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Climate variability in Dharamsala - a hill station in Western Himalayas

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ABSTRACT

Climate change worries the scientific community world over as the surface air temperature increased by 0.74ºC during 1906-2005. The impacts of warming in mountainous regions get magnified because of large variations in altitude within small distance. This study focuses on the variability and trends of air temperature and rainfall during 1951-2010 in Dharamsala, a hill station in Himachal Pradesh located in Western Himalaya , India. The results of the trend analysis show a statistically significant increase in monthly mean maximum temperature (January, April, November and December), mean temperature (January), mean diurnal temperature range (January to May, July to December), total monthly rainfall (June) and 24 hour heaviest rainfall (June). Statistically, significant decreasing trends are found in monthly mean minimum temperature (May to October), mean temperature (June), monthly rainfall (January and August) and rainy days (January). Seasonally, significant increasing trends are observed in mean maximum temperature (winter and post monsoon), mean temperature (winter) and diurnal temperature range (all seasons) and significant decreasing trends in minimum temperature for summer, monsoon and post monsoon. Annual mean maximum temperature and mean diurnal temperature range are significantly increasing at a rate +0.018ºC/year and +0.033ºC/year, respectively ,while annual mean minimum temperature is significantly decreasing by -0.018ºC/year. The trend analysis of air temperature and rainfall reveals a tendency of increase in maximum temperature, decrease in minimum temperature and rainfall , which may have impacts on agriculture, water resources, human health and natural environment in Dharamsala and surrounding region.

INTRODUCTION

Global warming is one of the most important issues of present times leading to numerous trend detection studies in all parts of the world. The Earth's atmosphere is warming and according to the Intergovernmental Panel on Climate Change (IPCC), global mean temperature has increased by approximately 0.74°C during 1906-2005 ,with more than half of this rise taking place in the last 25 years (IPCC, 2007). Mountains and cold climate regions are early indicators of climate change as the higher the altitude, the more rapid the warming is, a fact suggested by temperature records from Nepal (Shrestha et al., 1999) and China (Liu and Chen, 2000). Studies indicate that the Himalayan region is warming at a rate higher than the global average rate (Shrestha et al., 1999; Liu and Chen, 2000; New et al., 2002; Xu et al., 2009) and temperature differences are greater during the winter and autumn than during the summer. Under the influence of changing climate, mountainous regions are likely to experience wide ranging effects on the environment and biodiversity (Beniston, 2003).

Temperature trends over India have been studied by number of researchers (Hingane et al., 1985; Srivastava et al., 1992; Rupa Kumar et al., 1994; Sahai, 1998, Kothawale and Rupa Kumar, 2005; Bhutiyani et al., 2007; Das et al., 2007 and Jaswal, 2010). In general, warming trends in maximum and minimum temperatures over India have been reported by them. However, there has been a very few detailed researches on observed climate change in the mountains and generalisations have been made from scattered studies carried out at sites widely separated in space and time (IPCC, 2007; Nogues-Bravo et al., 2007). Studies on the Tibetan Plateau region (Liu and Chen, 2000; Liu et al., 2006; You et al., 2008) have also reported a warming trend but minimum temperature warming is more prominent than that of the maximum temperature. In contrast, trend studies over the Indian subcontinent and the Himalayan region found maximum temperature warming more prominently (Arora et al., 2005; Fowler and Archer, 2006; Bhutiyani et al., 2007; Jaswal, 2010; Pal and Tabbaa, 2010). According to Dash and Hunt (2007), winter maximum temperature over India has increased by 1°C during 1901-2003. Study of maximum and minimum temperature during months by Jaswal (2010) reveals significant increase in temperature in February over North India. Northwest Himalayan region has experienced significant rise in air temperature by 1.6° C during the last century (Bhutiyani et al., 2007) ,while the average annual maximum temperature of Kashmir valley has gone up by about 1.4ºC during 1976-2007 (Jaswal and Rao, 2010). Changes in the hydrological cycle may significantly change precipitation pattern. Using high resolution daily gridded rainfall data set, Goswami et al. (2006) have shown that there are significant rising trends in the frequency and magnitude of extreme rainfall events over central India during the monsoon season. Associated with global warming, there are indications of changes in rainfall patterns both on global and regional scale (Sahai, et al., 2003, Rajeevan et al., 2008).

Being a hill state in Western Himalaya, Himachal Pradesh is probably more sensitive to global warming. But, a very few studies on temperature and rainfall variability over Himachal Pradesh are available. In this study, we have analyzed temperature and rainfall variability in Dharamsala for the period of 1951-2010.

DATA AND METHODOLOGY

Study Area

Dharamsala is one of the important hill stations located between 31° 21' N to 32° 59' N latitude and 75° 47' 55" E to 77° 45' E longitude in Kangra district of Himachal Pradesh (Figure 1). It was destroyed by a massive earthquake in the year 1905 and was reconstructed to become a popular tourist and commercial destination of India. The peculiar geographical location of Dharamsala offers views of the snow-capped Dhauladhar ranges above and the Kangra valley below with dense pine and deodar forests. Situated on the southern slopes of the Western *Himalayas, t*he entire area of the district is traversed by the varying altitude of the *Shivaliks, Dhauladhar* and the *Himalayas* from northwest to southeast. The altitude of Kangra district varies from 500 metres to around 5000 metres above mean sea level. Dharamsala falls under wet temperate zone, where the annual mean temperature is about 19.1±0.5ºC and annual rainfall is about 2900±639 mm, as reported by 1951-2010 data.

Trend Detection

Trends are determined using a non-parametric Mann-Kendall test to assess the probability that there is a trend statistically different from zero. Evaluation of increasing or decreasing slope of trends in the time series of temperature and rainfall is carried out 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.

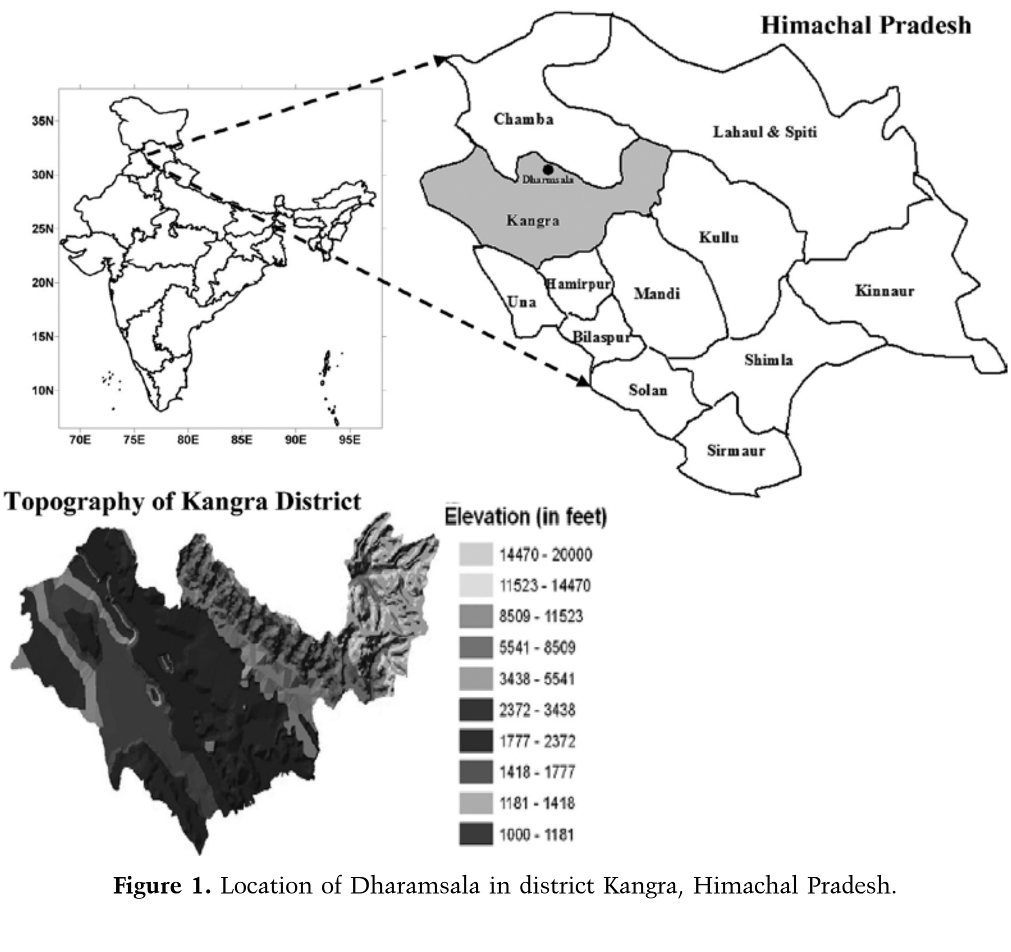

Figure 1. Location of Dharamsala in district Kangra, Himachal Pradesh.

The Mann–Kendall statistics is given by:

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

where n is the length of the data set, x_i and x_j are two generic sequential data values.

The function sign $(x_i - x_j)$ assumes the following values:

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

Under the hypothesis of independent and randomly distributed variables when $n \geq 8$, the statistic S is approximately normally distributed with zero mean and the variance Var(S) as follows:

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

where n is the length of the times-series. The standardized test statistic Z is given by:

$$Z= \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S-1}{\sqrt{Var(S)}} & if\ S < 0. \end{cases} \tag{4}$$

The presence of a statistically significant trend is evaluated using the Z value. This statistics is used to test the null hypothesis 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, the significance levels of 0.05, 0.01 and 0.001 are applied and the significant level p-value is obtained for each analyzed time-series. 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.

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

where b is the slope between data points X_j and X_i measured at times j and i respectively.

DATA AND COMPUTATIONAL METHOD

The meteorological data for Dharamsala station (32° 16' N 76° 23' E, 1211 m amsl)–are obtained from the archives of National Data Centre of India Meteorological Department (IMD) located at Pune. The monthly means of maximum and minimum temperature, monthly total rainfall, monthly total rainy days (days having rainfall more than 2.4 mm) and 24 hours heaviest rainfall in a month are acquired for the surface meteorological station Dharamsala for the period 1951-2010. In addition to mean maximum temperature and mean minimum temperature, mean temperature (average of maximum and minimum temperature) and diurnal temperature range (difference of maximum and minimum temperature) for each month of the year are also computed. From the monthly values, annual (January-December) and seasonal (winter: December, January, February; Summer: March-May; monsoon: June-September; post monsoon: October-

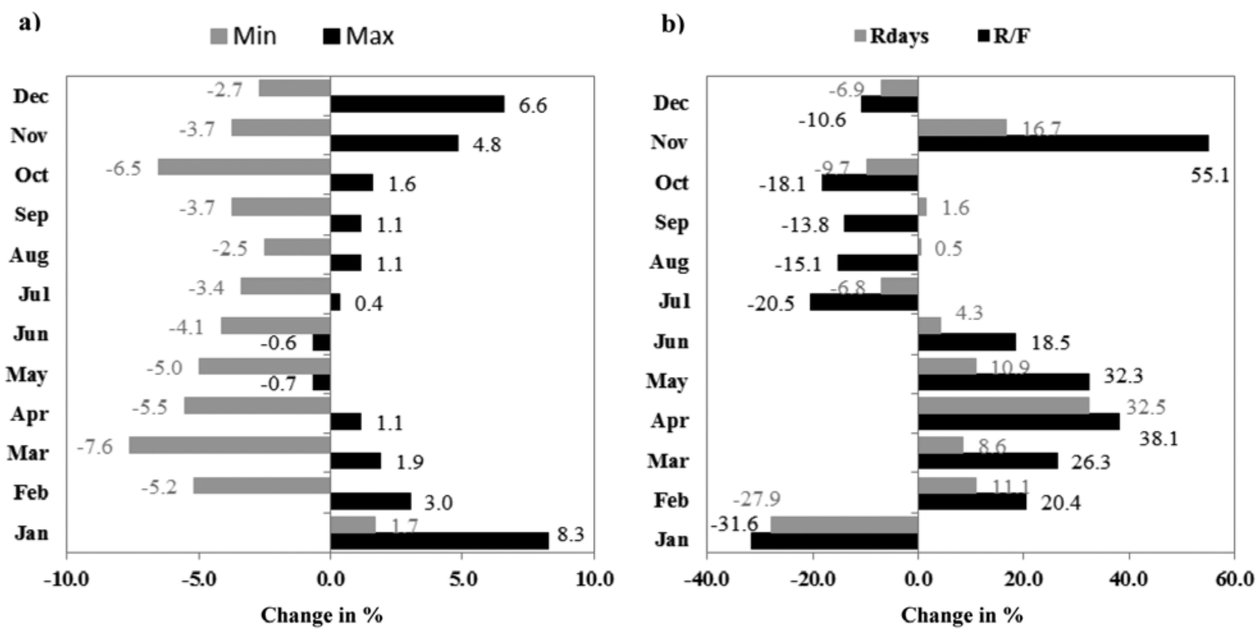

Figure 2. Monthly change (%) in 30 years climatological means of a) maximum temperature and minimum temperature, b) total rainfall and rainy days (Rdays) from 1951-1980 to 1981-2010 in Dharamsala

November) time series of all parameters under study viz. mean maximum temperature (T_{max}), mean minimum temperature (T_{min}), mean temperature (T_{mean}), mean diurnal temperature range (T_{dtr}), total rainfall (R_{total}), total rainy days (R_{days}) and 24 hours heaviest rainfall (R_{hvy}) are prepared. The monthly, seasonal and annual mean and coefficient of variation (CV) of $\mathbf{T_{max}}$, $\mathbf{T_{min}}$, $\mathbf{T_{mean}}$ and $\mathbf{T_{dtr}}$ for entire period of study (1951-2010) are computed and given in Table 1. Similarly, mean, CV and contribution of each month and season to the annual mean $\mathbf{R_{total}}$ and $\mathbf{R_{days}}$ are given in Table 2. Further, a comparison of long-term climatological means for 30 year period starting from 1951 viz. 1951-1980, 1961-1990, 1971-2000 and 1981-2010 for monthly T_{max}, T_{min}, R_{total} and R_{days} is calculated and given in Table 3. The change in monthly climatological means of T_{max}, T_{min} and R_{total}, R_{days} obtained for 1981-2010 from 1951-1980 expressed in % is shown in Figure 2. Behaviour of time series of individual months, seasons and annual mean $\mathbf{T_{max}}$, $\mathbf{T_{min}}$, $\mathbf{T_{mean}}$, $\mathbf{T_{dtr}}$, $\mathbf{R_{total}}$, $\mathbf{R_{days}}$ and $\mathbf{R_{hvy}}$ is studied by subjecting them to the non-parametric Mann-Kendall test. The results of trend analysis are presented in Table 4 and Table 5 where statistically significant trends are shown in boldface. Trend values marked '*' indicates significance at 95%, '**' indicates significance at 99% level and '***' indicates statistical significance at 99.9%. Time series of statistically significant monthly, seasonal and annual $\mathbf{T_{max}}$, $\mathbf{T_{min}}$, $\mathbf{T_{dtr}}$, $\mathbf{R_{total}}$, $\mathbf{R_{days}}$ and $\mathbf{R_{hvy}}$ are shown in Figure 3 to Figure 13. Incidence of heavy rainfall over Dharamsala is examined by preparing monthly, seasonal and annual data series of number of days that had daily rainfall exceeded 6.5 cm for 1951-2010. Temporal variation of number of days of heavy rainfall is shown in Figure 14.

The temporal variation and concentration of rainfall at Dharamsala is analyzed based on the Precipitation concentration Index (PCI) as given by Oliver (1980). It is a powerful tool to assess the temporal distribution and variability of precipitation. PCI values less than 10 represent a uniform precipitation, values 11 to 15 represent moderate precipitation concentration, values 16 to 20 represent irregular distribution of rainfall and values more than 20 represent a strong irregularity or high precipitation concentration at the station (Oliver, 1980). The PCI is calculated at annual and seasonal scale using following equation where P_i is the monthly total rainfall for the month i and the multiplication factor 100 in the formula represent 12 months of the year for $\mathbf{PCI_{annual}}$.

$$PCI_{annual} = \frac{\sum_{i=1}^{i=12} P_i^2}{\left(\sum_{i=1}^{i=12} P_i\right)^2} \ X\ 100 \tag{6}$$

Table 1. Monthly, annual and seasonal mean and coefficient of variation (CV) of maximum temperature (T_{max}), minimum temperature (T_{min}), mean temperature (T_{mean}) and diurnal temperature range (T_{dtr}) in Dharamsala for 1951-2010.

	$\mathbf{T_{max}}$		$\mathbf{T_{min}}$		$\mathbf{T_{mean}}$		$\mathbf{T_{dtr}}$	
	Mean (ºC)	**CV (%)**	**Mean (ºC)**	**CV (%)**	**Mean (ºC)**	**CV (%)**	**Mean (ºC)**	**CV (%)**
January	15.2	10.6	6.1	19.0	10.6	11.5	9.1	15.2
February	16.9	10.8	7.7	21.3	12.3	12.8	9.2	15.7
March	21.3	10.1	11.4	13.9	16.4	10.3	9.9	17.3
April	26.4	7.0	16.0	10.1	21.2	7.5	10.4	13.6
May	30.4	6.1	19.6	9.0	25.0	6.8	10.7	12.3
June	31.3	4.5	21.4	6.1	26.4	4.5	9.9	13.4
July	27.3	3.6	20.4	5.1	23.9	3.4	6.9	17.4
August	26.4	2.2	20.0	4.4	23.2	2.5	6.5	14.8
September	26.5	2.8	18.4	5.0	22.4	2.8	8.1	13.9
October	25.0	4.0	14.8	7.8	19.9	4.3	10.2	13.1
November	21.2	5.9	10.5	9.4	15.8	5.4	10.7	13.7
December	17.2	8.9	7.3	13.7	12.3	8.3	10.0	15.9
Annual	23.7	3.2	14.5	5.4	19.1	2.8	9.3	11.6
Winter	16.4	8.2	7.0	12.9	11.7	8.1	9.4	13.7
Summer	26.0	5.6	15.7	8.1	20.9	5.7	10.3	13.6
Monsoon	27.9	2.2	20.0	4.5	24.0	2.5	7.9	12.1
Post monsoon	23.1	4.3	12.7	7.7	17.9	4.1	10.4	12.7

Table 2. Monthly, annual and seasonal mean, coefficient of variation (CV) and percentage contribution to annual mean (Cont) of rainfall (R_{total}) and rainy days (R_{days}) in Dharamsala for 1951-2010.

	R_{total}			R_{days}		
	Mean (mm)	CV (%)	Cont (%)	Mean (days)	CV (%)	Cont (%)
January	96.3	67.2	3.3	5.4	61.8	5.4
February	111.0	66.0	3.8	5.7	48.9	5.7
March	115.3	66.7	4.0	6.2	51.5	6.2
April	56.6	73.9	2.0	4.5	54.8	4.6
May	67.6	80.1	2.3	4.8	52.0	4.8
June	231.1	73.6	8.0	9.6	43.2	9.7
July	868.3	36.1	29.9	21.3	17.2	21.4
August	851.3	29.2	29.3	22.0	19.0	22.2
September	371.0	62.0	12.8	12.8	37.9	12.9
October	60.2	153.9	2.1	2.9	92.6	3.0
November	20.5	138.0	0.7	1.3	115.9	1.3
December	51.4	100.4	1.8	2.8	71.1	2.8
Annual	2900.8	22.0	100.0	99.2	12.4	100.0
Winter	257.5	44.6	8.9	13.8	36.0	13.9
Summer	239.6	45.3	8.3	15.5	30.5	15.6
Monsoon	2321.7	26.4	80.0	65.6	15.8	66.2
Post monsoon	80.8	121.7	2.8	4.2	75.7	4.3

The multiplication factor changes to 25, 25, 33 and 17 for PCI_{winter} (for 3 months), PCI_{summer} (for 3months), $PCI_{monsoon}$ (for 4 months) and $PCI_{post\ monsoon}$ (for 2 months) respectively. The annual and seasonal PCI time series are subjected to test of significance using Mann-Kendall test. Temporal variations of significant PCI time series are shown in Figure 15.

RESULTS AND DISCUSSION

Understanding of climate change requires a careful examination and interpretation of climatic data to see if there is a change in a given period of time. Problems associated with modernisation like greenhouse gas emissions, air pollution, land use change, deforestation and land degradation are slowly creeping into mountain regions (Pandit et al., 2007). Mountains cover close to 20 percent of the Earth's surface, providing a home to approximately one-tenth of the global human population. It is well known that mountainous environments are particularly vulnerable for climatic changes (IPCC 2007; Beniston 2003).

Climatology

Long term means of temperature (T_{max}, T_{min}, T_{mean}, T_{dtr}) and rainfall (R_{total}, R_{days}) for the entire period of study (1951-2010) are given in Table 1 and Table 2 respectively. The climatological means (normals) of air temperature (T_{max} and T_{min}) and rainfall (R_{total} and R_{days}) for Dharamsala computed for four 30 years periods 1951-1980, 1961-1990, 1971-2000 and 1981-2010 are given in Table 3.

Station Climatology for 1951-2010

Long-term mean monthly T_{max} is the highest in June (31.3°C) and lowest in January (15.2°C) as given in Table 1. The coefficient of variation (CV) in T_{max} is highest in February (10.8%) and lowest in August (2.2%). Similarly, the highest and lowest monthly mean T_{min} and T_{mean} are occurring in June (21.4°C and 26.4°C) and January (6.1°C and 10.6°C) respectively. Long term monthly mean T_{dtr} is highest in May and November (10.7°C each) and lowest in August (6.5°C) with highest CV (17.4%) occurring in July. The long period average of annual T_{max}, T_{min}, T_{mean} and T_{dtr} for Dharamsala is 23.7°C (±0.8), 14.5°C (±0.8), 19.1°C (±0.5) and 9.3°C (±1.1) respectively. The deviation of annual mean T_{max} of individual years from the long-term average (23.7°C) reveals steady warming since 1998 reaching to +9.7% in 2010. The deviation of annual mean T_{min} of individual years from the long-term average (14.5°C) indicates considerable variations ranging between -17.2% in 2010 and +15.2% in 1952. The sharp fall in T_{min} at

Table 3. Monthly climatological means of maximum temperature (T_{max}) in °C, minimum temperature (T_{min}) in °C, total rainfall (R_{total}) in mm and total rainy days (R_{days}) for periods 1951-1980, 1961-1990, 1971-2000 and 1981-2010 for Dharamsala.

	1951-1980				1961-1990				1971-2000				1981-2010			
	T_{max}	T_{min}	R_{total}	R_{days}	T_{max}	T_{min}	R_{total}	R_{days}	T_{max}	T_{min}	R_{total}	R_{days}	T_{max}	T_{min}	R_{total}	R_{days}
January	14.5	5.9	114.5	6.1	14.6	5.6	93.3	5.1	15.0	5.7	92.9	5.1	15.7	6.0	78.3	4.4
February	16.6	7.7	100.7	5.4	16.2	7.1	108.4	5.9	16.5	7.1	116.9	5.7	17.1	7.3	121.2	6.0
March	21.1	11.8	98.8	5.8	20.8	11.1	112.0	6.3	20.8	10.9	120.9	6.4	21.5	10.9	124.8	6.3
April	26.2	16.3	48.6	4.0	26.1	15.8	55.0	4.5	26.2	15.6	64.6	5.0	26.5	15.4	67.1	5.3
May	30.5	20.1	59.1	4.6	30.0	19.4	72.5	5.1	30.2	19.6	67.5	4.8	30.3	19.1	78.2	5.1
June	31.4	21.8	202.7	9.3	31.0	21.3	233.3	10.2	30.9	21.2	230.0	10.3	31.2	20.9	240.3	9.7
July	27.2	20.7	959.7	22.0	27.2	20.4	868.8	21.3	27.2	20.4	834.0	21.3	27.3	20.0	763.4	20.5
August	26.3	20.2	909.2	22.2	26.4	20.0	843.8	22.0	26.5	20.1	784.8	21.9	26.6	19.7	772.3	22.3
September	26.3	18.7	404.8	12.8	26.4	18.3	322.5	11.9	26.5	18.2	333.4	12.8	26.6	18.0	348.9	13.0
October	24.8	15.3	66.3	3.1	24.9	14.8	41.3	2.7	25.0	14.6	41.2	2.5	25.2	14.3	54.3	2.8
November	20.7	10.7	16.7	1.2	20.8	10.3	21.5	1.4	21.1	10.4	23.3	1.4	21.7	10.3	25.9	1.4
December	16.7	7.4	54.0	2.9	16.6	6.9	61.2	3.2	16.9	7.1	51.6	3.0	17.8	7.2	48.3	2.7

Dharamsala since 1998 is noteworthy.

The long period average (1951-2010) of rainfall reveals that Dharamsala receives an annual R_{total} of 2900.8 mm (±639.1) with considerable CV (22%) and the highest monthly R_{total} 868.3 mm in July and the lowest R_{total} 20.5 mm in November as given in Table 2. The highest seasonal mean R_{total} is 2321.7 mm in monsoon and lowest is 80.8 mm in post monsoon. With 80% of the annual rainfall in Dharamsala occurring in monsoon season, monthly contribution of rainfall to the annual mean is highest in July (29.9%) followed by August (29.3%) as given in Table 2. Monthly CV of R_{total} is highest in October (153.9%) but incidentally it contributes just 2.1% to the annual mean. Further analysis of rainfall and rainy days time series of Dharamsala shows that the highest annual R_{total} 4721.2 mm has occurred in 1958 (wettest year) and the driest year R_{total} is 1609.0 mm in 1965. Deviation analysis between long period average (1951-2010) and total amount of rainfall received in every individual year at Dharamsala shows large variability (+62.8% in 1958 to -44.5% in 1965). The long period average of annual rainy days for Dharamsala is 99.2 days. The time series of R_{days} reveals that the lowest annual R_{days} (73) is in 1974 while the highest annual R_{days} (127) is in 1997. Similar to annual rainfall, deviation between long period average and total number of rainy days occurred in every individual year at Dharamsala shows large variability (-26% in 1974 to +24% in 1997). Monthly mean R_{days} are highest in August (22.0 days) and lowest in November (1.3 days) with highest CV (115.9%) as given in Table 2. Monsoon month August (22.2%) and monsoon season (66.2%) has the highest contribution to the annual mean R_{days}. One day heaviest rainfall in Dharamsala during the study period (1951-2010) is 381.7 mm which has occurred on 10th July, 1998.

Climatological changes in 30 years periods

The climatological means of air temperature (T_{max} and T_{min}) and rainfall (R_{total} and R_{days}) for Dharamsala computed for four 30 years periods 1951-1980, 1961-1990, 1971-2000 and 1981-2010 as given in Table 3 reveal appreciable changes in these climatic elements. According to Yao et al. (2006), the Himalayan region has shown consistent warming trends during the past 100 years. The difference in monthly climatological mean T_{max} and T_{min} for 1981-2010 from 1951-1980 means indicates increase in maximum temperature and decrease in minimum temperature as shown in Figure 2a. While 1981-2010 mean T_{max} has positive difference for all months except May and June, T_{min} has negative difference for all months except January as compared with 1951-1980 mean values. The highest increase in T_{max} is in winter months of January (+8.3%) and December (+6.6%). The decrease in mean T_{min} during the same period is highest in March (-7.6%) and October (-6.5%). Changes in monthly mean R_{total} and R_{days} for 1981-2010 (with reference to 1951-1980 mean) indicate decrease in rainfall and rainy days in January, July to October and December and increase in rest of the months as shown in Figure 2b. The highest decrease in R_{total} and R_{days} is in December (-31.6% and -27.9% respectively) ,while the highest increase is in November (+55.1% and +16.7% respectively). The decrease in R_{total} for January (-31.6%) and peak monsoon months July (-20.5%) and August (-15.1%) is a cause of worry.

Table 4. Mann-Kendall test results (Z and p-value) and Sen's slope estimate of trend (b) in monthly, seasonal and annual mean temperature (T_{mean}), mean diurnal temperature range (T_{dtr}), mean maximum temperature (T_{max}) and mean minimum temperature (T_{min}) in Dharamsala for 1951-2010. Significant trend values are in boldface where *, ** and *** indicate significance at 95%, 99% and 99.9% level respectively.

	T_{max}			T_{min}			T_{mean}			T_{dtr}		
	Z	p	b (°C/yr)	Z	p	b (°C/yr)	Z	p	b (°C/yr)	Z	p	b (°C/yr)
January	4.34	0.000	+0.050***	0.77	0.440	+0.008	3.16	0.002	+0.030**	3.88	0.000	+0.036***
February	1.49	0.137	+0.020	-0.92	0.358	-0.010	0.46	0.646	+0.006	3.08	0.002	+0.033**
March	1.67	0.096	+0.028	-1.88	0.060	-0.026	0.53	0.596	+0.007	4.75	0.000	+0.050***
April	2.06	0.039	+0.029*	-1.02	0.307	-0.013	0.82	0.414	+0.011	4.65	0.000	+0.043***
May	0.06	0.954	0.000	-2.38	0.017	-0.033*	-1.35	0.176	-0.017	3.26	0.001	+0.029**
June	-1.24	0.213	-0.017	-3.61	0.000	-0.038***	-2.71	0.007	-0.025**	1.51	0.132	+0.013
July	0.00	1.000	0.000	-2.93	0.003	-0.017**	-1.85	0.065	-0.012	2.18	0.029	+0.018*
August	1.40	0.161	+0.006	-2.46	0.014	-0.011*	-0.78	0.438	+0.000	3.77	0.000	+0.026***
September	1.55	0.122	+0.008	-3.81	0.000	-0.023***	-1.65	0.099	-0.008	4.57	0.000	+0.034***
October	1.82	0.069	+0.015	-4.50	0.000	-0.035***	-1.75	0.080	-0.012	5.53	0.000	+0.051***
November	4.38	0.000	+0.033***	-1.87	0.062	-0.013	1.65	0.099	+0.010	5.06	0.000	+0.049***
December	3.20	0.001	+0.037**	-1.80	0.073	-0.013	1.59	0.112	+0.012	4.61	0.000	+0.054***
Annual	3.53	0.000	+0.018***	-2.88	0.004	-0.018**	-0.20	0.843	0.000	5.06	0.000	+0.033***
Winter	3.61	0.000	+0.035***	-0.38	0.706	-0.002	2.18	0.029	+0.016*	4.28	0.000	+0.037***
Summer	1.93	0.054	+0.017	-2.37	0.018	-0.023*	-0.17	0.868	0.000	4.64	0.000	+0.041***
Monsoon	-0.06	0.954	0.000	-3.84	0.000	-0.021***	-2.94	0.003	-0.014**	3.97	0.000	+0.023***
Post monsoon	3.21	0.001	+0.024**	-3.64	0.000	-0.022***	0.29	0.774	0.000	5.45	0.000	+0.050***

Air Temperature

Using non-parametric Mann-Kendall test, the results of the standardized test statistics Z, significance level p-value and the slope b corresponding to the monthly, seasonal and annual mean temperature variables T_{max}, T_{min}, T_{mean}, and T_{dtr} are given in Table 4.

Monthly Temperature Trends

Monthly mean T_{max} shows an increasing trend practically for all months except June. However, the increasing T_{max} trends are statistically significant at the level 0.05 for April (+0.029°C/year), at the level 0.01 for December (+0.037°C/year) and at the level 0.001 for January (+0.05°C/year) and November (+0.033°C/year), as given in Table 4. The highest warming trend obtained in maximum temperature is +0.05°C/year in January, which is statistically significant at 0.001 level. Monthly time series of statistically significant trends are shown in Figure 3. T_{min} is showing decreasing trends for all months except January when it is increasing (Table 4). Statistically significant decrease in minimum temperature is noted for May (-0.033°C/year) and August (+0.011°C/year) at 0.05 level, for July (+0.017°C/year) at 0.01 level and for June (+0.038°C/year), September (+0.023°C/year) and October (+0.035°C/year) at 0.001 level. The monthly time series of statistically significant T_{min} for 1951-2010 are shown in Figure 4. A closer examination of T_{min} time series reveals sharp decline in minimum temperature in last decade (2001-2010). T_{mean} trends are increasing for January to May, August, November and December. Trends in T_{mean} are increasing significantly for January (+0.03°C/year) and decreasing significantly for June (-0.025°C/year), both at 0.01 level. Figure 5 shows statistically significant trends in T_{mean} in Dharamsala. T_{dtr} trends are increasing significantly for all months except June. The increasing trends in T_{dtr} are statistically significant at 0.05 level for July (+0.018°C/year), at 0.01 level for February (+0.033°C/year) and May (+0.029°C/year), at 0.001 level for January (+0.036°C/year), March (+0.05°C/year), April (+0.043°C/year), August (+0.026°C/year), September (+0.034°C/year), October (+0.051°C/year), November (+0.049°C/year) and December (+0.054°C/year) as given in Table 4. Monthly time series of statistically significant trends in T_{dtr} are shown in Figure 6.

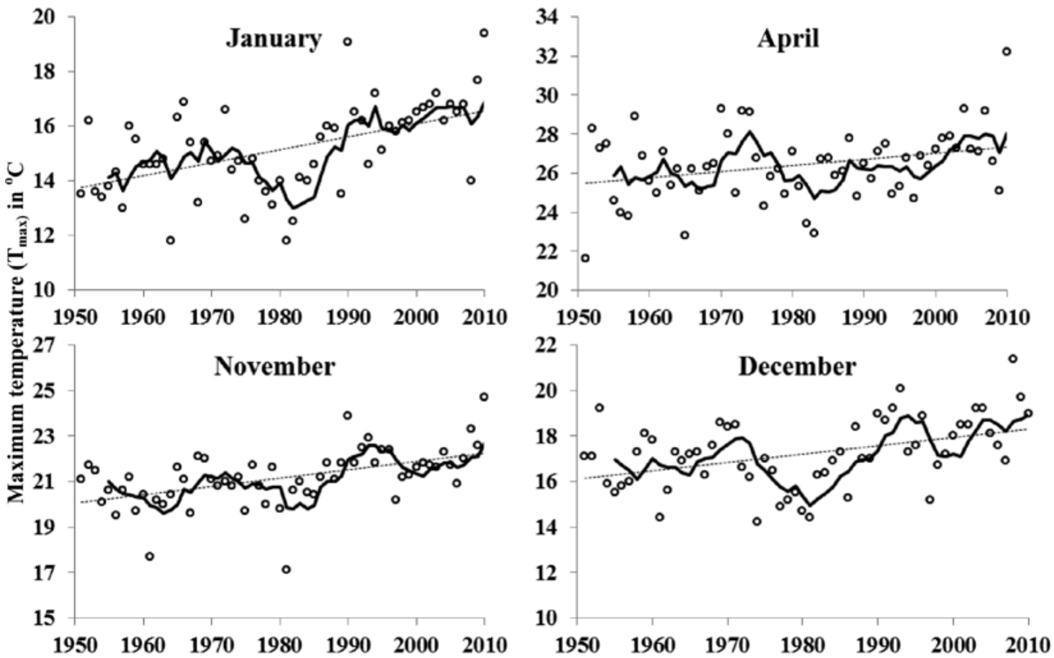

Figure 3. Monthly mean maximum temperature (Tmax) trends for January, April, November and December in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line

Table 5. Mann-Kendall test results (Z and p-value) and Sen's slope estimate of trend (b) in monthly, seasonal and annual total rainfall (R_{total}), total rainy days (R_{days}) and 24-hour heaviest rainfall (R_{hvy}) in Dharamsala for 1951-2010. Significant trend values are shown in boldface where * and ** indicate significance at 95% and 99% level respectively.

	R_{total}			R_{days}			R_{hvy}		
	Z	p	b (mm/yr)	Z	p	b (days/yr)	Z	p	b (mm/yr)
January	-2.06	0.039	-1.164*	-2.38	0.017	-0.059*	-0.86	0.391	-0.165
February	1.29	0.198	+0.790	0.77	0.442	0.000	1.15	0.248	0.243
March	0.06	0.955	+0.018	-0.02	0.983	0.000	-1.07	0.283	-0.205
April	0.81	0.416	+0.242	1.12	0.263	+0.014	1.27	0.205	+0.143
May	0.66	0.506	+0.213	0.81	0.416	0.000	0.38	0.700	+0.050
June	2.03	0.043	+1.806*	1.22	0.222	+0.040	2.17	0.030	+0.570*
July	-1.27	0.206	-2.602	-0.95	0.341	-0.024	-0.57	0.571	-0.186
August	-2.60	0.009	-4.623**	-0.48	0.628	0.000	-1.42	0.155	-0.591
September	-0.73	0.467	-1.330	0.49	0.625	0.000	-0.80	0.425	-0.376
October	-0.47	0.640	-0.043	-0.27	0.785	0.000	-1.08	0.281	-0.117
November	-0.23	0.820	0.000	0.56	0.574	0.000	-0.31	0.758	0.000
December	-0.66	0.506	-0.175	-0.38	0.704	0.000	-0.90	0.366	-0.109
Annual	-1.43	0.151	-7.575	0.69	0.493	+0.078	-0.65	0.516	-0.242
Winter	-0.53	0.596	-0.458	-1.32	0.187	-0.053	1.04	0.299	+0.162
Summer	0.86	0.392	+0.754	0.91	0.364	+0.027	-0.37	0.708	-0.068
Monsoon	-1.56	0.118	-6.970	0.48	0.630	+0.040	-0.64	0.525	-0.242
Post monsoon	-0.22	0.827	-0.075	-0.21	0.837	0.000	-1.04	0.299	-0.191

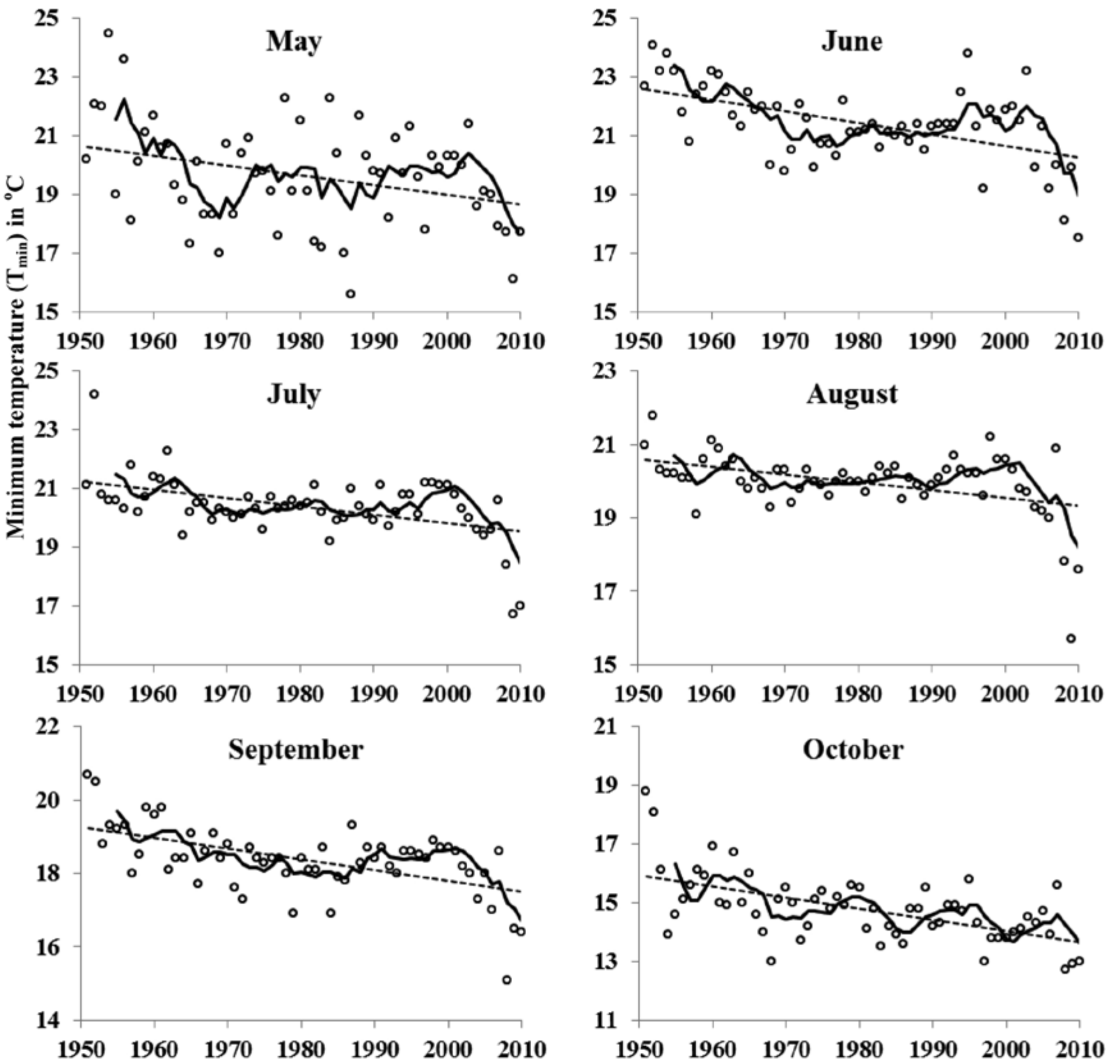

Figure 4. Monthly mean minimum temperature (T_{min}) trends for May, June, July, August, September and October in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line.

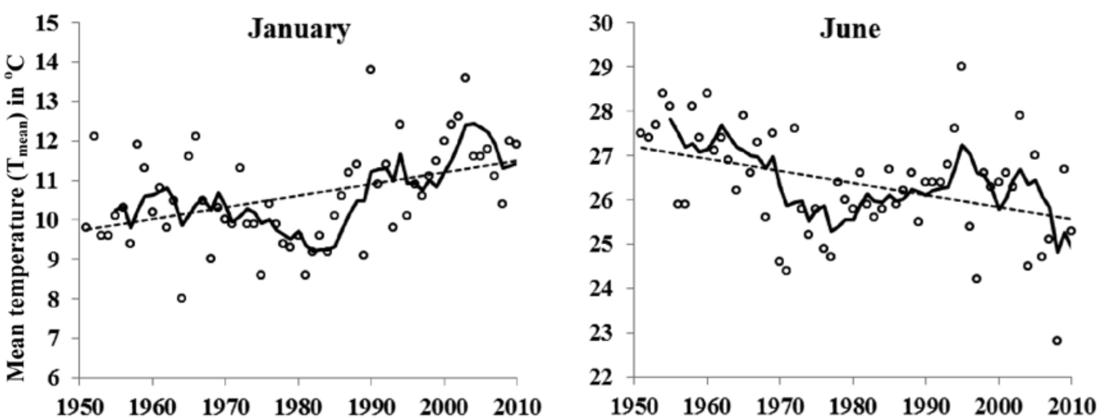

Figure 5. Monthly mean temperature (T_{mean}) trends for January and February in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line

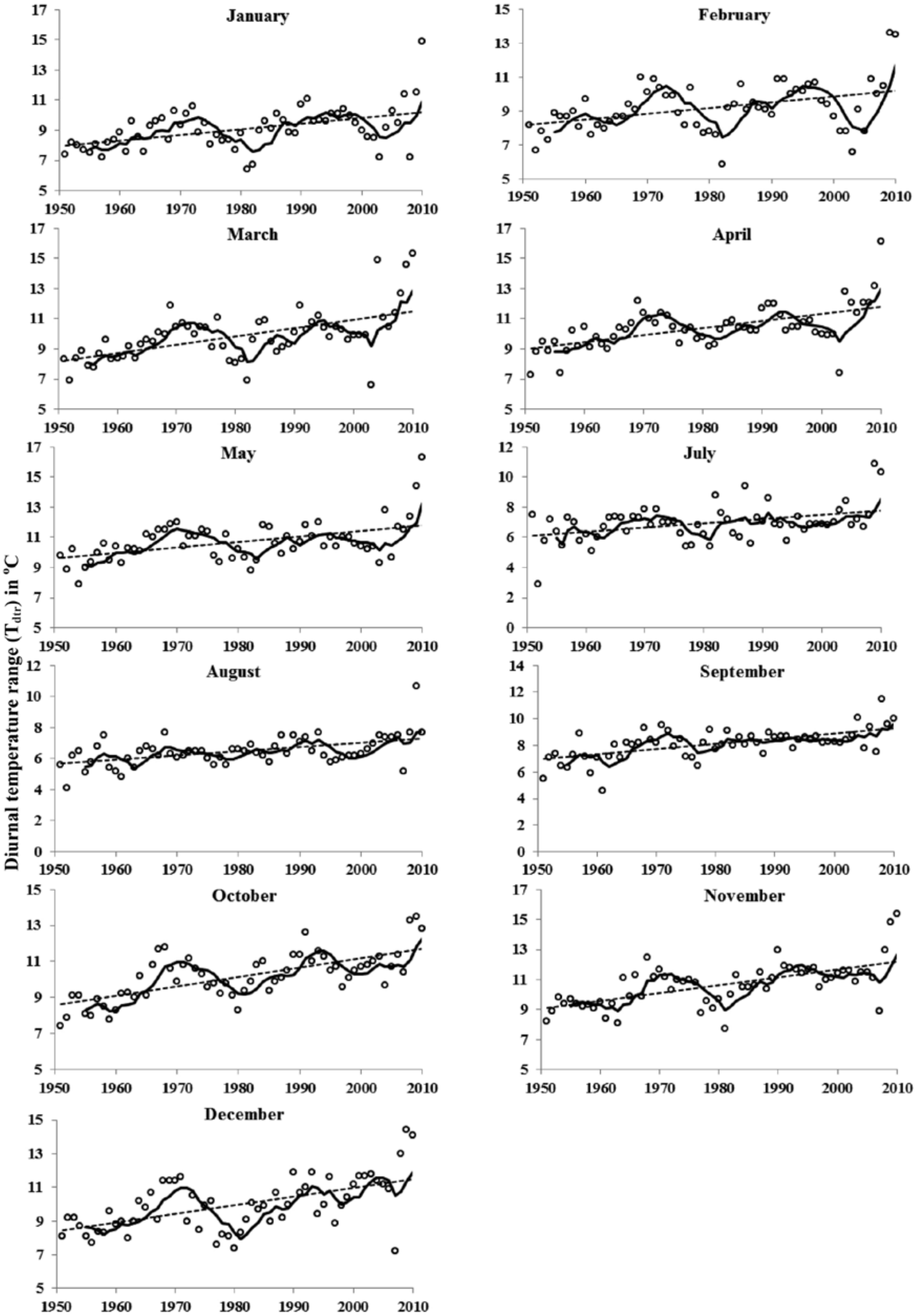

Figure 6. Monthly mean diurnal temperature range (T_{dtr}) trends for January, February, March, April, May, July, August, September, October, November and December in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line

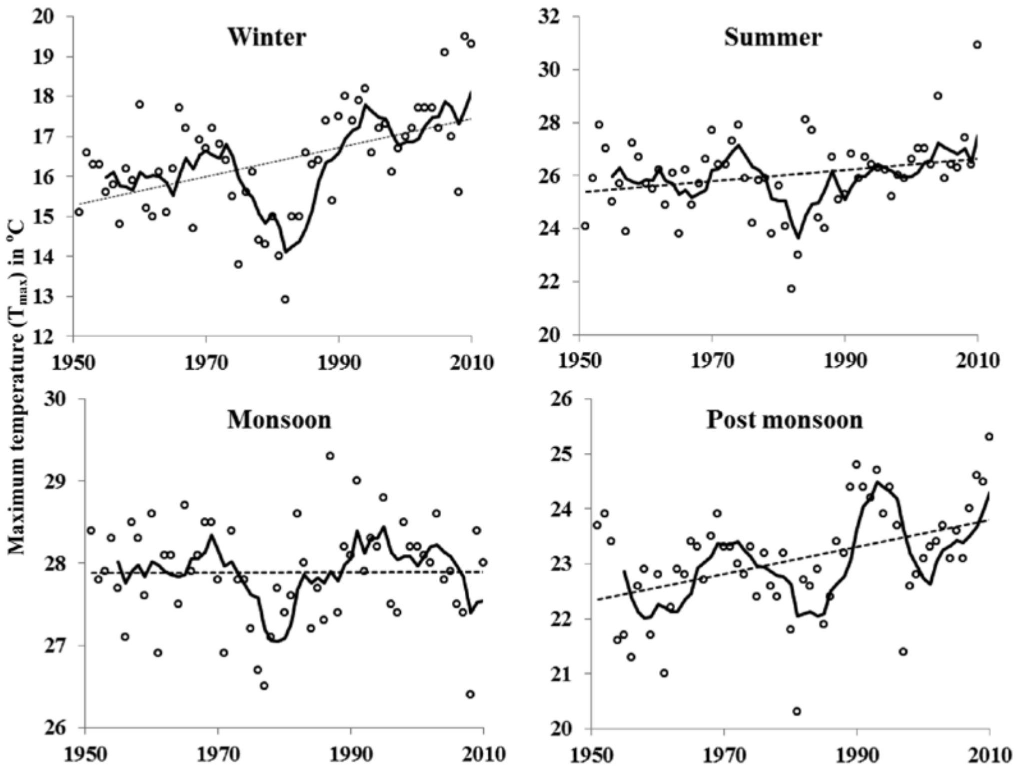

Figure 7. Seasonal mean maximum temperature (T_{max}) trends for winter and post monsoon in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line

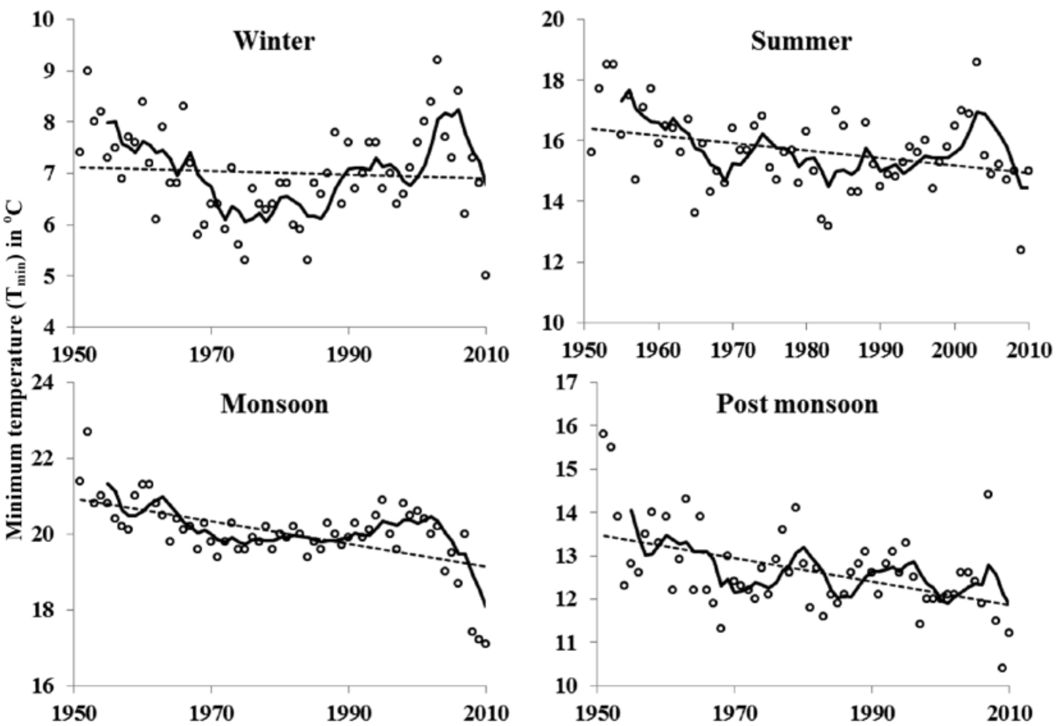

Figure 8. Seasonal mean minimum temperature (T_{min}) trends for summer, monsoon and post monsoon in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line

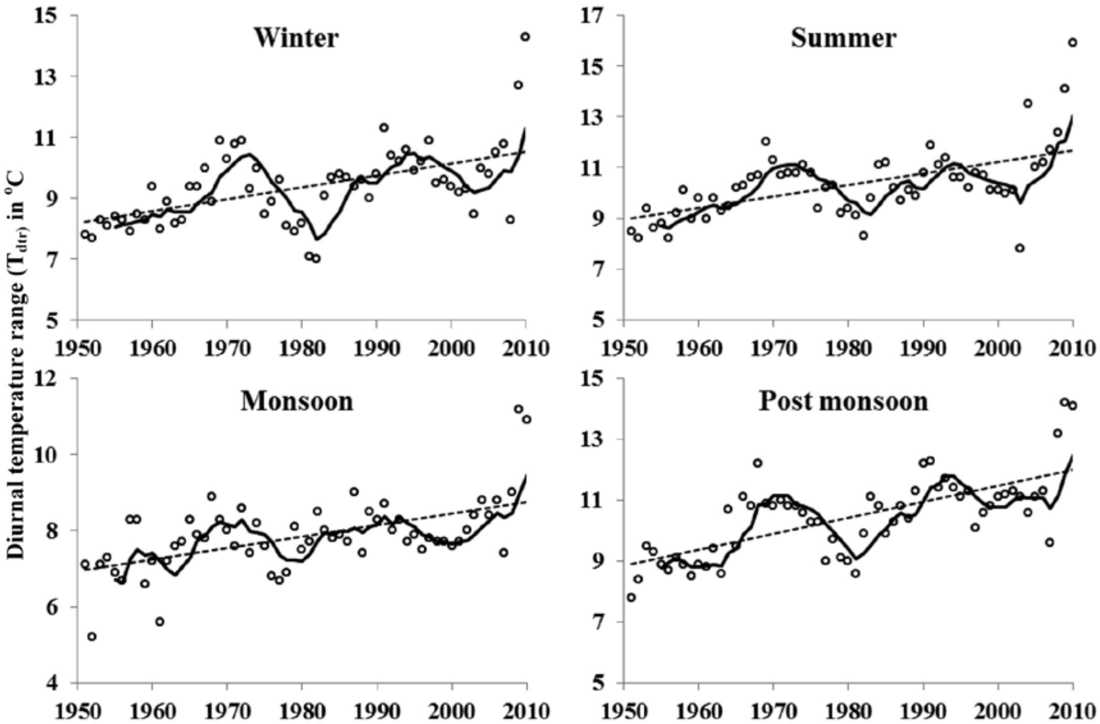

Figure 9. Seasonal mean diurnal temperature range (T_{dtr}) trends for winter, summer, monsoon and post monsoon in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line.

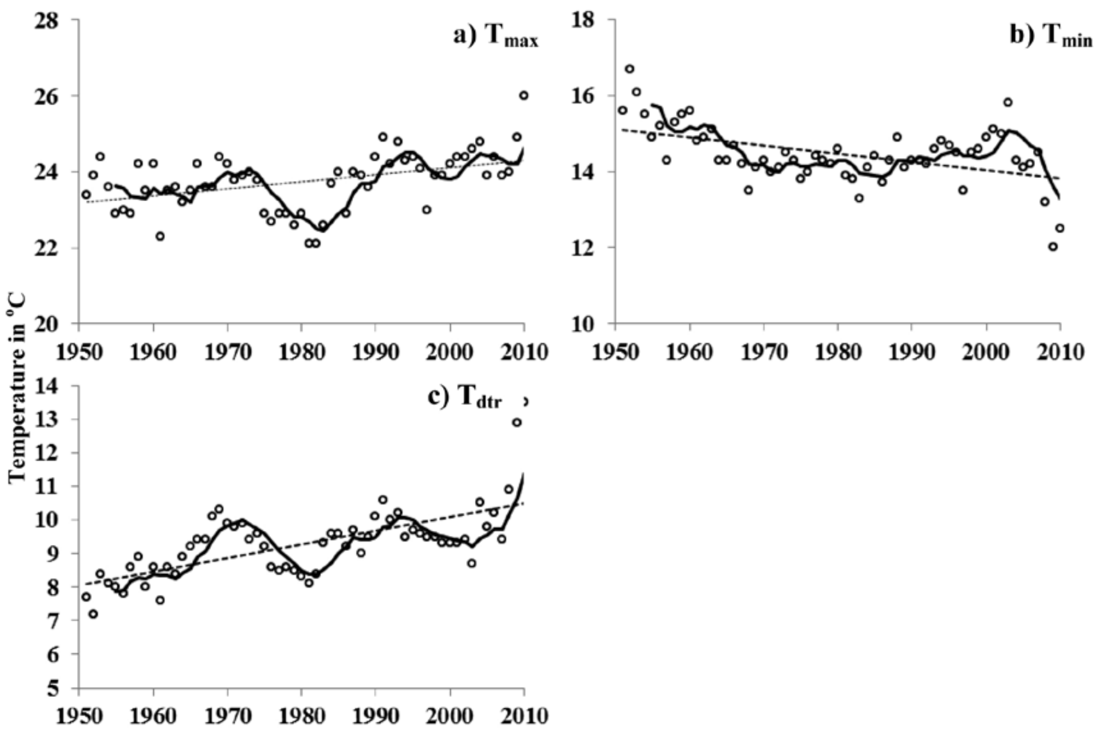

Figure 10. Trends in annual mean a) maximum temperature (T_{max}), b) minimum temperature (T_{min}) and c) diurnal temperature range (T_{dtr}) in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line

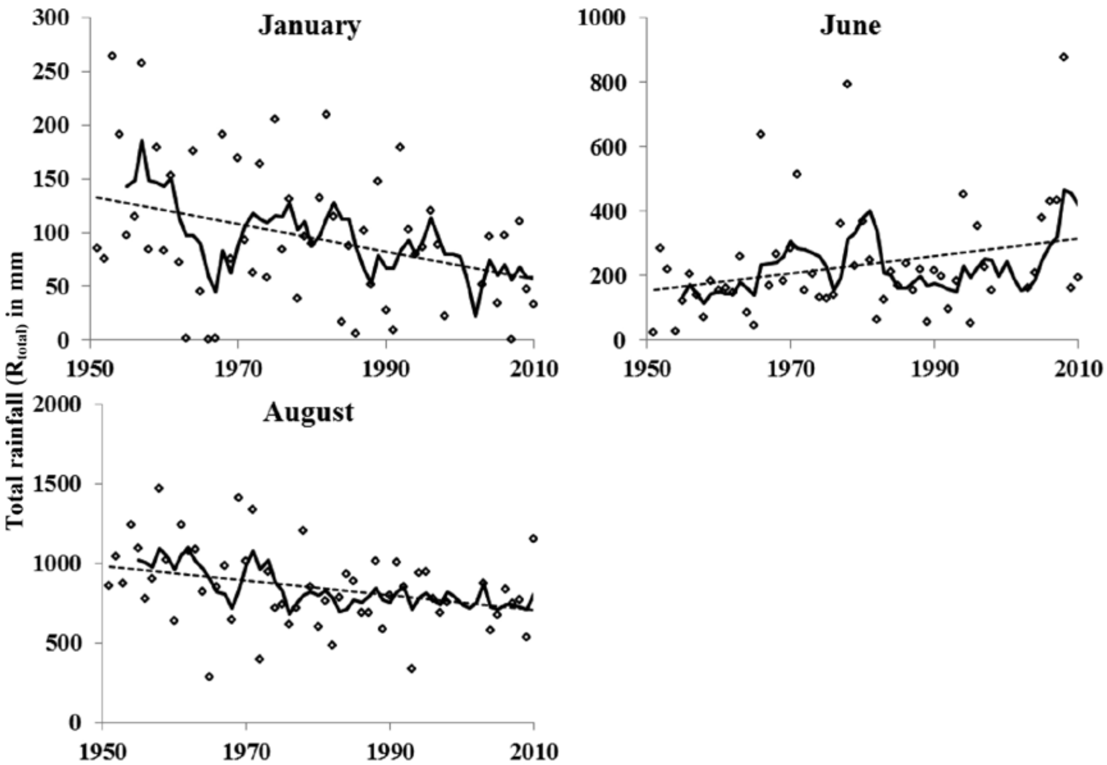

Figure 11. Monthly total rainfall (R_{total}) trends for January, June and August in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line.

Seasonal Temperature Trends

The seasonal mean T_{max}, T_{min}, T_{mean} and T_{dtr} trends for the period 1951-2010 for Dharamsala are shown in Table 4. The analyzed time series shows increase in mean maximum temperature, decrease in mean minimum temperature and consequently increase in diurnal range of temperature for all seasons. However, the mean temperature is increasing in winter and post monsoon but decreasing in summer and monsoon. Statistically, the Mann-Kendall test indicates that the trends are significant for T_{max} (winter at +0.035ºC/yr and post monsoon at +0.024ºC/yr), T_{min} (summer at -0.023ºC/yr, monsoon at -0.021ºC/yr and post monsoon at -0.022ºC/yr)), T_{mean} (winter at +0.016ºC/yr and monsoon at -0.014ºC/yr) and T_{dtr} (winter at +0.037ºC/yr, summer at +0.041ºC/yr, monsoon at -0.023ºC/yr and post monsoon at -0.050ºC/yr). Temporal variations of seasonal time series of T_{max}, T_{min} and T_{dtr} statistically significant are shown in Figures 7 to 9 respectively.

Annual Temperature Trends

The calculated trends in the time series of annual means of T_{max}, T_{min}, T_{mean} and T_{dtr} for 1951-2010 are presented in Table 4. The Mann-Kendall test indicates that annual mean T_{max}, and T_{dtr} are significantly increasing while T_{min} is significantly decreasing. The obtained trends in T_{max}, T_{min} and T_{dtr} are +0.018ºC/yr, -0.018ºC/yr and +0.033ºC/yr respectively which are significant at 99.9%. Temporal variations of annual time series of T_{max}, T_{min} and T_{dtr} statistically significant are shown in Figures 10a to 10c respectively. This trend in maximum and minimum temperature corresponds to increase in annual T_{max} and decrease in annual T_{min} in Dharamsala by 1.08ºC for the entire period analyzed (1951-2010).

The significant increasing trends in T_{max} are consistent with increasing trends in western Himalaya reported by Bhutiyani et al. (2007) and Pal and Tabba (2010). Some studies have shown that the anthropogenic factors due to land-use and land-cover changes may also significantly modify the temperature trends (Bonan, 1997; Gallo et al., 1999; Chase et al., 2000; Christy et al., 2006). The changes in land-use and land-cover modify the underlying land surface conditions which in turn change the exchange of energy and moisture between land surface and the atmosphere (Arnfield, 2003). The variability of T_{min} trends may be due to local forcing caused by deforestation and land degradation as suggested by Rupa Kumar et al. (1994) and Yadav et al. (2004).

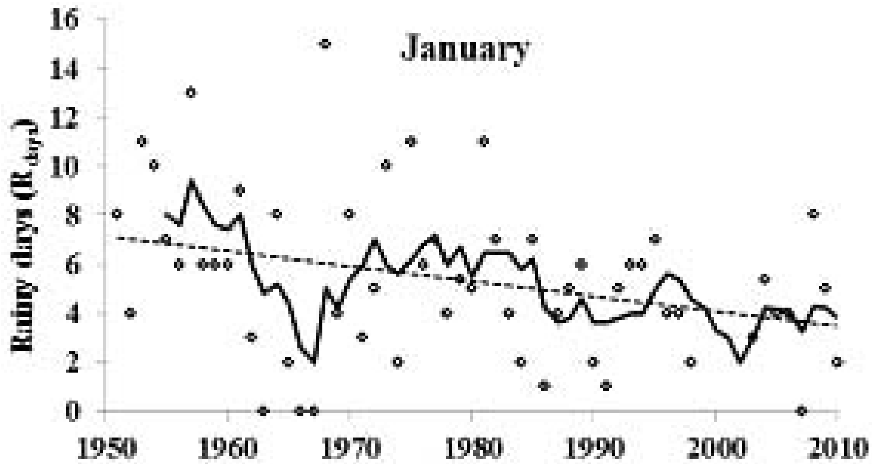

Figure 12. Monthly total rainy days (R_{days}) trends for January in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line

Rainfall, rainy days and heaviest rainfall

There are clear indications that the frequency and magnitude of high intensity rainfall events are increasing (Goswami et al., 2006) which will have negative implications for groundwater recharge, long-term soil moisture and water accessibility for plants. While rainfall occurs all round the year, monsoon season (June-August) has the highest contribution (80%) to the annual total rainfall of Dharamsala as given in Table 2. Any change in monsoon season rainfall in Dharamsala will have profound effects on agriculture, tourism, natural ecosystems and availability of water for household.

Monthly R_{total}, R_{days}, R_{hvy} trends

Being enclosed by high mountains on all sides, Dharamsala receives the highest rainfall out of all the districts of Himachal Pradesh. Mann-Kendall test statistics shows that monthly R_{total} is decreasing in January, July to December and increasing in February to June (Table 5). The trends are statistically significant for January, June and August. While monthly R_{total} is decreasing significantly for January (at -1.164 mm/yr) and August (at -4.623 mm/yr), it is significantly increasing for June (at +1.806 mm/yr) as shown in Figure 11. Trends in monthly R_{days} are decreasing for January, March, July, August, October, December and increasing for February, April to June, September and November. But the trend in monthly R_{days} is statistically significant for January (-0.059 days/yr) only as shown in Figure 12. The decreasing trends in R_{days} obtained here are similar to the reported trends of rainfall over Himachal Pradesh by Prasad and Rana (2010). The trend analysis of monthly R_{hvy} for Dharamsala shows decrease in January, March, July to December and increase in February, April to June. Similar to R_{total} trend, R_{hvy} trend is significantly increasing in June (Figure 13).

Seasonal and annual R_{total}, R_{days}, R_{hvy} trends

Analysis of seasonal time series of R_{total}, R_{days}, R_{hvy} using Mann-Kendall test shows that R_{total} is decreasing in winter, monsoon and post monsoon and increasing in summer as given in Table 5. R_{days} is decreasing in winter and post monsoon and increasing in summer and monsoon. R_{hvy} is increasing in winter and decreasing in summer, monsoon and post monsoon. However, the seasonal trends in R_{total}, R_{days} and R_{hvy} are statistically not significant for any season. Annual time series of R_{total}, R_{days} and R_{hvy} for 1951-2010 indicates a decreasing trend in R_{total}, increasing trend in R_{days} and decreasing trend in R_{hvy} as given in Table 3. Similar to seasonal trends, annual trends in R_{total}, R_{days}, R_{hvy} are also statistically not significant. The decreasing trends in R_{total} and R_{days} are similar to the rainfall trends over Himachal Pradesh found by Prasad and Rana (2010).

Trends in heavy rainfall events

Study of heavy rainfall events is crucial for agricultural practices, watershed management and climate change studies. Analysis of extreme events over India is available in literature (e.g. Goswami et. al. 2006; Dash et. al. 2007; Rajeevan et al. 2008). In this study, we have examined the occurrence of heavy rainfall events at Dharamsala during 1951-2010 using the threshold value of 6.5 cm. Figure 14 shows the temporal variation of heavy rainfall events for June to September, annual and monsoon season. The trend analysis shows that heavy rainfall events are decreasing significantly at 95% level for July (-0.04 days/yr) and at 99% level for August (-0.05 days/yr). Heavy rainfall events are

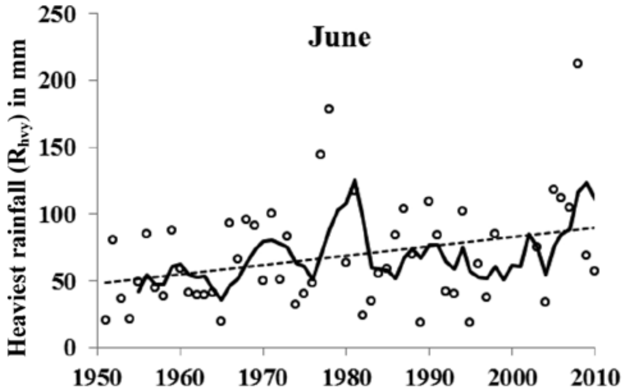

Figure 13. Monthly 24 hour heaviest rainfall (R_{hvy}) trends for June in Dharamsala. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line.

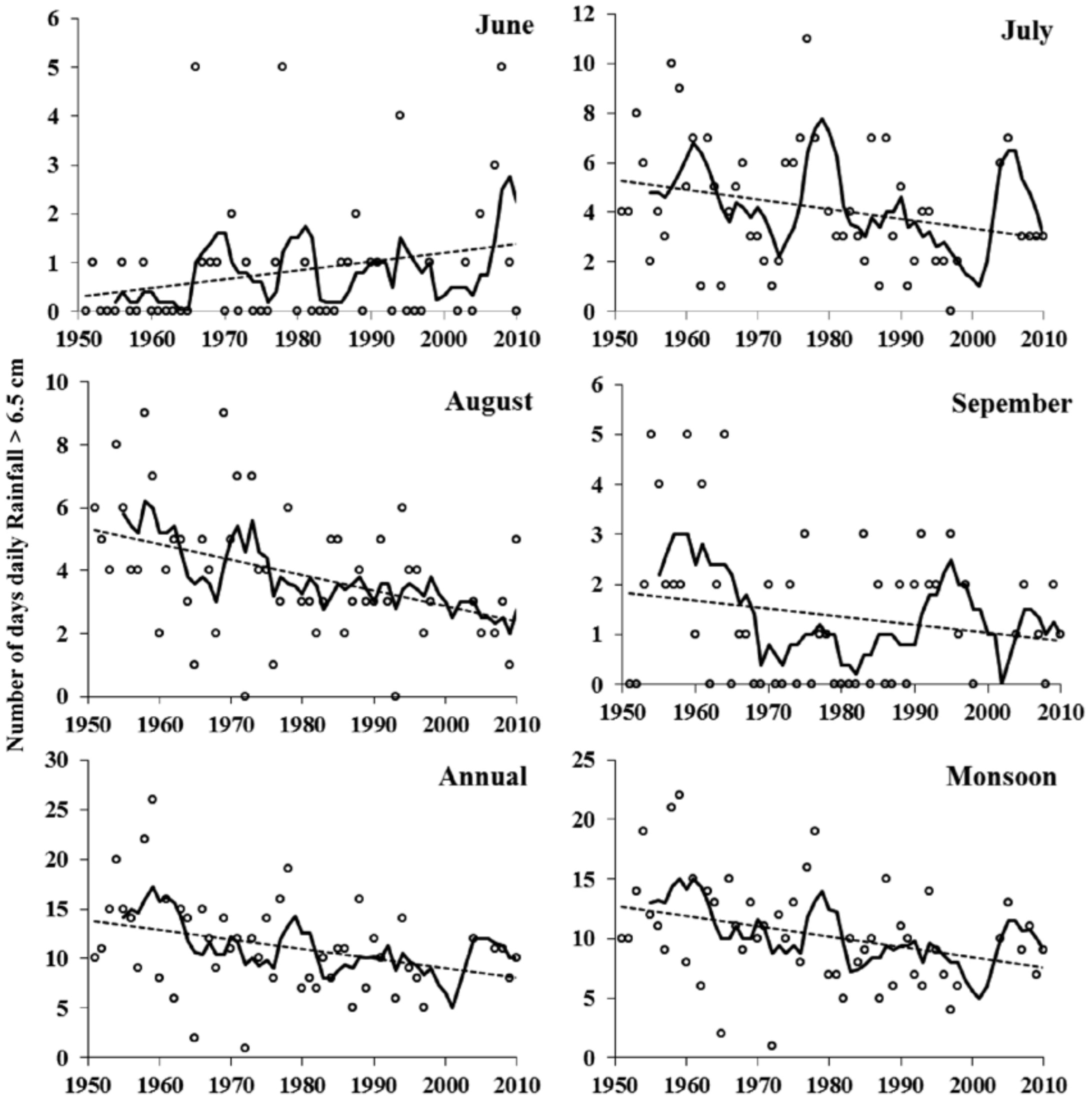

Figure 14. Trends in heavy rainfall events (number of days daily rainfall more than 6.5 cm) for Dharamsala during 1951-2010. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line

increasing non-significantly for June (+0.02 days/yr) and decreasing for September (-0.02 days/yr). For other months, there is no-trend in heavy rainfall events. On seasonal scale, heavy rainfall events are significantly decreasing at 95% level for monsoon (-0.08 days/yr). However, other seasons are not showing any trend in heavy rainfall events. Annually, heavy rainfall events in Dharamsala are decreasing at the rate of -0.09 days/yr which is significant at 95% level.

Precipitation Concentration Index (PCI) trends

Among various precipitation indices, PCI provides information on long-term total variability in the amount of rainfall received at a place. In this study, the PCI is calculated for Dharamsala on annual and seasonal scales. As the PCI value increases, the more concentrated precipitation becomes. Long-period averages (1951-2000) of annual, winter, summer, monsoon and post monsoon PCI time series are 22.2, 12.3, 11.3 11.2 and 13.3 respectively. The coefficient of variation in PCI is the highest (30%) in post monsoon and the lowest in monsoon (12%). The calculated PCI values show that during 1951-2010 on 73% of the years, annual rainfall fell within the high precipitation concentration range (PCI>20) indicating that the total precipitation occurred in 4 months. Winter rainfall in Dharamsala remained within moderate precipitation range (11≤PCI≤15) on 43% of the years and on 30% of the years rainfall distribution remained uniform (PCI≤10). On 59% of the years, summer precipitation in Dharamsala fell within moderate concentration range. Monsoon season precipitation remained in moderate concentration range on 68% of the years. Post monsoon season precipitation remained irregular (16≤PCI≤20) on 45% of the years, moderate on 25% and regular on 30% of the years suggesting high rainfall variability. The trends in PCI are decreasing for annual, monsoon and post monsoon and increasing for winter and summer. Statistically, the PCI trends are significantly decreasing for annual and monsoon as shown in Figure 15. Since 74% of the years the PCI_{annual} was highly concentrated, the significant decreasing trends suggest decrease in annual rainfall concentration in Dharamsala during 1951-2000. Similarly, the significant decreasing trends in $PCI_{monsoon}$ suggest decline in moderate rainfall concentration range in the temporal series.

In this paper, we have analyzed long-term trends and variability of monthly, seasonal, and annual surface air temperature (T_{max}, T_{min}, T_{mean}, and T_{dtr}) and rainfall (R_{total}, R_{days} and R_{hvy}) over Dharamsala, during the period 1951–2010. Besides this, the annual and seasonal precipitation concentration index (PCI) is also examined. For all the periods considered, there is increase in T_{max} (except in June and monsoon season) and decrease in T_{min} (except in January) in Dharamsala. However, the increasing T_{max} trends are significant for the months of January, April, November, December, and winter & post monsoon seasons and annual. The increasing trends in T_{max} found in Dharamsala are similar to the trends reported by Bhutiyani et al. (2007). In contrast, the decreasing trends in T_{min} are significant for May, June, July, August, September, October, summer, monsoon, post monsoon and annual. The decreasing trends in T_{min} agree with the reported trends in minimum temperature over Western Himalaya by Yadav et al. (2004) and Arora (2005). The magnitude of T_{max} trend is the highest in January (+0.050ºC/yr) which is significant at 99.9%. At -0.038ºC/yr, the decrease in T_{min} trend is the highest in June which is also significant at 99.9%. Generally, humidity, cloudiness, wind velocity and the orientation of the valley as well as drainage patterns of cold airflow from hilltops and slopes may influence the minimum temperature (Gouvas et al., 2011). In our analysis of trends of T_{dtr} over Dharamsala, it is observed that the variations in the T_{max} and T_{min} are uniformly opposite throughout the year leading to highly significant increase in diurnal temperature range. Trends in seasonal (in or off) temperatures showed that the diurnal asymmetry of T_{max} and T_{min} trends is maintained throughout the year, with winter being the season with highest T_{max} trends and

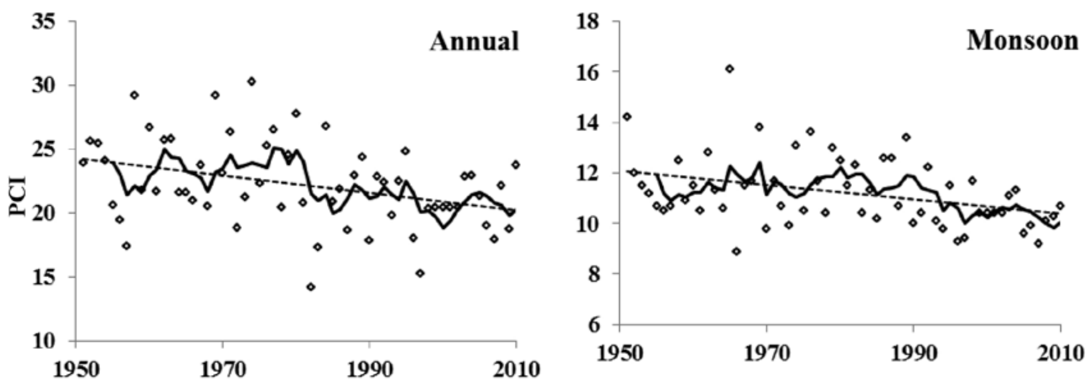

Figure 15. Temporal variation of Precipitation Concentration Index (PCI) for Dharamsala during 1951-2010. Dashed line indicates linear trend in the time series while 5-year moving average is shown by thick solid line,

summer being the season with highest T_{min} trends. The asymmetric T_{max} and T_{min} trends has resulted in sharp rise in T_{dtr} in Dharamsala region which is increasing (or revealed) in all periods considered in this study. T_{dtr} trends are significantly rising except for June. The magnitude of T_{dtr} trend is highest in December (+0.054ºC/yr) which is significant at 99.9%. T_{dtr} showed significant changes in all seasons, with the fastest increase in post monsoon (more asymmetry between T_{max} and T_{min}) and slowest in monsoon (less asymmetry between T_{max} and T_{min}). Monthly analysis of T_{dtr} reveals that all the months are contributing significantly to the increase in annual T_{dtr}, except June in which cooling in T_{max} is observed. The maximum significant increase in T_{dtr} has been observed in December (T_{max} increased significantly, while T_{min} has decreased) and in October (T_{min} is decreasing significantly) months. Urbanisation and changes in land use and land cover during the last three decades in Dharamsala is also contributing to the magnitude and type of surface air temperature trends. According to Gallo et al. (1996), land-use and land-cover changes even within 10 km radius can significantly influence the diurnal temperature range which can be one of the factors responsible for significant rise in T_{dtr} in the study area. Because of opposite T_{max} and T_{min} trends, T_{mean} trends are weak and significantly increasing in January and winter and significantly decreasing in June and monsoon during 1951-2010. Overall, R_{total} trends are decreasing except for February to June and summer. While R_{total} trends are significantly decreasing in January (-1.164 mm/yr) and August (-4.623 mm/yr), it is significantly increasing in June (+1.806 mm/yr). R_{days} and R_{hvy} trends are weak and significantly decreasing for January (-0.059 days/yr) and significantly increasing for June (-0.057 mm/yr) respectively. Since contribution of August rainfall is 29.3% to (or of) the annual total, significant decreasing trend is a cause of worry. With just 8% contribution to the annual total rainfall the significant increasing trends in June cannot compensate for the loss in August. We have also examined the heavy rainfall events during 1951-2010, taking threshold value of daily rainfall exceeding 6.5 cm as a heavy rainfall event. It is found that heavy rainfall events are significantly decreasing for main monsoon months of July and August at the rate of -0.04 days/yr and -0.05 days/yr respectively. At seasonal scale, heavy rainfall events are significantly decreasing for monsoon at a rate of -0.08 days/yr. Annual heavy rainfall events are also significantly decreasing at the rate of -0.09 days/yr. However there is non-significant increase in heavy rainfall events in June month. Temporal variation of heavy rainfall events of the study area suggests steady decrease in August during 1951-2010 and sharp increase in June and July during last decade (2001-2010).

Rapid expansion of tourism and other economic activities during the last three decades has led to a spate of human activities in the mountainous areas of the Himalayas resulting in increase in population, unplanned construction and change in land use. This study provides clear evidence of rising temperatures over Dharamsala and potential links to the hydrological cycle and water resources in the region. Increased incidences of forest fire are another prominent change that is linked with climate change as forest fires depend on weather and climate in addition to structure and composition of the forest. According to Bhatta (2007), a record 8195 hectares of forest in Himachal Pradesh was lost to fire in 2005-2006. The increase in temperature and decrease in rainfall in Dharamsala may impact adversely large percentage of the population of this hilly region who depend on natural resources. In view of these findings, further study of climate data records of all stations in Himachal Pradesh is required to ascertain the trends over different regions of the state.

CONCLUSIONS

In this study, we have investigated air temperature and rainfall variability during 1951-2010 in Dharamsala, a hill station in the state of Himachal Pradesh. The results of variability and trend analysis are summarized below:
On monthly scale, the rate of change in maximum and minimum temperature is highly asymmetric resulting in highly significant rise in diurnal temperature range (except in June) and mixed pattern of change in mean temperature at Dharamsala. The highest rate of increase in maximum temperature is in January (+0.050ºC/yr) and highest decrease in minimum temperature is in June (-0.038ºC/yr), both significant at 99.9%. While rainfall is decreasing significantly in January (-1.164 mm/yr at 95%) and August (-4.623 mm/yr at 99%), it is significantly increasing in June (+1.806 mm/yr at 95%). Rainy days are significantly decreasing in January at 95%. The one day heaviest rainfall is significantly increasing at 95% level in June (+1.570 mm/yr).

Seasonally, maximum temperature trends are significantly increasing for winter (+0.035ºC/yr at 99.9%) and post monsoon (+0.024ºC/yr at 99%). While summer season has non-significant increase in maximum temperature, monsoon season is showing no trend at Dharamsala during 1951-2010.

Seasonal minimum temperature trends at Dharamsala are significantly decreasing for all seasons except in winter during the period of study. The rate of decrease is -0.002ºC/yr in winter (non-significant), -0.023ºC/yr in summer (significant at 95%), -0.021ºC/yr in monsoon (significant at 99.9%) and -0.022ºC/yr in post monsoon (significant at 99.9%).

With asymmetric trends in day and night temperatures, diurnal temperature range is significantly increasing (at 99.9% level) for all seasons, the rate of increase being highest in post monsoon (+0.050ºC/yr). Mean temperature is significantly increasing in winter (+0.016ºC/yr) at 95% level and significantly decreasing in monsoon (-0.014ºC/yr) at 99% level. Although winter, monsoon and post monsoon rainfall is decreasing, none of the trends is significant on seasonal scale.

On annual basis, maximum temperature at Dharamsala during 1951-2000 is significantly increasing at the rate of +0.018ºC/yr, minimum temperature is significantly decreasing at the rate of -0.018ºC/yr ,resulting in sharp rise in diurnal temperature range at the rate of +0.033ºC/yr, which is significant at 99.9% level of significance. Even though annual rainfall is decreasing, none of the trends in rainfall or rainy days is significant.

Total rainfall in Dharamsala increased marginally in summer (+0.754 mm/yr) and decreased in winter, monsoon and post monsoon (-0.458, -6.970 and -0.075 mm/yr respectively) during 1951-2010. On the other hand, insignificant decrease in rainy days in winter and increase in summer and monsoon seasons is observed during the period of study.

Trend analysis of heavy rainfall events (daily rainfall more than 6.5 cm) shows significant decrease for main monsoon months of July (-0.04 days/yr) and August (-0.05 days/yr). On seasonal scale, heavy rainfall events are significantly decreasing for monsoon at a rate of -0.08 days/yr. Annual heavy rainfall events are also significantly decreasing at the rate of -0.09 days/yr at Dharamsala during 1951-2010.

Annual and monsoon season precipitation concentration at Dharamsala for 1951-2010 is significantly decreasing at 95% and 99% level respectively, the decrease being caused by the significant decrease in rainfall in January and main monsoon month August.

The results of this study provide additional and specific information that corroborate with the general increase in temperature over Western Himalayas reported by many researchers. On average, people in Dharamsala would be more susceptible to climate variability.

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