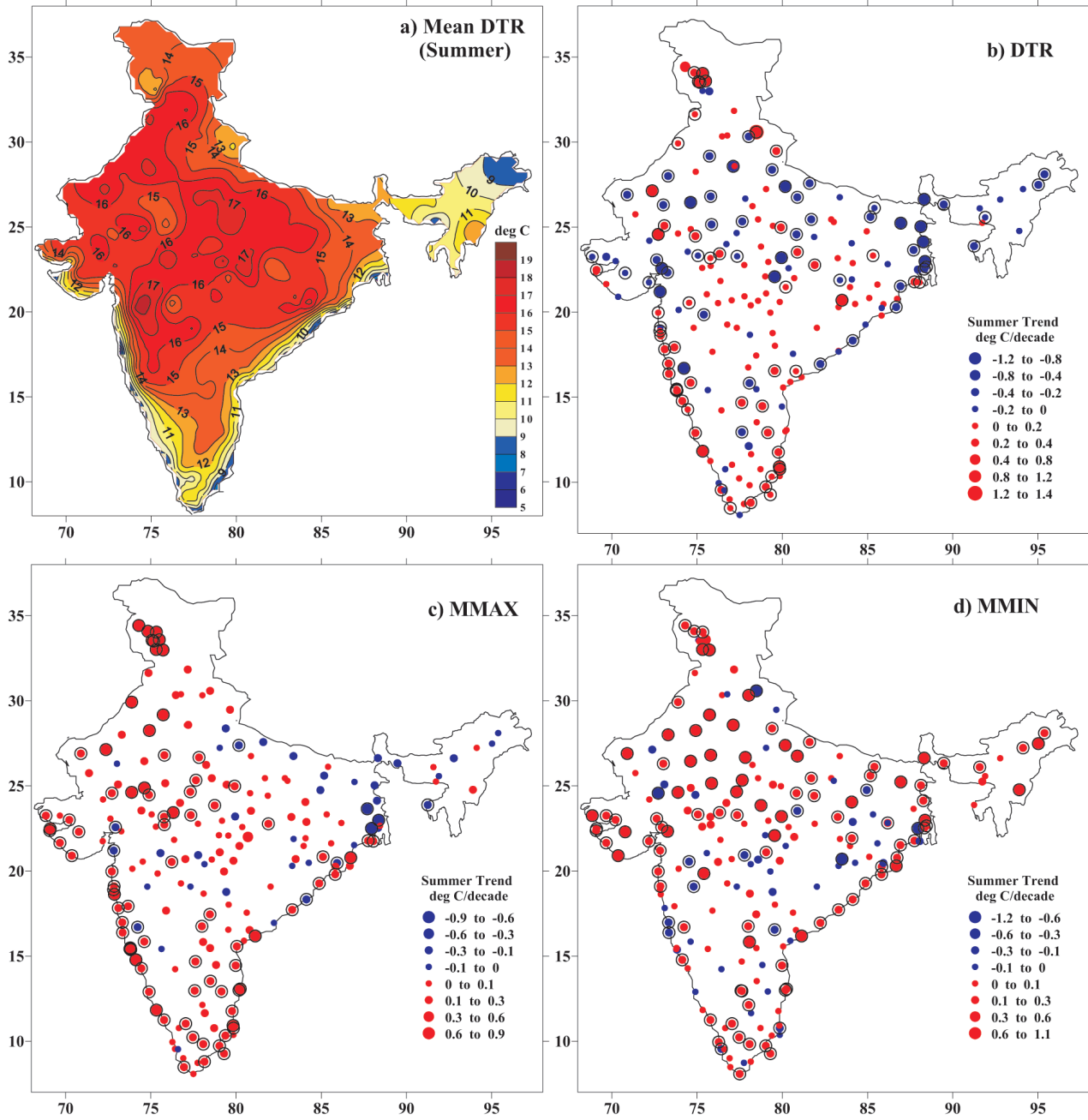


Figure 7: Spatial patterns of summer (a) climatology of diurnal temperature range (DTR), (b) trends in DTR, (c) trends in mean maximum temperature (MMAX) and (d) trends in mean minimum temperature (MMIN) during 1961-2010. Trends statistically significant at 95% level are marked by an outer circle.

Spatial patterns of monsoon season MMAX are shown in Figure 8(c). Out of 215 stations, 162 stations are exhibiting increase in MMAX out of which trends are significant for 81 stations as given in Table 2. The significant increasing trends in MMAX are spatially coherent over northwest, west central, west, northeast and southern peninsula where many stations are having trends in the range +0.4 to +0.6 °C/decade. Figure 8(d)

presents spatial patterns of monsoon MMIN suggesting a general increase over all parts of the country except a few stations showing decreasing trends. In this season, 161 stations are exhibiting increase in MMIN out of which trends are significant for 113 stations as given in Table 3. The significant increasing trends in annual MMIN are spatially coherent over Western Himalayas, the Indo-Gangetic plains, northwest, north central, west,

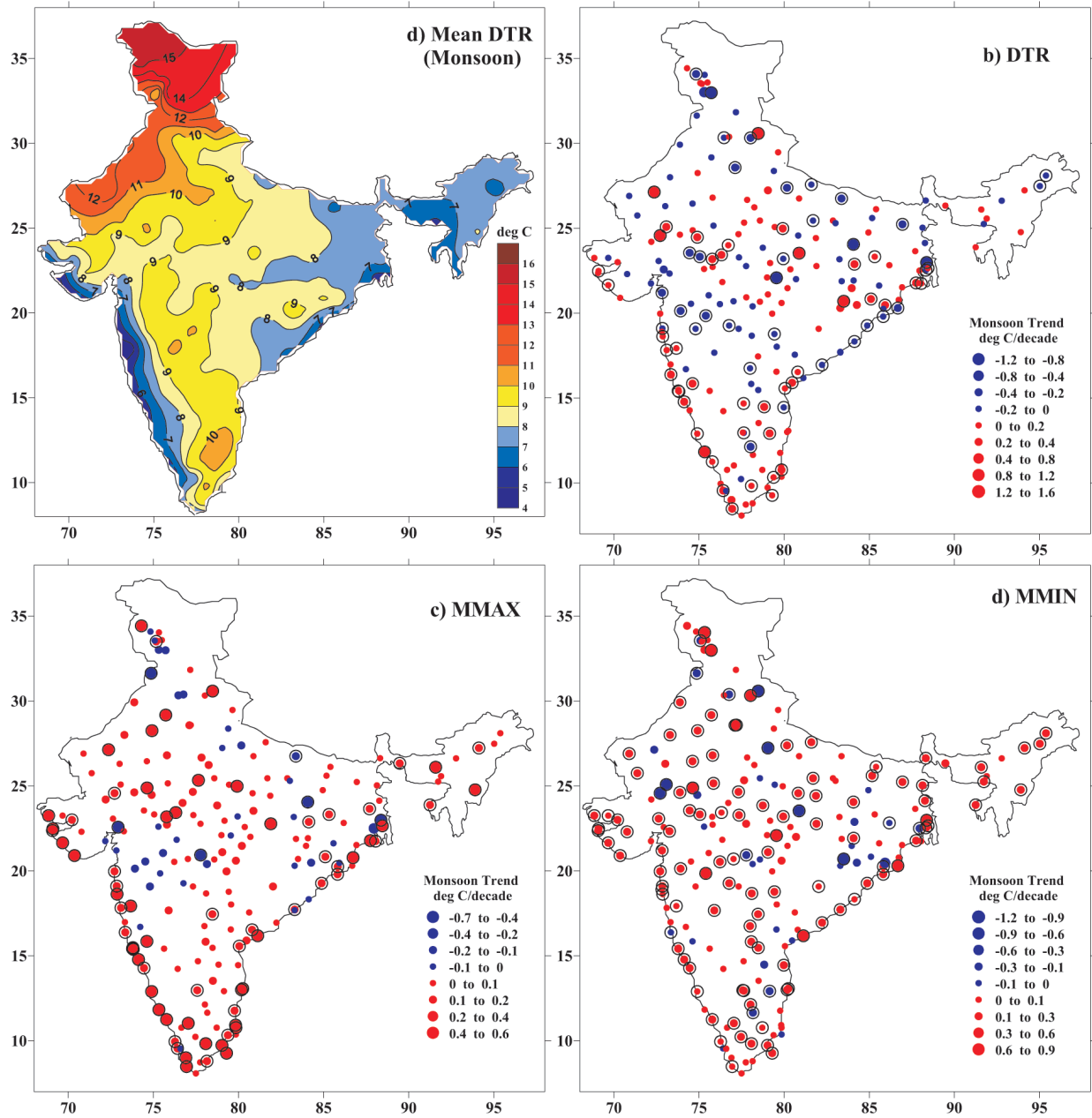


Figure 8: Spatial patterns of monsoon (a) climatology of diurnal temperature range (DTR), (b) trends in DTR, (c) trends in mean maximum temperature (MMAX) and (d) trends in mean minimum temperature (MMIN) during 1961-2010. Trends statistically significant at 95% level are marked by an outer circle.

northeast and along coasts of India where many stations are having trends in the range $+0.5$ to $+0.8$ $^{\circ}\text{C}/\text{decade}$.

Post Monsoon

Long-term climatological post monsoon season mean DTR based upon 215 stations is shown in Figure 9(a). The spatial patterns of mean DTR indicate higher temperature values over Western Himalayas, northwest and central India where temperatures are above 15°C in many pockets. Post monsoon season mean DTR values

are lower ($<10^{\circ}\text{C}$) in northeast, south peninsula south of 15°S and along east coast of India.

Spatial patterns of post monsoon season DTR trends over India are shown in Figure 9(b). Numbers of stations having decreasing trends are 113 while 102 stations are having increasing trends in DTR of this season as given in Table 1. Stations showing significant decrease and increase in DTR are 51 and 45 respectively. However, spatial patterns of DTR trends give a picture of decrease

in northern half and increase in southern half of the country with some exceptions. Stations in the Indo-Gangetic plains, west, central and northeast India are having significant decreasing trends in the range -1.2 to -0.4 °C/decade in this season. Many stations in Western Himalayas and along west coast of India are having significant increasing trends in post monsoon DTR which is in the range $+0.8$ to $+1.7$ °C/decade.

Post monsoon season MMAX trends are shown in Figure 9(c). Out of 215 stations, 170 stations are exhibiting increase in MMAX out of which trends are significant for 98 stations as given in Table 2. The

significant increasing trends in MMAX are spatially coherent over Western Himalaya, west central, west, northeast and both coasts of India where many stations are having trends in the range $+0.4$ to $+0.9$ °C/decade. Figure 9(d) presents spatial patterns of post monsoon season MMIN suggesting a general increase over all parts of the country except a few stations showing decreasing trends. In this season, 149 stations are exhibiting increase in MMIN out of which trends are significant for 111 stations as given in Table 3. The significant increasing trends in post monsoon season MMIN are spatially coherent over the Indo-Gangetic

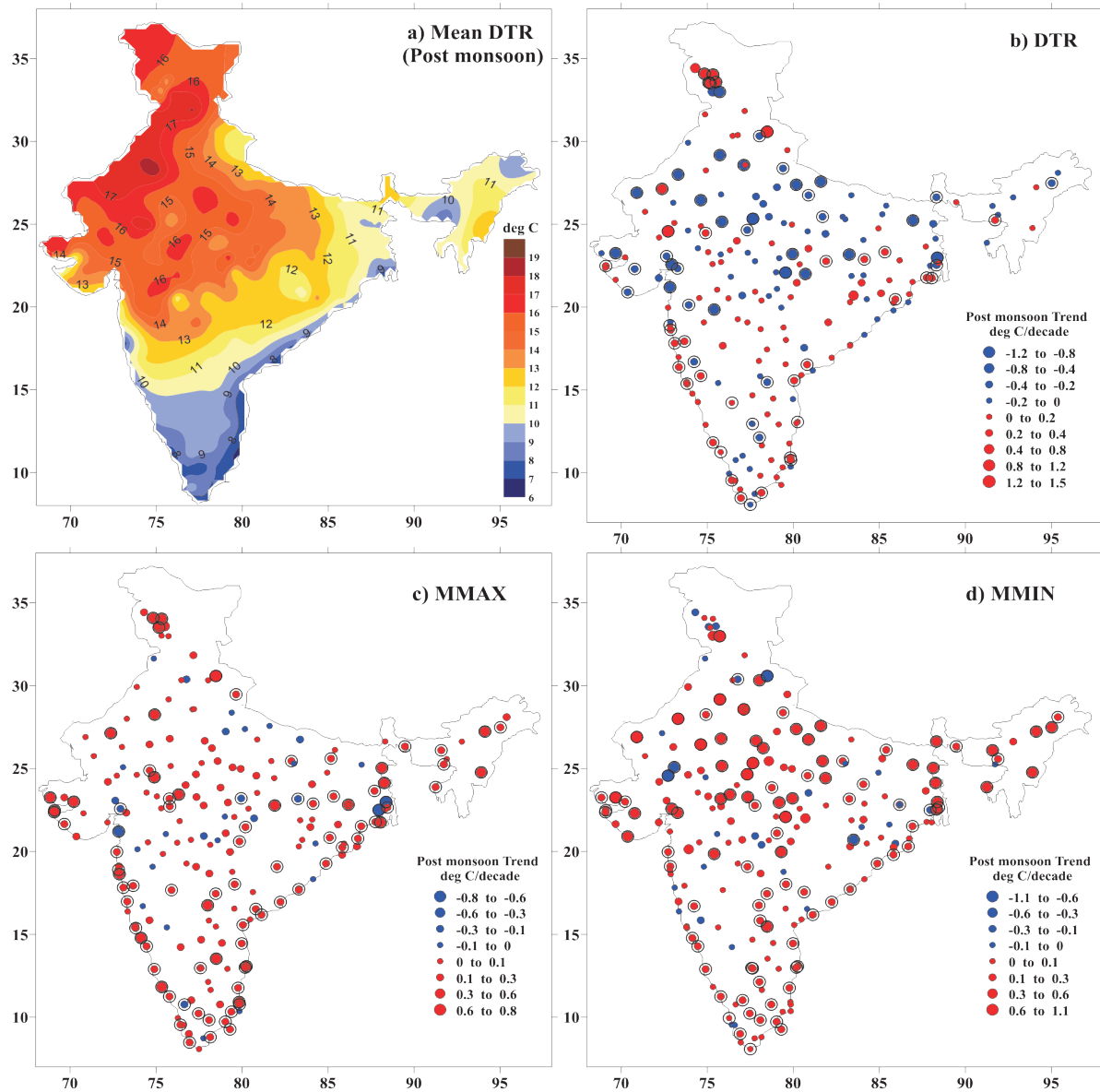


Figure 9: Spatial patterns of post monsoon (a) climatology of diurnal temperature range (DTR), (b) trends in DTR, (c) trends in mean maximum temperature (MMAX) and (d) trends in mean minimum temperature (MMIN) during 1961-2010. Trends statistically significant at 95% level are marked by an outer circle.

plains, northwest, central, west, northeast and along both coasts of India where many stations are having trends in the range +0.6 to +1.3 °C/decade.

Relationship between DTR and Associated Climatic Variables LCC and NRD

Studies undertaken to determine the controlling factors of diurnal temperature range have shown that it responds strongly to forcing from cloud cover, precipitation and soil moisture (Plantico et al., 1990; Karl et al., 1993; Stenchikov and Robock, 1995; Dai et al., 1999, 2001; Stone and Weaver, 2003). Many other additional factors that affect diurnal temperature range include land use/land cover changes (Gallo et al., 1996), irrigation (Karl et al., 1988), station shifting, desertification and other climatic effects (Karl et al., 1993). Impact of urbanization also has been investigated in many studies (Karl et al., 1988; Landsberg, 1981; Wang et al., 2012). It was found that as the population of an urban centre increases, the diurnal temperature range would shift in an asymmetrical manner (Karl et al., 1991). So, diurnal temperature range is also an important indicator for climate change (Karl et al., 2004).

Scatter plot of all India averaged detrended time series of annual and seasonal DTR, LCC and NRD (Figures 10 and 12) show relationship between these variables. DTR values should usually have a significant negative relationship with observed low cloud and the number of rainy days. The spatial patterns of correlation coefficients of DTR & LCC and DTR & NRD are shown in Figures 11 and 13, respectively. In our study, the regions having significantly negative correlations between DTR and LCC have also significantly negative correlations between DTR and NRD suggesting a closer relationship between them. Many researchers have proposed that increases in cloud cover and precipitation lead to decreasing DTR (Plantico et al., 1990; Karl et al., 1993; Dai et al., 1997, 1999).

Correlation between DTR and LCC

The low cloud cover over India has two opposing seasonal patterns. It is lowest during winter with long-term (1961-2010) mean low cloud cover ~10.5%. With the progression of the season the cloud cover increases. It reaches ~15.6% during pre-monsoon season, peaks to ~39.4% during the monsoon season and then drops to ~15.9% in the post monsoon. The relationship between detrended mean DTR and LCC for annual and four seasons during the period 1961 to 2010 is shown in Figure 10. The notable feature of this scatter plot is the opposite relationship between DTR and LCC during all periods indicating significant negative correlation

between these two atmospheric parameters as shown in Figures 10(a-e). Upon comparing the two time series, strong correlations were found in the annual means (−0.84), and also for the different seasons: winter (−0.87), summer (−0.84), monsoon (−0.88) and post monsoon (−0.92). All correlations are significant at the 95% level of confidence. With coefficient of determination in the range 0.71 to 0.85, there is strong relationship between these two variables explaining the DTR variability. It is clear that the higher the correlations, the bigger the influence of LCC on DTR; indeed the highest values can be found in post monsoon, monsoon, followed by winter and summer season.

Spatial patterns of correlation between DTR and LCC are shown in Figure 11 where regions having moderate to strong correlation (less than −0.4 or more than +0.4) are shaded. Correlation between mean DTR and LCC is negative over most of the country as 81%, 94%, 86%, 84% and 94% stations are negatively correlated for annual, winter, summer, monsoon and post monsoon, respectively as given in Table 4 which provides additional confidence in the data utilized in the study. However, the observed coincident decrease in DTR and LCC or increase in DTR and LCC at some stations suggests that other mechanisms may have been involved in changing the DTR. The magnitude of correlation of annual mean DTR and LCC detrended time series is between −0.69 and +0.66. Shaded region in Figure 11(a) indicates moderate to strong correlation between annual mean DTR and LCC, which are primarily located in Indo-Gangetic plains, northwest, northeast and southeast India. Correlation coefficients of winter mean DTR and LCC time series is between −0.90 and +0.50. Spatial patterns of winter mean DTR and LCC correlations (Figure 11b) suggest regions of moderate to strong negative correlation over most parts of the country except in some pockets over west and southeast India. Figure 11(c) shows spatial patterns of summer mean DTR and LCC correlation which are moderate to strong over northwest and some pockets over east, northeast and south India. Summer season DTR and LCC correlation coefficients are between −0.71 and +0.47 while for monsoon season correlations are between −0.81 and +0.57. Spatially, regions of moderate to strong correlations between monsoon DTR and LCC are located over north, west, central, east and south peninsula as shown in Figure 11(d). Post monsoon season correlation coefficients of DTR and LCC are between −0.87 and +0.57 with moderate to strong correlations over most parts of the country as shown by the shaded region in Figure 11(e).

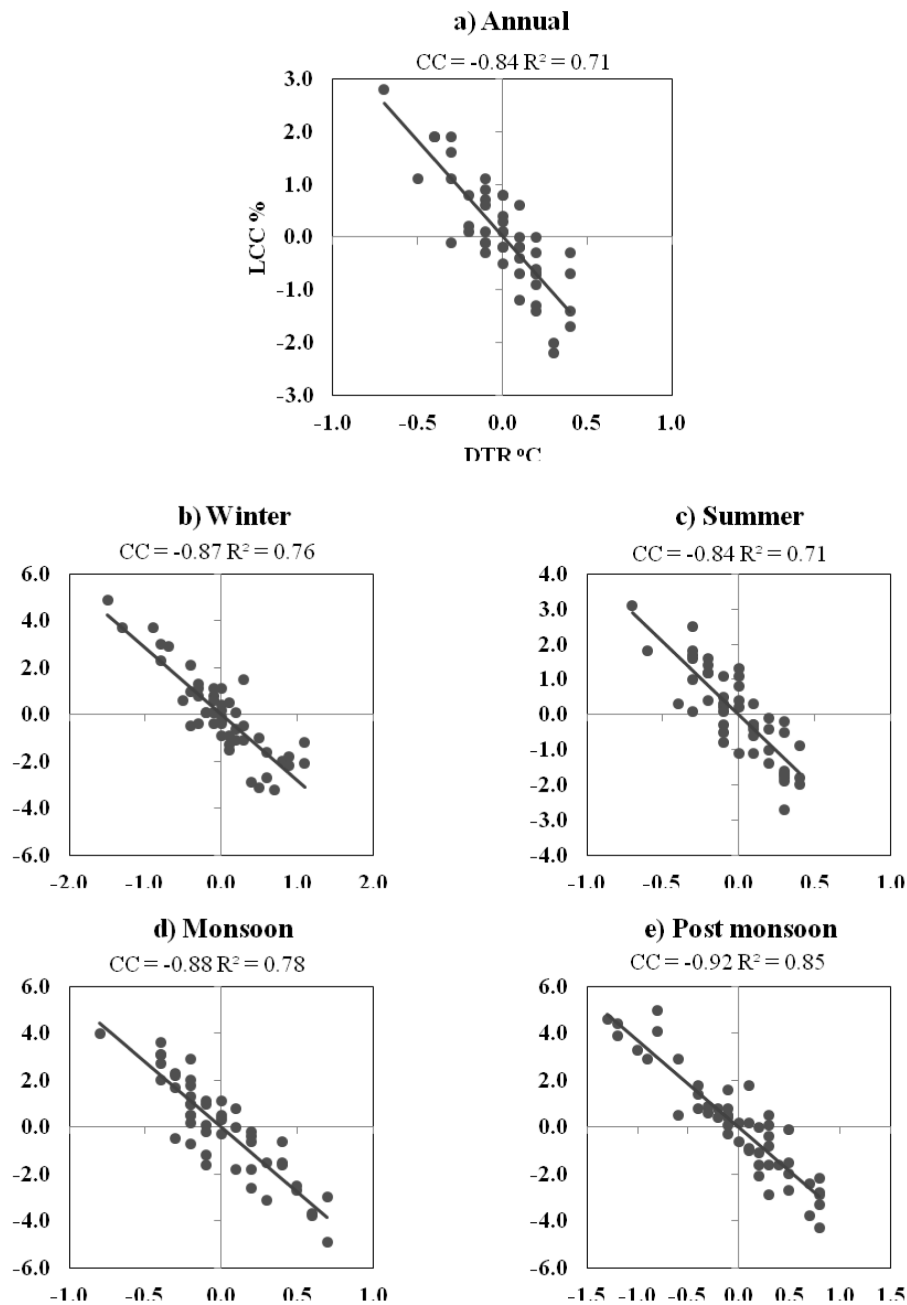


Figure 10: Scatter plot of all India mean diurnal temperature range (DTR) and low cloud cover (LCC) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon.

Data series are linearly detrended for 1961-2010.

Table 4: Number of stations having positive/negative correlation between diurnal temperature range (DTR) and low cloud cover (LCC) and number of rainy days (NRD) for annual, winter, summer, monsoon and post monsoon

Sign of correlation		Number of stations				
		Annual	Winter	Summer	Monsoon	Post monsoon
DTR & LCC	Positive	41	13	31	35	12
	Negative	174	202	184	180	203
DTR & NRD	Positive	17	4	29	12	2
	Negative	198	211	186	203	213

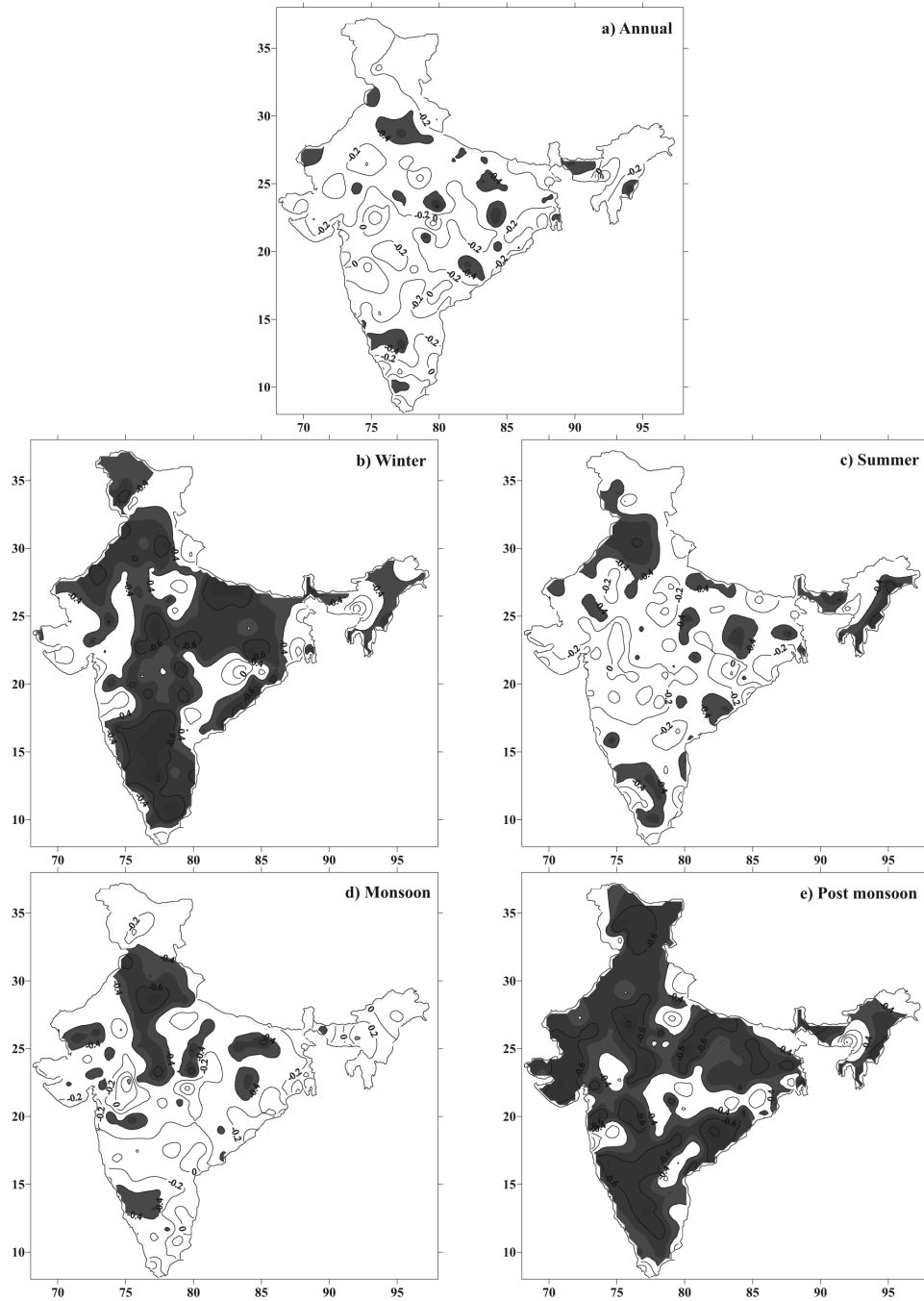


Figure 11: Spatial patterns of correlation coefficient (CC) between diurnal temperature range (DTR) and low cloud cover (LCC) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon. Regions having CC less than -0.4 or more than $+0.4$ are shaded.

Correlation between DTR and NRD

The relationship between mean DTR and NRD for annual and four seasons during the period 1961 to 2010 is shown in Figure 12. Strong correlations were found between DTR and NRD in the annual (-0.76) and also for winter (-0.82), summer (-0.77), monsoon (-0.84) and post monsoon (-0.86) seasons. All correlations

are significant at the 95% level of confidence. With coefficient of determination (R^2) in the range 0.57 to 0.75, there is strong relationship between these two variables explaining their variability. It is clear that the higher the correlations, the bigger the influence of NRD on DTR. The highest correlation is found in post monsoon followed by monsoon, winter and summer.

The relationship between DTR and NRD obtained here are consistent with the results reported by Dai et al. (1997).

Spatial patterns of correlation between DTR and NRD are shown in Figure 13 where regions having moderate to strong correlations are shaded. Correlation between mean DTR and NRD is negative over most of the country as 92%, 98%, 87%, 94% and 99% stations

are negatively correlated for annual, winter, summer, monsoon and post monsoon respectively as given in Table 4 which provides additional confidence in the data utilized in the study. However, the observed coincident decrease in DTR and NRD or increase in DTR and NRD over some regions suggests that other mechanisms may have been involved in changing the DTR. The magnitude of correlation of annual mean DTR and NRD

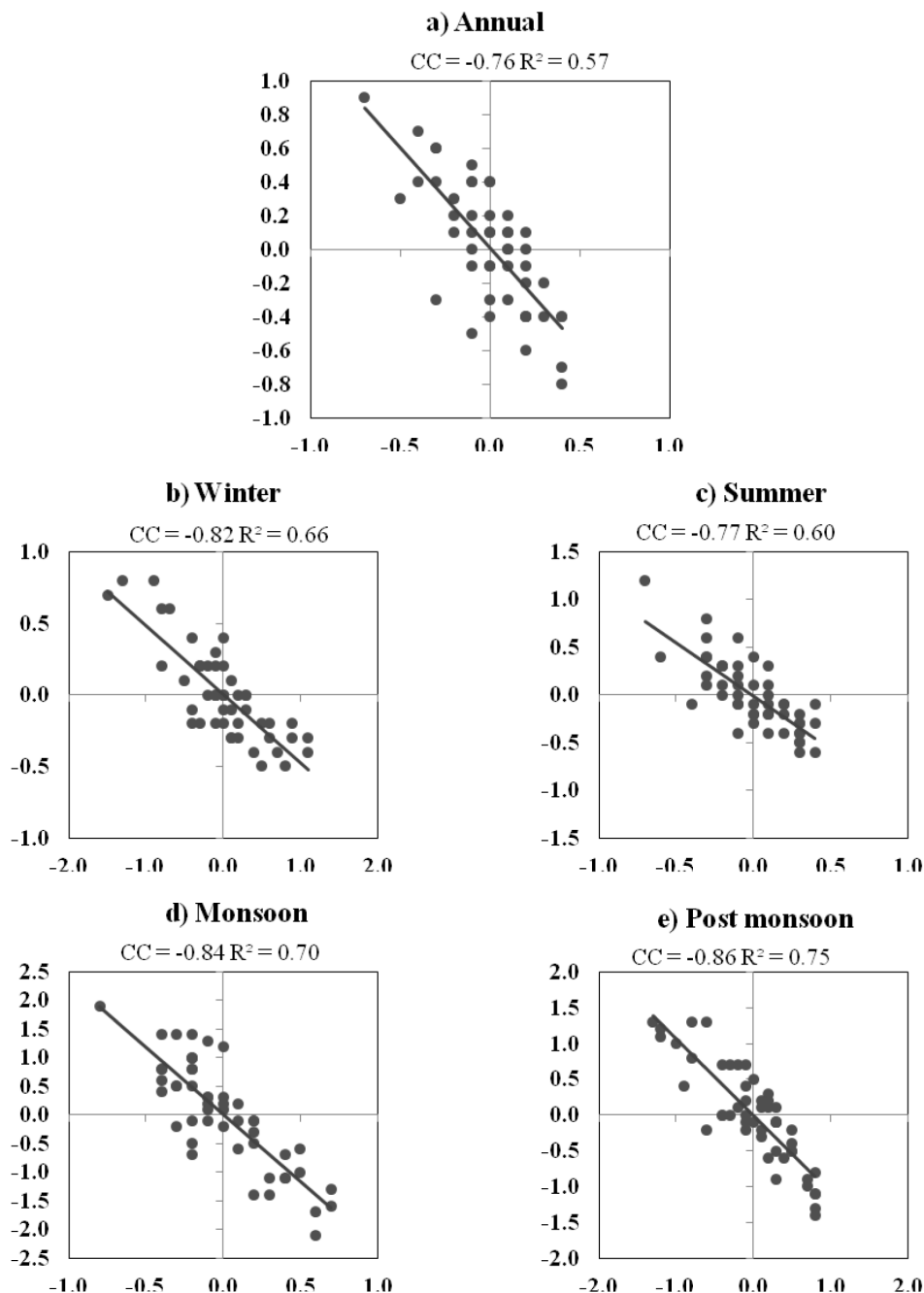


Figure 12: Scatter plot of all India mean diurnal temperature range (DTR) and number of rainy days (NRD) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon. Data series are linearly detrended for 1961-2010.

is between -0.72 and $+0.25$. Shaded regions in Figure 13(a) indicate moderate to strong correlation between annual mean DTR and NRD. Correlation coefficients of winter mean DTR and NRD are between -0.84 and $+0.19$. Spatial patterns of winter mean DTR and NRD correlations (Figure 13 b) suggest regions of moderate to strong negative correlation over all over India except

in west. Summer season correlation coefficients between DTR and NRD are between -0.77 and $+0.35$. Figure 13(c) shows spatial patterns of summer mean DTR and NRD correlation which have moderate to strong correlation over northwest, east and northeast India. Monsoon season mean DTR and NRD correlations are between -0.76 and $+0.54$. Spatially, regions of moderate

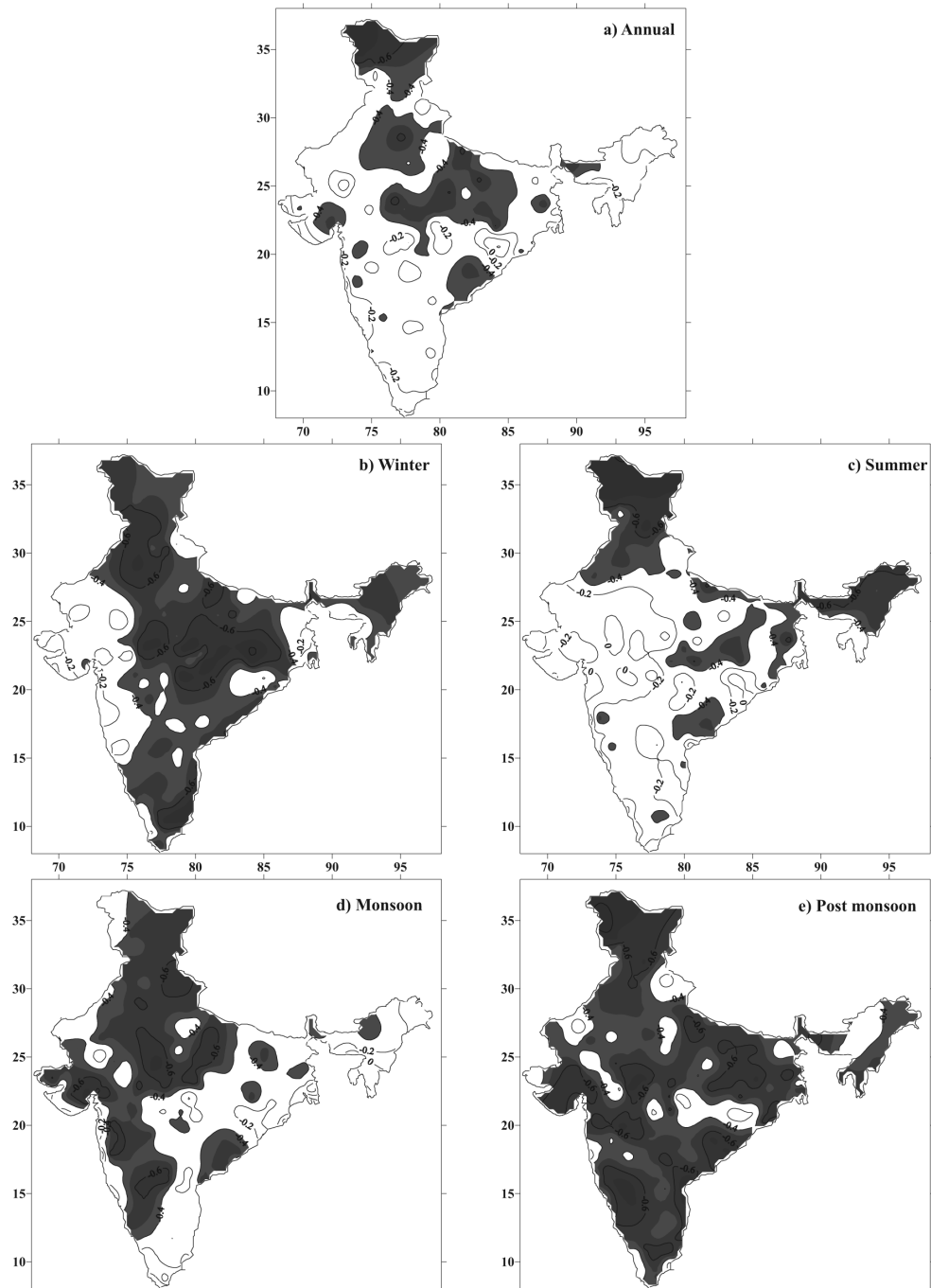


Figure 13: Spatial patterns of correlation coefficients (CC) between total cloud cover (TCC) and diurnal temperature range (DTR) for (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon. Regions having CC less than -0.4 or more than $+0.4$ are shaded.

to strong correlations are mainly located over northwest, central, west and south peninsula as shown in Figure 13(d). Post monsoon season correlation coefficients of DTR and NRD are between -0.85 and $+0.03$. Moderate to strong correlation between post monsoon season DTR and NRD is seen over almost entire country (Figure 13e).

Annual and seasonal trends in DTR over India and their relationship with climatic variables, low cloud cover and rainy days are investigated for 1961-2010. The notable feature of this study is a distinct north-south spatial divide of obtained trends in DTR over India. As seen in figures of trends in previous sections, annual and seasonal DTR is decreasing in northern half of India and increasing in the southern half during 1961-2010. A closer look on spatial patterns of trends shows milder increase in MMAX at stations in the northern half as compared to the southern half of the country. But there have been strong increase in MMIN at most of the stations in the northern half of India as compared to the southern half as shown in the spatial patterns of trends in MMIN. Since MMIN have been increasing at a greater rate than MMAX, even where MMAX are also increasing, there has been a resulting decrease in annual and seasonal DTR at stations in northern half of the country. Similarly, in southern half annual and seasonal MMAX have been increasing at a greater rate than annual and seasonal MMIN resulting in increase in annual and seasonal DTR at most of the stations. Many scientists have noted that rise in temperatures is not uniform with less increase observed in day temperatures and substantial increase in night temperatures (Karl et al., 1993; Easterling et al., 1997; Dai et al., 1997; Braganza et al., 2004). Therefore, the decrease in DTR over the northern half of India obtained in this study is a manifestation of a rise in the minimum temperature which has occurred at a rate much higher than that of the maximum temperature during the period of study.

The significant increase in DTR over Western Himalayas for annual, winter, summer and post monsoon is similar to earlier reported by Rupa Kumar et al. (1994), Yadav et al. (2004), Fowler and Archer (2006) and Bhutiyani et al. (2007). Changes in land surface properties such as deforestation may be one of the main causes of increase in DTR over Western Himalayas as suggested by Yadav et al. (2004). Removal of tree canopies in hilly regions facilitate heating of soil in daytime and intense radiation cooling in night-time leading to increase in temperature range. Venkataraman et al. (2005) have shown that seasonal biomass-burning smoke and dust storms are the major sources of black

carbon and aerosols in the Indo-Gangetic plains which is showing strong increasing trends (Sarkar et al., 2006). Concentration of aerosols contributes to the local effects in the form of daytime cooling and nighttime warming, effectively reducing the temperature range. Therefore, anthropogenic aerosols may be one of the main causes of significant decrease in DTR over the Indo-Gangetic plains as suggested by Karl et al. (1995) and Dai et al. (1999).

Further, it is found that for most cases, mean annual and seasonal DTR are significantly negatively correlated with annual and seasonal mean LCC and NRD, providing additional confidence in the data utilised in the study. Durre and Wallace (2001) reported that the spatial patterns of DTR trends are physically consistent with the pattern of trends in cloud cover areas. In our study also, areas of moderate to strong negative correlations between DTR and LCC & NRD have significant decreasing trends in DTR. Almost all the cases of DTR decreases were moderate and negatively correlated with LCC and NRD. As is clear from Figures 13(a)-(e), detrended time series of number of days with precipitation are well correlated with those of DTR over India during 1961-2010. With seasonal coefficient of determination of DTR and LCC in the range 0.71 to 0.85 and DTR and NRD in the range 0.60 to 0.75 signaling strong relationship, LCC and NRD explain most of the variance of DTR in India. Like in other parts of the world reported by various studies (Henderson-Sellers, 1992; Plantico et al., 1990; Jones and Henderson-Sellers, 1992; Karl et al., 1993; Dai et al., 1997, 1999), cloud cover and precipitation are the main factors responsible for seasonal, temporal and spatial variations of DTR in India. Having negative correlation between DTR and cloud cover and precipitation, it is expected that areas of long-term decrease in DTR would have increase in cloud cover and precipitation. However, the simultaneous decrease (increase) in DTR and decrease (increase) in cloud cover and precipitation suggest other mechanisms may be involved in changing the DTR at regional scales. Obviously there may be many other factors such as surface properties, irrigation, greenhouse gases and atmospheric aerosols, which might be contributing to DTR variance.

The rise in temperatures over India may affect agriculture, horticulture, water resources and human health. Higher temperatures create an environment in which plant diseases and pests thrive and pose a serious threat to crops. Kalra et al. (2008) have found signs of stagnation or decrease in yield of rabi crops following rise in temperature at four northern states of India.

A faster rising minimum temperature and narrowing DTR can have significant effect if warmer night time temperature allows for longer growing season. Further work is required to understand the impacts of changes in DTR on agriculture, horticulture and human health over India.

Conclusions

Analysis of surface temperatures and associated variables such as low cloud cover and number of rainy days carried out in this investigation provides spatially and temporally detailed results for changes in diurnal temperature range in India based upon long-term (1961-2010) quality checked data. The results of this study are summarized as follows:

- (a) The data analysis indicates that all India averaged DTR is having distinct spatial contrast in trends over the country during past 50 years (1961-2010). Northern half of India is having decrease in DTR while southern half is having increase in DTR for all periods.
- (b) All India averaged annual and seasonal DTR is showing mixed trends. Winter and post monsoon DTR is decreasing, monsoon DTR is increasing and annual and summer DTR is showing no trend. However, both MMAX and MMIN are showing increase except MMIN in monsoon season.
- (c) Annual and seasonal (except monsoon) DTR is significantly increasing at stations in Western Himalayas which can be attributed to change in land surface and deforestation. The persistent decrease in annual and seasonal DTR over the Indo-Gangetic plains may be attributed to increase in anthropogenic aerosols and urbanization, in addition to increase in cloud cover and rainy days.
- (d) Spatially, MMAX and MMIN are increasing over India with amplitude of MMAX trends higher in south India and that of MMIN trends higher in north India.
- (e) DTR variability with related meteorological parameters LCC and NRD is physically consistent during the period of study.

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