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Seasonal and annual rainfall trends in Himachal Pradesh during 1951-2005

A. K. JASWAL, S. C. BHAN*, A. S. KARANDIKAR and M. K. GUJAR

India Meteorological Department, Shivajinagar, Pune – 411 005

**India Meteorological Department, Lodi Road, New Delhi – 110 003*

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e mail : jaswal4@gmail.com

सार - इस शोध पत्र में हमने हिमाचल प्रदेश में वर्षा और वर्षा के दिनों में मौसमी और वार्षिक प्रवृत्तियों का विश्लेषण किया है। 1951-2005 तक की अवधि के लिए 37 स्टेशनों के वर्षा के आँकड़ों के आधार पर यह देखा गया कि राज्य के निचले दक्षिण-पश्चिमी भाग में मॉनसून वर्षा कुल वार्षिक वर्षा के 60 से 80% के बीच रही जबकि राज्य के उत्तरी भागों में ऊँचाई पर स्थित स्टेशनों में केवल 35% के लगभग रही। राज्य की औसत वर्षा जनवरी (-0.61 mm प्रति वर्ष), जुलाई (-1.83 mm प्रति वर्ष), अगस्त (-1.49 mm प्रति वर्ष) तथा अक्तूबर (-0.90 mm प्रति वर्ष) के लिए 95 प्रतिशत स्तर तक महत्वपूर्ण रूप से कम हो रही है। मौसमी पैमाने पर, वर्षा और वर्षा के दिन, मॉनसून (क्रमश: -3.68 mm प्रति वर्ष और -0.09 दिन प्रति वर्ष) तथा मॉनसूनोत्तर (क्रमश: -0.98 mm प्रति वर्ष तथा -0.03 दिन प्रति वर्ष) के लिए महत्वपूर्ण रूप से कमी की प्रवृत्ति दर्शा रहे हैं। वार्षिक वर्षा और वर्षा के दिन क्रमश: -4.58 mm प्रति वर्ष और -0.13 दिन प्रति वर्ष की कमी की प्रवृत्ति दर्शा रहे हैं। हिमाचल प्रदेश के दक्षिणी और पूर्वी भागों में, विशेष रूप से शिवालिक और मध्य हिमालयी क्षेत्र में मॉनसून की वर्षा और वर्षा के दिनों का स्थानिक पैटर्न महत्वपूर्ण कमी की प्रवृत्ति दर्शाता है। ग्रीष्मकालीन वर्षा और वर्षा के दिनों में वृद्धि की प्रवृत्ति दर्शाने वाले स्टेशन शिवालिक और मध्य हिमालय से स्थानिक रूप से संबंद्ध हैं। हिमाचल प्रदेश की राजधानी शिमला में मौसमी वर्षा शीत ऋतु (+1.47 mm प्रति वर्ष) और ग्रीष्म ऋतु (+1.77 mm प्रति वर्ष) में वृद्धि की प्रवृत्ति तथा मॉनसून ऋतु में महत्वपूर्ण कमी की प्रवृत्ति दर्शाता है। हिमाचल प्रदेश के दक्षिणी भागों (हमीरपुर, कोटखाई, नाहन, नूरपुर, रैनुका (रैनका) और पछाड़) में दैनिक भारी वर्षा महत्वपूर्ण रूप से कमी की प्रवृत्ति दर्शाती है। वार्षिक दैनिक भारी वर्षा में महत्वपूर्ण रूप से वृद्धि की प्रवृत्ति दर्शाने वाले स्टेशन मध्य हिमालय [चिनी (कल्पा) तथा पालमपुर] में स्थित हैं।

यदि भविष्य में भी वर्षा और वर्षा के दिनों में कमी की प्रवृत्ति बनी रहती है तो इससे न केवल राज्य में अपितु नीचे वाले राज्यों की कृषि और बागवानी पर भी प्रतिकूल प्रभाव पड़ेगा। तथापि इस विश्लेषण से हिमाचल में वर्षा की परिवर्तिता की जानकारी में सहयोग मिलेगा तथा पश्चिमी हिमालय के इस महत्वपूर्ण राज्य में कृषि, बागवानी और जल संसाधन के योजनाकारों को निर्णय लेने में मदद मिलेगी।

ABSTRACT. In this study, we have analysed seasonal and annual trends in rainfall and rainy days over Himachal Pradesh, an Indian state located in Western Himalayas. Based upon rainfall data of 37 stations for the period 1951-2005, it is found that the contribution of monsoon rainfall for the lower southwest part of the state is in the range of 60 to 80% of the annual total, while it is only around 35% for the higher elevation stations in the northern parts of the state. State averaged rainfall is decreasing significantly at 95% level for January (-0.61 mm/year), July (-1.83 mm/year), August (-.49 mm/year) and October (-0.90 mm/year). On seasonal scale, rainfall and rainy days are showing significantly decreasing trends for monsoon (-3.68 mm/year and -0.09 days/year respectively) and post monsoon (-0.98 mm/year and -0.03 days/year respectively). Annual rainfall and rainy days are showing significantly decreasing trends by -4.58 mm/year and -0.13 days/year respectively. Spatial patterns of monsoon rainfall and rainy days indicate significant decrease in southern and eastern parts of Himachal Pradesh, particularly in the Shivaliks and the middle Himalayas. Stations showing significant increasing trends in summer rainfall and rainy days are spatially coherent in the Shivaliks and the middle Himalaya. Seasonal rainfall is showing significantly increasing trend in winter (+1.47 mm/year) and summer (+1.77 mm/year) and significantly decreasing trend in monsoon (-3.71 mm/year) for Shimla, the capital of Himachal Pradesh. The daily heaviest rainfall is showing significantly decreasing trends in the southern parts of Himachal Pradesh (Hamirpur, Kotkhai, Nahan, Nurpur, Renuka (Rainka) and Pachhad. Stations showing significant increasing trends in annual daily heaviest rainfall are located in middle Himalayas [Chini (Kalpa) and Palampur].

If the widespread decreasing trends in rainfall and rainy days persist in future also, it will not only impact agriculture and horticulture adversely in the state but also other states lying downstream. However, this analysis will contribute to the knowledge of rainfall variability and trends over Himachal Pradesh and help agricultural, horticultural and water resources planners in decision-making in this important Western Himalayan state.

Key words – Climate change, Rainfall, Rainy days, Trends.

1. Introduction

Warming of the climate system is unequivocal as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. Most climate change models predict that global warming will disrupt the hydrological cycle and intensify the temporal and spatial variation in precipitation, snow melt and water availability. Evidence suggests that global climate is changing in an unprecedented manner largely due to increase in global mean temperatures (IPCC, 2007) and perceptible changes in precipitation patterns in many parts of the world including India (Goswami *et al*., 2006). Anthropogenic warming in the last three decades and its projected continuation may influence long-term rainfall patterns impacting the availability of water, along with the increasing occurrences of droughts and floods.

Several studies relating to changing pattern of rainfall over India have observed that there is no clear trend of increase or decrease in average rainfall over the country (Mooley and Parthasarthy, 1984; Thapliyal and Kulshrestha, 1991; Lal, 2001; Sinha Ray and De, 2003; Kumar and Jain, 2010). Though the all India monsoon rainfall exhibited no significant trend over a long period of time, pockets of significant long-term rainfall changes on regional scale were identified in some studies (Jagannathan and Parthasarathy, 1973; Raghavendra, 1974; Chaudhary and Abhyankar, 1979; Singh and Sen Roy, 2002; Kumar *et al*., 2005; Goswami *et al*., 2006; Guhathakurta and Rajeevan, 2006; Dash *et al*., 2007; Singh *et al*., 2008; Kumar and Jain, 2010; Kumar *et al*., 2010). Using high resolution gridded rainfall data (1951-2003), Goswami *et al*. (2006) have found increase in frequency and magnitude of extreme rainfall events during monsoon season over central India. Dash *et al*. (2007) have found decreasing trend in monsoon and an increasing trend in the pre-monsoon and post-monsoon rainfall during 1871-2002. Singh *et al*. (2008) have found an increasing trend in annual rainfall in nine river basins of northwest and central India. Based on high resolution daily gridded rainfall data of 1901-2004, Rajeevan *et al*. (2008) have concluded that the frequency of extreme rainfall events shows significant inter-annual and inter-decadal variations.

A significant impact of climate change in recent years is on precipitation patterns on regional scale. Regional and local rainfall analyses are therefore important for a large country like India because regional variations get masked in a country wide analysis. Studies have shown that contributions of westerly disturbances to the precipitation are greater at higher elevations in parts of the Greater Himalaya (Singh *et al*., 1995) and trans-Himalayan areas (Archer and Fowler, 2004). Snow is a significant contributor to total precipitation in Himachal Pradesh as seen in the estimated contributions to runoff in rivers which drain the state. Singh *et al*. (1997) has estimated 49% of runoff resulting from snow and glacier melt in the Chenab catchment. Similar estimate for Satluj are 60% (Singh and Jain, 2002) and for Beas are 35% (Kumar *et al*., 2005). Singh and Kumar (1997) have suggested that snow and rain contribute equally at 2000 m in some parts of the Western Himalaya. Guhathakurta and Rajeevan (2006) have found decrease in monsoon season rainfall in Himachal Pradesh by 61 mm during last 100 years. Examining length of monsoon rainy season, Prasad and Rana (2010) have found decrease in rainy days for the period 1974-2004 at Palampur in Himachal Pradesh. Kumar *et al*. (2005) found an increasing trend in rainfall at some stations and a decreasing trend at other stations in Himachal Pradesh. A slight downward trend in monsoon rainfall and a slight upward trend in winter rainfall were found for the river Beas catchment in Himachal Pradesh by Singh and Sen Roy (2002). According to Duan and Yao (2003), monsoon rainfall in the central Himalayas has decreased over the past decades in the condition of global warming. Studying total precipitation and snowfall at Shimla in Himachal Pradesh during 1992-2011, Bhan and Singh (2011) have found decrease in precipitation and snowfall for all months, which is highest in January. Bhutiyani *et al*. (2010) have found significant decreasing trend in the monsoon precipitation over northwestern Himalayas.

Much of the literature on spatial and temporal variability of rainfall in India is focused on all India scale, excluding hilly regions. With very less research studies available, trend analysis of rainfall at stations in Himachal Pradesh still remains relatively underexplored. We have analysed seasonal and annual rainfall and rainy days trends for 37 spatially well distributed stations in Himachal Pradesh and the results are presented in section 4.

2. Study area

Himachal Pradesh is a mountainous state of India which lies in the Western Himalayas, bounded by Jammu and Kashmir in the north, Uttarakhand in the southeast, Haryana in the south and Punjab in the west and in the east it forms India’s international boundary with Tibet (China). Himachal Pradesh has a population of 6.8 million (as per Census 2011) and has an area of 55,673 sq km which accounts for 5.8 per cent of the total land area in India. Himachal Pradesh is located between 30° 22' and 33° 12' N and between 75° 47' and 79° 04' E having altitude ranging from 350 to 7000 meter above mean sea level, covering a geographical area of 5.57 million hectare

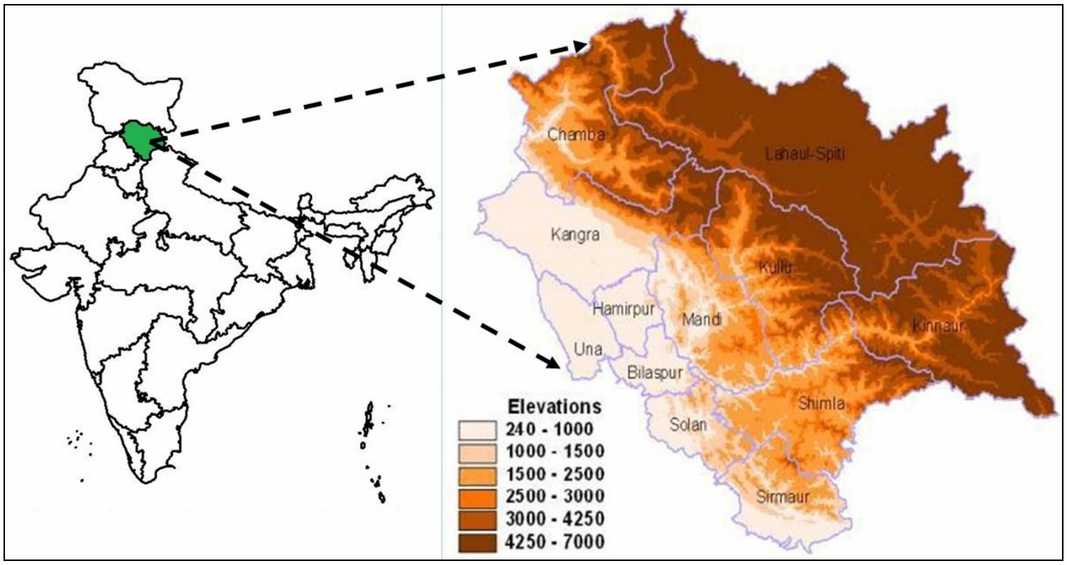


Fig. 1. Elevation map of Himachal Pradesh state of India

as shown in Fig. 1. The mountainous terrains and difficult agro-climatic conditions at several places do not present a hospitable environment for human settlement resulting in uneven distribution of population among the districts in the state. The quantum of rainfall and its proper distribution are the most crucial variables for the state like Himachal Pradesh where the development of irrigation infrastructures is restricted by its topography. But still agriculture and horticulture sectors are important contributors to the state's economy.

Topographically, the state can be divided into three main regions namely Shiwaliks (outer Himalayas), the lesser Himalayas (middle Himalayas) and the greater Himalayas. There is a large variation in the climate of Himachal Pradesh which varies from hot and sub-humid tropical (altitude 450-900 metres) in the southern low tracts, warm and temperate (altitude 900-1800 metres), cool and temperate (altitude 1900-2400 metres), cold high mountain (altitude 2400-4000 metres) and snowy frigid alpine (altitude > 4000 metres) in the northern and eastern high mountain ranges. The cold desert area remains practically devoid of rainfall and experiences heavy snowfall in winter season. The basic weather patterns giving precipitation in Himachal Pradesh are governed by the southwest monsoon and western disturbances of Asian continental air mass. However, according to Singh *et al*. (1995), rainfall and snowfall exhibited different trends with elevation on the windward and leeward slopes of the three ranges of Himalayas in Himachal Pradesh. Precipitation declines from west to the east and south to the north in the state. As such the highest rainfall in Himachal Pradesh occurs in Kangra district and lowest in Lahaul-Spiti district. Even though the state has nine major river systems, about 95% of the geographical area of Himachal Pradesh is drained by five namely the Sutlej, the Beas, the Chenab, the Yamuna and the Ravi.

3. Data and methodology

3.1. *Data used*

Since many stations in Himachal Pradesh experience snowfall during the winter months, rainfall data used in this study also contains amount of precipitation contributed by snowfall whenever it happened. There are 23 snow measuring stations in Himachal Pradesh. The method used by India Meteorological Department (IMD) to convert snowfall to equivalent rainfall is by adding a known quantity of hot water to snow collected on the rain-gauges and then subtracting this from the total amount of measured water to get the equivalent rainfall amount. In general, one cm snowfall is equivalent to 1 mm of rainfall. Therefore, daily rainfall data wherever mentioned includes both liquid and solid precipitation. The daily rainfall data for stations in Himachal Pradesh are obtained from the National Data Centre (NDC) of IMD, which processes and archives all atmospheric data of the country. The rainfall observations are first manually scrutinized at designated center before data keying. These data are then put through stringent quality control checks both at data keying-in and archival stages at NDC. Although the data recordings from some individual stations in Himachal Pradesh started prior to 1901 but stations with continuous data are very few and to represent the rainfall trends for entire state, we used

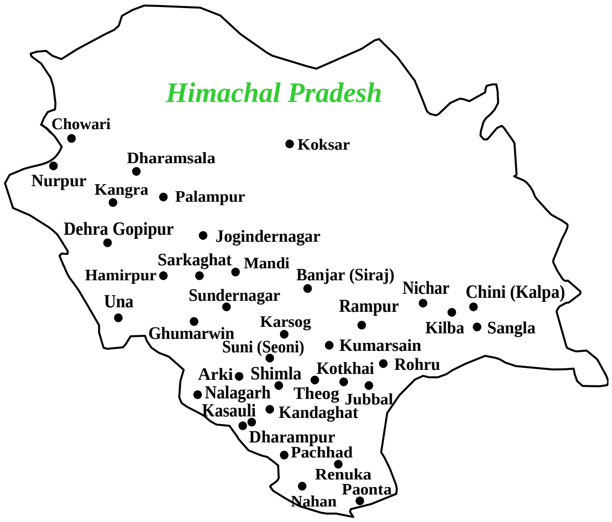
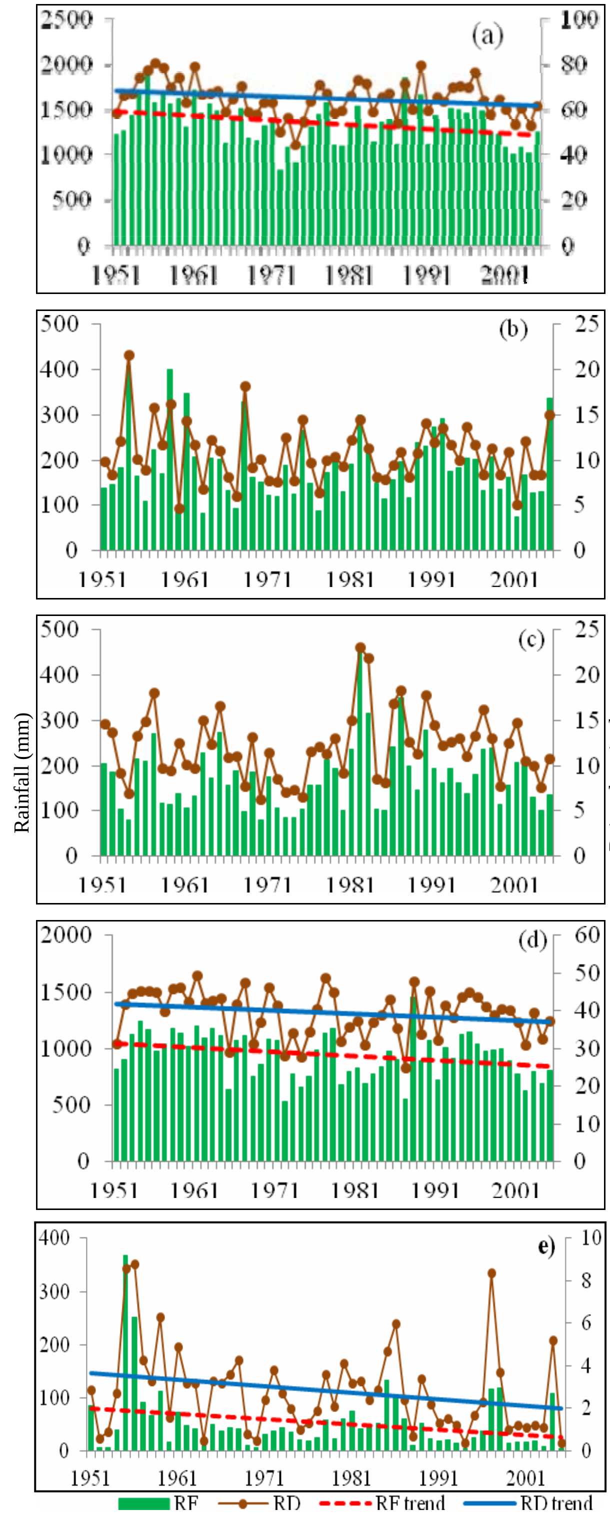


Fig. 2. Location of 37 rainfall stations selected for study in Himachal Pradesh

data from 37 stations having more than 90% data availability and majority of them have started in 1951. The stations selected are well distributed across the state of Himachal Pradesh with all 12 districts having one or more rainfall station. As such, the period of study is restricted to 1951-2005 for which maximum numbers of stations are having near complete data series. From the daily rainfall values, monthly total rainfall and rainy days (days having rainfall more than 2.4 mm) in a month are prepared for the 37 rainfall measuring stations in Himachal Pradesh for the study period 1951-2005. Annual daily heaviest rainfall data series for all 37 stations is also prepared from the daily rainfall values. The annual daily heaviest rainfall data series is also examined manually for any data keying error by checking the suspected values with the manuscripts. Out of the selected 37 stations, 14 stations have elevation less than 1000 meters, 15 stations are located at elevation between 1000 meters and 2000 meters while 8 stations have elevation above 2000 meters. The geographical location of these 37 rainfall measuring stations is depicted in Fig. 2 while the station name, district name, location (latitude and longitude), data period and elevation are given in Table 1.

3.2. *Methodology*

In order to investigate the changes in rainfall and rainy days for different seasons, a year was divided into four seasons: winter (December-February), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-November). From the monthly values, annual and seasonal time series of rainfall and rainy days are prepared. Monthly, annual and seasonal state average



Figs. 3(a-e). Temporal variations and linear trends in (a) annual, (b) winter, (c) summer, (d) monsoon and (e) post monsoon rainfall and rainy days for Himachal Pradesh during 1951-2005. Data series are rainfall and rainy days averaged over 37 rainfall stations where trends are drawn for statistically significant at 95% level series only

TABLE 1

Summary of rainfall stations in Himachal Pradesh used in this study

Station Name	District	Data period	Latitude (°N)	Longitude (°E)	Elevation M (amsl)
Arki	Solan	1951-2005	31° 09'	76° 57'	1130
Banjar (Saraj)	Kullu	1951-2005	31° 38'	77° 20'	1520
Chini (Kalpa)	Kinnaur	1951-2005	31° 32'	78° 15'	2781
Chowari	Chamba	1951-2001	32 ° 27'	76° 01'	716
Dehra Gopipur	Kangra	1951-2005	31° 53'	76° 13'	436
Dharampur	Solan	1951-2005	30° 54'	77° 01'	1986
Dharamsala	Kangra	1951-2005	32° 16'	76° 23'	1211
Ghumarwin	Bilaspur	1958-2005	31° 27'	76° 42'	687
Hamirpur	Hamirpur	1951-2005	31° 42'	76° 32'	786
Jogindarnagar	Mandi	1951-2005	31° 55'	76° 45'	1221
Jubbal	Shimla	1951-2005	31° 06'	77° 40'	2000
Kandaghat	Solan	1954-2005	30 ° 58'	77 ° 07'	1425
Kangra	Kangra	1951-2005	32° 06'	76° 15'	701
Karsog	Mandi	1951-2005	31° 23'	77° 12'	1347
Kasauli	Solan	1954-2005	30° 53'	76° 58'	1783
Kilba	Kinnaur	1951-2004	31° 30'	78° 08'	2583
Koksar	Lahaul and Spiti	1951-2005	32° 25'	77° 14'	3204
Kotkhai	Shimla	1951-2005	31° 07'	77° 32'	1560
Kumarsain	Shimla	1951-2005	31° 19'	77° 27'	1700
Mandi	Mandi	1951-2005	31° 43'	76° 56'	807
Nahan	Sirmaur	1951-2005	30° 33'	77° 18'	932
Nalagarh	Solan	1954-2005	31° 03'	76° 43'	616
Nichar	Kinnaur	1951-2005	31° 33'	77° 58'	2086
Nurpur	Kangra	1951-2005	32° 18'	75° 55'	616
Pachhad	Sirmaur	1951-2005	30° 43'	77° 12'	1685
Palampur	Kangra	1951-2005	32° 08'	76 ° 32'	1217
Paonta	Sirmaur	1951-2005	30 ° 28'	77 ° 37'	399
Rampur	Shimla	1951-2005	31° 26'	77° 38'	1067
Renuka (Rainka)	Sirmaur	1951-2005	30° 40'	77° 30'	690
Rohru	Shimla	1951-2005	31° 13'	77° 45'	1333
Sangla	Kinnaur	1951-2005	31° 25'	78 ° 16'	2860
Sarkaghat	Mandi	1951-2005	31° 42'	76° 44'	914
Shimla	Shimla	1951-2005	31° 06'	77° 10'	2202
Sundernagar	Mandi	1951-2005	31° 32'	76° 53'	1193
Suni (Seoni)	Shimla	1951-2005	31° 15'	77° 07'	670
Theog	Shimla	1958-2005	31° 08'	77 ° 22'	2086
Una	Una	1951-2005	31° 28'	76° 17'	365

TABLE 2

Monthly, annual and seasonal rainfall and rainy days mean, standard deviation (SD), coefficient of variation (CV) and trends for Himachal Pradesh. Data series is all Himachal Pradesh averaged based upon 37 rainfall stations for 1951-2005. Trend values significant at 95% level are shown in bold and marked '*'

	Rainfall				Rainy days			
	Mean (mm)	SD (mm)	CV (%)	Trend (mm/year)	Mean (days)	SD (days)	CV (%)	Trend (days/year)
January	77.1	40.52	53	**-0.61***	4.4	2.05	46	**-0.04***
February	76.0	45.03	59	+0.36	4.4	2.05	46	+0.02
March	78.0	44.87	58	+0.08	4.9	2.16	44	no trend
April	43.6	26.5	61	+0.24	3.4	1.64	49	no trend
May	53.3	34.11	64	+0.21	3.9	1.69	43	+0.02
June	115.6	47.09	41	+0.39	6.1	1.74	28	+0.02
July	345.1	95.68	28	**-1.83***	13.3	2.66	20	**-0.04***
August	329.9	85.48	26	**-1.49***	13.1	2.45	19	**-0.04***
September	150.4	77.17	51	-0.74	6.8	2.63	38	-0.02
October	38.5	60.76	158	**-0.90***	1.9	1.78	94	**-0.03***
November	14.1	17.04	121	-0.07	0.9	0.92	97	no trend
December	33.5	31.41	94	-0.19	1.9	1.32	68	-0.01
Annual	1353.4	234.26	17	**-4.58***	65.1	7.88	12	**-0.13***
Winter	186.2	77.35	42	-0.34	10.8	3.23	30	no trend
Summer	174.8	73.57	42	+0.51	12.2	3.68	30	+0.02
Monsoon	940.7	197.99	21	**-3.68***	39.4	5.99	15	**-0.09***
Post monsoon	52.4	61.32	117	**-0.98***	2.8	2.01	71	**-0.03***

rainfall and rainy days data series for 1951-2005 are also prepared by averaging the data for all 37 stations. State averaged monthly, seasonal and annual means, standard deviations and coefficient of variations of rainfall and rainy days for Himachal Pradesh are computed and given in Table 2. Temporal variations of state averaged annual and seasonal series of rainfall and rainy days during 1951-2005 are shown Fig. 3. Spatial variations in long term annual mean rainfall and rainy days and their coefficient of variations are shown in Fig. 4. Based upon the long term means of rainfall and rainy days, percentage contributions of seasonal means of rainfall and rainy days to their annual total are computed for all 37 stations and the statistics is given in Table 3. 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.

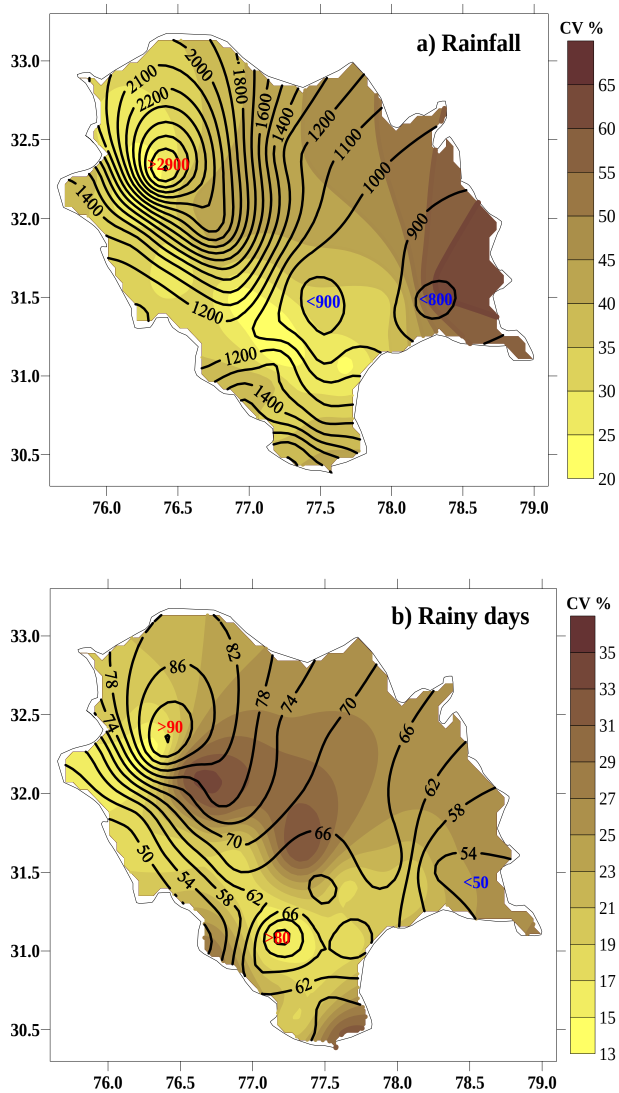
The Mann-Kendall statistic is given by:

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

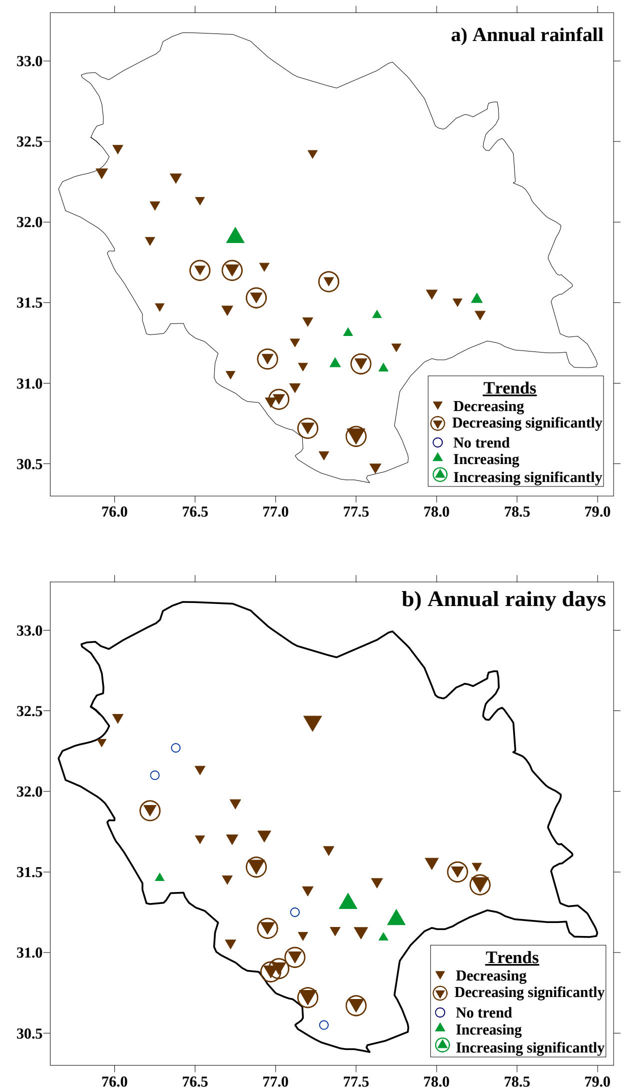
where, n is the length of the data set, x_i and x_j are two generic sequential data values.

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

$$\text{Sign}(x_i - x_j) = \begin{cases} +1, \; if \; (x_i - x_j) > 0 \\ 0, \; if \; (x_i - x_j) = 0 \\ -1, \; if \; (x_i - x_j) < 0 \end{cases} \qquad (2)$$



Figs. 4(a&b). Spatial variations in annual means of (a) rainfall in mm and (b) rainy days in days based upon 37 rainfall stations in Himachal Pradesh during 1951-2005. Spatial variation in coefficient of variation (CV) is shown in the background



Figs. 5(a&b). Spatial variations in annual a) rainfall and b) rainy days trends for stations in Himachal Pradesh during 1951-2005. Trends significant at 95% level of significance are shown by an outer circle

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 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 then computed as given by Hirsch *et al*. (1993):

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

The presence of a statistically significant trend is evaluated using the Z value. This statistic is used to test the null hypothesis (H_o) such that no trend exists. A positive Z indicates an increasing trend in the time-series, while a negative Z indicates a

TABLE 3

Percentage contribution of seasonal mean rainfall (RF) and rainy days (RD) to the annual mean for 37 rainfall stations in Himachal Pradesh for 1951-2005

Station	Elevation	Winter		Summer		Monsoon		Post monsoon	
	M (amsl)	RF	RD	RF	RD	RF	RD	RF	RD
Arki	1130	14	17	12	16	71	64	3	3
Banjar (Saraj)	1520	17	18	23	26	56	52	5	5
Chini (Kalpa)	2781	35	28	36	34	22	32	6	6
Chowari	716	15	17	11	16	70	62	4	4
Dehra Gopipur	436	12	17	8	15	77	64	4	4
Dharampur	1986	12	15	10	15	74	66	5	5
Dharamsala	1211	9	14	8	15	80	66	3	4
Ghumarwin	687	13	15	10	15	74	66	3	4
Hamirpur	786	12	16	9	15	75	66	4	4
Jogindarnagar	1221	10	14	11	17	77	65	3	4
Jubbal	2000	19	17	21	25	56	54	5	5
Kandaghat	1425	15	16	12	16	68	64	5	4
Kangra	701	10	15	8	14	79	67	3	4
Karsog	1347	17	17	17	22	62	57	5	4
Kasauli	1783	10	13	8	12	78	71	4	4
Kilba	2583	31	23	35	32	27	40	7	6
Koksar	3204	31	29	29	30	33	34	8	8
Kotkhai	1560	17	17	19	23	60	56	5	5
Kumarsain	1700	17	19	21	25	58	52	5	5
Mandi Sadar	807	11	15	11	16	76	66	3	4
Nahan	932	8	13	5	10	84	74	3	4
Nalagarh	616	10	13	7	11	81	72	3	4
Nichar	2086	26	19	27	27	42	49	5	5
Nurpur	616	13	17	8	14	76	65	4	4
Pachhad	1685	12	15	9	13	75	68	4	4
Palampur	1217	10	13	9	15	79	67	3	4
Paonta	399	7	11	4	9	85	78	3	3
Rampur	1067	18	18	22	23	55	54	4	4
Renuka (Rainka)	690	12	14	9	14	76	69	4	3
Rohru	1333	21	19	20	23	54	54	5	5
Sangla	2860	37	23	30	30	27	41	6	6
Sarkaghat	914	9	14	9	14	80	68	3	3
Shimla	2202	10	13	14	18	72	64	4	5
Sundernagar	1193	12	16	12	16	72	63	4	4
Suni (Seoni)	670	15	18	16	20	65	58	4	4
Theog	2086	16	16	20	23	61	57	3	4
Una	365	11	15	8	14	78	67	4	4

decreasing trend. In this study, if $Z > +1.96$ or $Z < -1.96$, the null hypothesis (H_o)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.

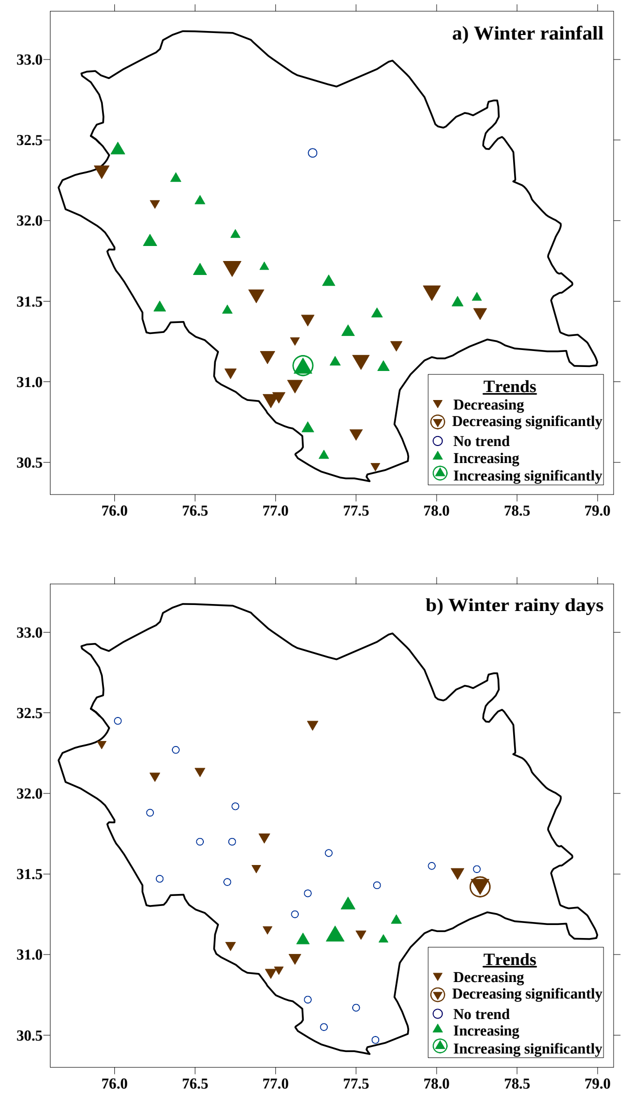
$$b = \text{median}\left[\frac{(X_j - X_i)}{(j-i)}\right], \; for\, all\, i < j \qquad (5)$$

where, b is the slope between data points X_j and X_i measured at times *j* and *i* respectively. Trends in annual and seasonal rainfall and rainy days data series for all 37 stations are tested using the Mann-Kendal technique and the trend value is computed using Sen's method. The spatial distribution of annual and seasonal trends in rainfall and rainy days over Himachal Pradesh during 1951-2005 are shown in Figs. 5-9, where trends significant at 95% level of confidence are indicated by outer circle circumscribing the sign of trend. Annual one day heaviest rainfall trends are shown in Fig. 10.

4. Results and discussion

4.1. *State averaged rainfall and rainy days in Himachal Pradesh*

The mountain barriers between different stations in Himachal Pradesh having varying elevation makes the prospect of having a broad pattern of long term distribution of rainfall and number of rainy days difficult. However, to have an overall view of changes in rainfall over Himachal Pradesh, we have prepared long-term monthly, annual and seasonal mean rainfall and rainy days for the period 1951-2005. The state averaged mean, standard deviation, coefficient of variation and trends of rainfall and rainy days are given in Table 2. The monthly mean rainfall is highest in July (345.1 mm) followed by August (329.9 mm). With lower coefficient of variation (CV) 28% and 26% in July and August months respectively, these two months contribute ~25% each to the annual total rainfall of Himachal Pradesh. The long term mean rainfall is lowest in November which receives only 14.1 mm rainfall. Rainfall in Himachal Pradesh is highly variable in October and November months having large CV, 158% and 121% respectively. The long-term mean annual rainfall for Himachal Pradesh is 1353.4 mm with standard deviation 234.3 mm resulting in lower CV (17%). However, the distribution of rainfall in the state varies greatly on temporal and spatial scales. Thus most of the rainfall is received in the monsoon when flash floods and cloud bursts also occur on many occasions. The post monsoon season rainfall is lowest (52.4 mm)



Figs. 6(a&b). Spatial variations in winter (a) rainfall and (b) rainy days trends for stations in Himachal Pradesh during 1951-2005. Trends significant at 95% level of significance are shown by an outer circle

and highly variable in Himachal Pradesh with CV 117%. The monsoon season accounts for 70% of the annual total of rainfall while winter and summer seasons contribute equally ~13% each. The state averaged monthly numbers of rainy days for Himachal Pradesh are highest in July (13.3 days) and August (13.1 days) as given in Table 2. The contribution of monthly rainy days to the annual total is highest in July and August (both ~20% each) and lowest in November (~1%). Annual mean numbers of rainy days in Himachal Pradesh are 65.1 with lower CV 12%. The seasonal numbers of rainy days are highest in monsoon season (39.4 days) with lowest CV (15%) and lowest in post monsoon season (2.8 days) with highest

CV (71%) indicating higher rainfall variability in the state in the post monsoon season.

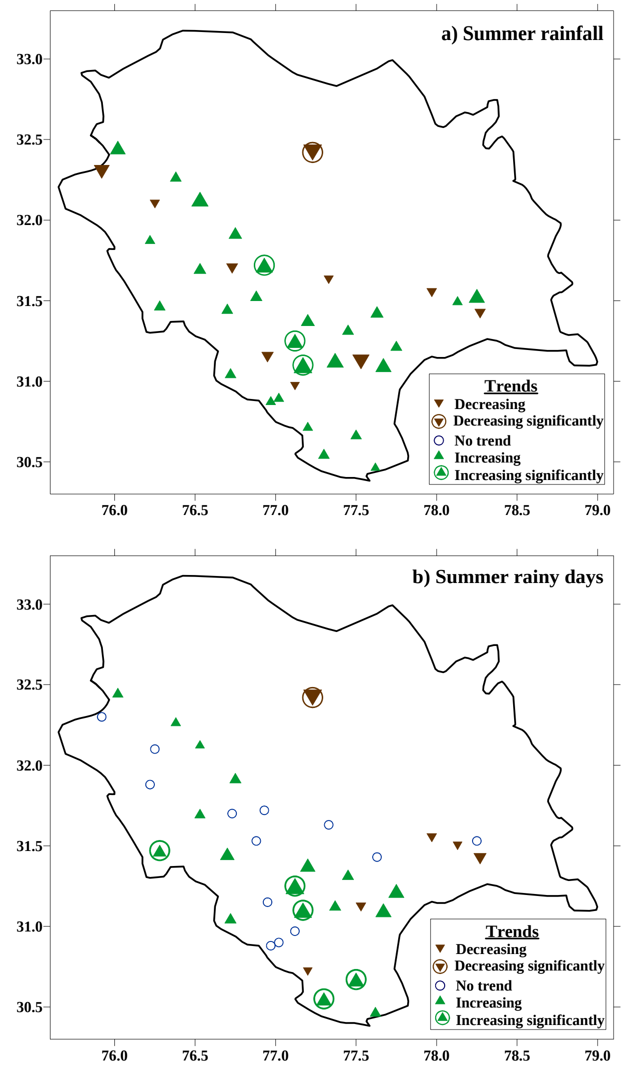
The trend analysis of state averaged monthly rainfall suggests significant decreasing trends for January (-0.61 mm/year), July (-1.83 mm/year), August (-1.49 mm/year) and October (-0.90 mm/year) as given in Table 2. Similar to rainfall, trends in monthly rainy days are significant for January (-0.04 days/year), July (-0.04 days/year), August (-0.04 days/year) and October (-0.03 days/year). Temporal variations and linear trends in state averaged annual and seasonal rainfall and rainy days are shown in Figs. 3 (a-e). State averaged annual rainfall and rainy days trends are decreasing significantly by -4.58 mm/year and -0.13 days/year respectively. On seasonal scale, rainfall and rainy days trends in Himachal Pradesh are significantly decreasing for monsoon (-3.68 mm/year and -0.09 days/year respectively) and post monsoon (-0.98 mm/year and -0.03 days/year respectively).

4.2. *Station annual means of rainfall and rainy days*

The spatial patterns of long-term (1951-2005) mean annual rainfall and rainy days in Himachal Pradesh indicates regions of highest (lowest) rainfall and rainy days in the western (eastern) part of the state as shown in Figs. 4(a&b) respectively. With long-term mean annual rainfall 2923.4 mm, Dharamsala is the wettest place in Himachal Pradesh having highest number of rainy days (99.3 days). The driest place in Himachal Pradesh is Sangla having annual mean rainfall 757.3 mm and annual mean rainy days 54.6 only. Long-term annual means of rainfall and rainy days in Himachal Pradesh indicates that precipitation declines from west to the east and south to the north.

4.3. *Contribution of seasonal means of rainfall and rainy days to annual means*

It is evident from Table 3 that the seasonal regime for the higher elevation stations in northern parts of Himachal Pradesh is quite different from those in the southern parts of the state. Whereas the monsoon rainfall for the lower southwest part of the state is generally in the range of 60 to 80% of the annual total, it is only around 35% for the higher elevation stations (Koksar, Kilba, Chini and Sangla) - this inspite of the fact that the annual totals for these stations are quite different. Winter season rainfall in Sangla is contributing highest (37%) to its mean annual rainfall while Koksar is contributing highest (29%) to its mean annual number of rainy days. Summer season rainfall contribution is higher (around 35%) in the north eastern parts of Himachal Pradesh. Summer season rainfall and rainy days in Chini (Kalpa) are contributing



Figs. 7(a&b). Spatial variations in summer (a) rainfall and (b) rainy days trends for stations in Himachal Pradesh during 1951-2005. Trends significant at 95% level of significance are shown by an outer circle

highest (36% and 34% respectively) to their respective annual means. Summer season rainfall and rainy days contribution to annual mean is lowest (4% and 9% respectively) at Paonta. The contribution of monsoon season rainfall and rainy days to their respective annual means is highest in low elevation station Paonta (85% and 78% respectively) in southern part of the state and lowest in high elevation station Chini (Kalpa) (22% and 32% respectively). Post monsoon season rainfall is very less in all parts of Himachal Pradesh as no station is having contribution more than 8% to the annual mean rainfall with majority of stations having 3 to 4% contribution to the annual mean as given in Table 3. The highest contribution of rainfall and rainy days obtained for post

TABLE 4

Annual and seasonal rainfall (RF) and rainy days (RD) trend using Man-Kendall test and Sen's estimator of magnitude for rainfall stations in Himachal Pradesh having continuous data for 1951-2005. Magnitudes of RF trends are in mm/year and RD are in days/year. Trend values significant at 95% level are shown in bold and marked '*'

	Annual		Winter		Summer		Monsoon		Post monsoon	
Station	RF mm/yr	RD days/yr	RF mm/yr	RD days/yr	RF mm/yr	RD days/yr	RF mm/yr	RD days/yr	RF mm/yr	RD days/yr
Arki	**-7.05***	**-0.23***	-0.82	-0.02	-0.47	no trend	**-5.87***	**-0.17***	-0.24	no trend
Banjar (Saraj)	**-2.30***	-0.09	0.56	no trend	-0.06	no trend	**-1.52***	-0.08	**-0.61***	**-0.03***
Chini (Kalpa)	+1.36	-0.03	+0.10	no trend	+1.28	no trend	no trend	-0.02	-0.24	-0.01
Chowari	-3.45	-0.08	+0.83	no trend	+1.19	+0.02	-3.75	-0.11	-0.33	-0.03
Dehra Gopipur	-1.73	**-0.17***	+0.74	no trend	+0.18	no trend	-0.85	-0.17	-0.14	no trend
Dharampur	**-7.04***	**-0.24***	-0.54	-0.02	+0.20	no trend	**-6.25***	**-0.22***	no trend	-0.02
Dharamsala	-6.30	no trend	+0.23	no trend	+0.44	+0.01	-5.98	no trend	-0.04	no trend
Ghumarwin	-5.90	-0.06	+0.15	no trend	+0.43	+0.06	-5.49	-0.06	-0.40	-0.02
Hamirpur	**-3.85***	-0.03	+0.70	no trend	+0.59	+0.02	-4.13	-0.05	no trend	no trend
Jogindarnagar	+4.81	-0.10	+0.08	no trend	+0.77	+0.03	+2.61	no trend	-0.19	no trend
Jubbal	+0.52	+0.10	+0.47	+0.01	+1.31	+0.08	-0.27	no trend	-0.18	-0.02
Kandaghat	-4.65	**-0.20***	-0.91	-0.05	-0.03	no trend	-2.75	-0.08	-0.49	**-0.05***
Kangra	-2.81	no trend	-0.08	-0.03	-0.09	no trend	-2.64	+0.05	**-0.81***	-0.02
Karsog	-3.48	-0.10	-0.58	no trend	+0.85	+0.07	**-3.34***	-0.13	-0.30	no trend
Kasauli	-6.18	**-0.25***	-1.00	-0.04	+0.18	no trend	-4.17	-0.11	**-0.78***	**-0.06***
Kilba	-0.61	**-0.16***	+0.37	-0.06	+0.17	-0.02	-0.43	-0.04	-0.14	-0.03
Koksar	-1.13	**-0.42***	no trend	-0.04	**-1.48***	**-0.16***	0.65	-0.04	**-0.89***	**-0.06***
Kotkhai	**-9.03***	-0.22	-1.16	-0.03	-1.21	-0.03	**-5.46***	**-0.17***	**-0.51***	-0.03
Kumarsain	+0.41	+0.12	+0.62	+0.05	+0.44	+0.03	+0.14	+0.01	no trend	no trend
Mandi	-2.16	-0.20	+0.01	-0.04	**+1.50***	no trend	-2.89	-0.13	-0.13	-0.01
Nahan	-2.79	no trend	+0.14	no trend	+0.42	**+0.07***	-1.27	-0.04	-0.39	no trend
Nalagarh	-0.60	-0.09	-0.39	-0.03	+0.39	+0.03	+0.20	no trend	-0.11	no trend
Nichar	-5.48	-0.21	-1.23	no trend	-0.15	-0.03	-1.85	-0.12	-0.52	-0.02
Nurpur	-7.73	-0.01	-0.90	-0.02	-1.03	no trend	-5.57	no trend	**-0.73***	**-0.03***
Pachhad	**-10.77***	**-0.38***	+0.50	no trend	+0.18	-0.02	**-8.43***	**-0.30***	-0.33	-0.03
Palampur	-0.29	-0.07	0.21	-0.03	1.45	no trend	-0.13	0.01	-0.48	**-0.03***
Paonta	-6.04	no trend	-0.03	no trend	0.03	0.02	-2.64	-0.02	-0.62	**-0.03**
Rampur	+0.25	-0.11	+0.33	no trend	+0.72	no trend	-0.23	-0.10	-0.46	-0.03
Renuka (Rainka)	**-24.97***	**-0.29***	-0.55	no trend	+0.36	**+0.08***	**-21.81***	**-0.33***	-0.21	no trend
Rohru	-0.70	+0.12	-0.39	+0.02	+0.43	+0.08	-0.66	+0.02	-0.23	no trend
Sangla	-3.62	**-0.38***	-0.63	**-0.11***	-0.29	-0.07	**-1.56***	**-0.13***	**-0.47***	-0.04
Sarkaghat	**-12.59***	-0.13	-1.33	no trend	-0.37	no trend	**-9.48***	-0.10	-0.27	no trend
Shimla	-0.88	-0.04	**+1.47***	+0.04	**+1.77***	**+0.10***	**-3.71***	**-0.17***	-0.44	-0.03
Sundernagar	**-7.81***	**-0.36***	-0.94	-0.02	+0.51	no trend	**-6.06***	**-0.28***	-0.50	**-0.04***
Suni (Seoni)	-1.11	no trend	-0.05	no trend	**+1.31***	**+0.11***	-2.45	**-0.12***	-0.30	no trend
Theog	+1.08	-0.06	+0.23	+0.08	+1.47	+0.03	+0.55	-0.09	-0.27	-0.03
Una	-0.21	+0.10	+0.48	no trend	+0.39	**+0.05***	-0.09	+0.06	-0.05	no trend

monsoon season is 8% each in high elevation station Koksar in greater Himalayas.

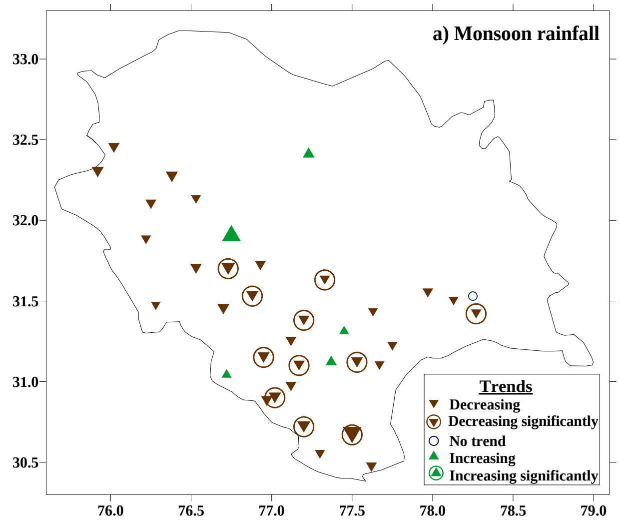
4.4. *Annual and seasonal rainfall and rainy days trends*

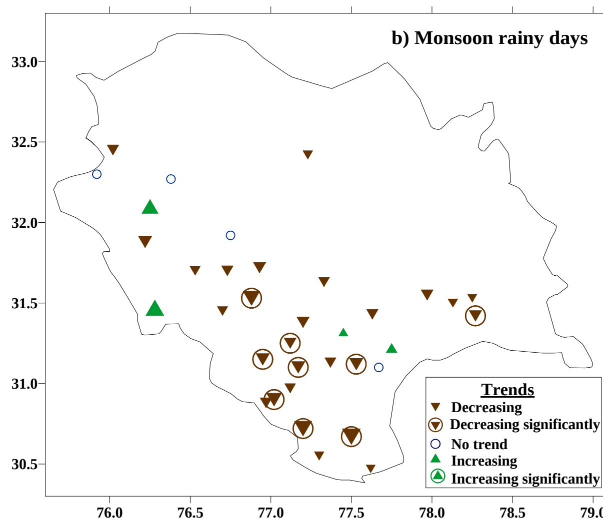
4.4.1. *Annual*

Out of 37 stations in Himachal Pradesh under study, annual rainfall is decreasing at 31 stations and increasing at 6 stations as given in Table 4. The spatial distribution of annual rainfall trends suggests significant decrease in south and central Himachal Pradesh as shown in Fig. 5(a). The decreasing trends in annual rainfall is significant for Arki (-7.05 mm/year), Banjar (Saraj) (-2.30 mm/year), Dharampur (-7.04 mm/year), Hamirpur (-3.85 mm/year), Kotkhai (-9.03 mm/year), Pachhad (-10.77 mm/year), Renuka (Rainka) (-24.97 mm/year), Sarkaghat (-12.59 mm/year) and Sundernagar (-7.81 mm/year). Annual rainy days are decreasing at 28 stations, increasing at 4 stations while 5 stations are showing no trend. The spatial distribution of annual rainy days trends suggests significant decrease in south, central and east Himachal Pradesh as shown in Fig. 5(b). Stations showing significant decrease in annual rainy days are Arki (-0.23 days/year), Dehra Gopipur (-0.17 days/year), Dharampur (-0.24 days/year), Kandaghat (-0.20 days/year), Kasauli (-0.25 days/year), Kilba (-0.16 days/year), Koksar (-0.42 days/year), Pachhad (-0.38 days/year), Renuka (Rainka) (-0.29 days/year), Sangla (-0.38 days/year) and Sundernagar (-0.36 days/year). No station in Himachal Pradesh is showing significant increasing trend in annual rainfall and rainy days during 1951-2005 as shown in Figs. 5(a&b).

4.4.2. *Winter*

Seasonal total rainfall in winter is decreasing at 17 stations and increasing at 19 stations while one station is showing no trend during 1951-2005 as given in Table 4. The spatial pattern of winter rainfall trends in Himachal Pradesh is mixed with non-significant decrease and increase occurring close by as shown in Fig. 6(a). The magnitude of decreasing trends in winter rainfall are between -0.03 mm/year at Paonta and -1.33 mm/year at Sarkaghat. The increasing trend in winter rainfall varies between +0.01 mm/year and +1.47 mm/year with Shimla showing a significant increase by +1.47 mm/year. Winter rainy days are decreasing at 14 stations, increasing at 5 stations while 18 stations are showing no trend. The spatial pattern of winter rainy days trends in Himachal Pradesh suggests a non-significant decrease in western and eastern parts and increase in south central part of the state as shown in Fig. 6(b). However, only one station Sangla is showing significant decrease (-0.11 days/year) in winter rainy days.

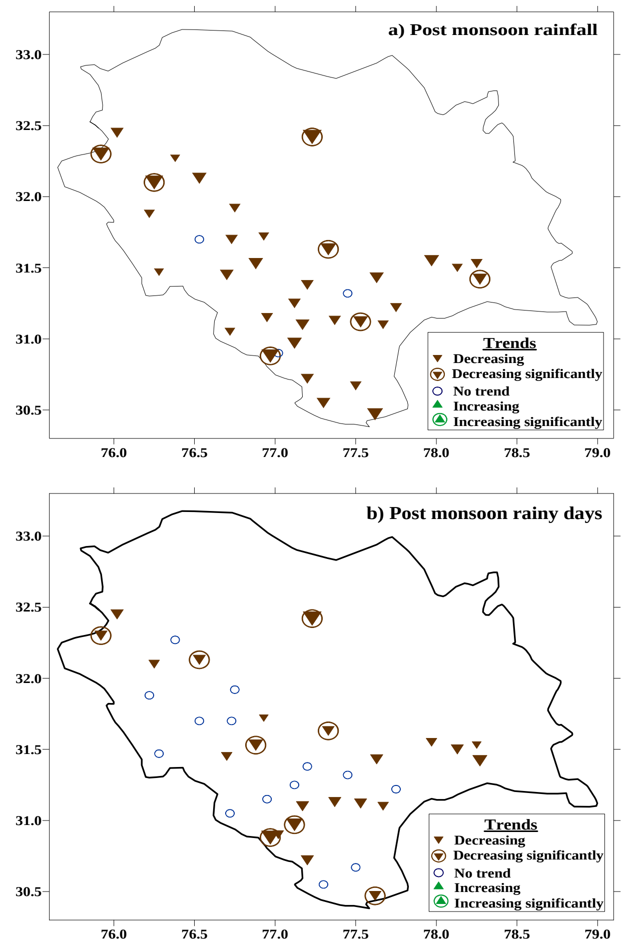




Figs. 8(a&b). Spatial variations in monsoon (a) rainfall and (b) rainy days trends for stations in Himachal Pradesh during 1951-2005. Trends significant at 95% level of significance are shown by an outer circle

4.4.3. *Summer*

Trend analysis of summer rainfall at 37 stations in Himachal Pradesh for 1951-2005 shows increasing trends at 27 stations and decreasing trends at 10 stations as given in Table 4. The spatial pattern of summer rainfall trends in the state suggest increase in almost all parts except extreme north where it is significantly decreasing as showing significant increasing trends are Mandi (+1.50 mm/year), Shimla (+1.77 mm/year) and Suni (Seoni) (+1.31 mm/year). The magnitude of decreasing trend in summer rainfall are between -0.03 mm/year and -1.48 mm/year. However, summer rainfall is decreasing significantly at Koksar (-1.48 mm/year) only. Summer



Figs. 9(a&b). Spatial variations in post monsoon a) rainfall and b) rainy days trends for stations in Himachal Pradesh during 1951-2005. Trends significant at 95% level of significance are shown by an outer circle

rainy days are increasing at 18 stations, decreasing at 6 shown in Fig. 7(a). The magnitude of increasing trends lies between +0.03 mm/year and +1.77 mm/year. Stations stations, while 13 stations are showing no trend as given in Table 4. The spatial pattern of summer rainy days trends in the state suggest increase or no-trend in almost all parts except extreme north and east where it is decreasing as shown in Fig. 7(b). The increasing trends are significant at Nahan (+0.01 days/year), Renuka (Rainka) (+0.08 days/year), Shimla (+0.10 days/year), Suni (Seoni) (+0.11 days/year) and Una (+0.05 days/year). However, only one station Koksar is showing significant decrease (-1.48 days/year) in summer rainy days.

4.4.4. *Monsoon*

Monsoon season rainfall and rainy days trend analysis shows decreasing trends at most of the stations in

TABLE 5

Annual daily heaviest rainfall trends for rainfall stations in Himachal Pradesh having continuous data for 1951-2005. Magnitudes of trends are in mm/year. Trend values significant at 95% level are shown in bold and marked '*'

Station	Trend (mm/year)
Arki	-0.36
Banjar (Saraj)	-0.12
Chini (Kalpa)	**+1.68***
Chowari	+0.40
Dehra Gopipur	+0.02
Dharampur	+0.06
Dharamsala	-0.50
Ghumarwin	-0.24
Hamirpur	**-0.68***
Jogindarnagar	+0.93
Jubbal	+0.19
Kandaghat	-0.43
Kangra	-0.17
Karsog	-0.04
Kasauli	-0.39
Kilba	-0.46
Koksar	0.01
Kotkhai	**-0.46***
Kumarsain	-0.02
Mandi Sadar	+0.36
Nahan	**-0.95***
Nalagarh	-0.29
Nichar	+0.04
Nurpur	**-1.17***
Pachhad	**-0.72***
Palampur	**+0.91***
Paonta	-0.29
Rampur	+0.15
Renuka (Rainka)	**-2.28***
Rohru	-0.33
Sangla	-0.71
Sarkaghat	-0.30
Shimla	+0.47
Sundernagar	-0.50
Suni (Seoni)	+0.29
Theog	+0.47
Una	-0.24

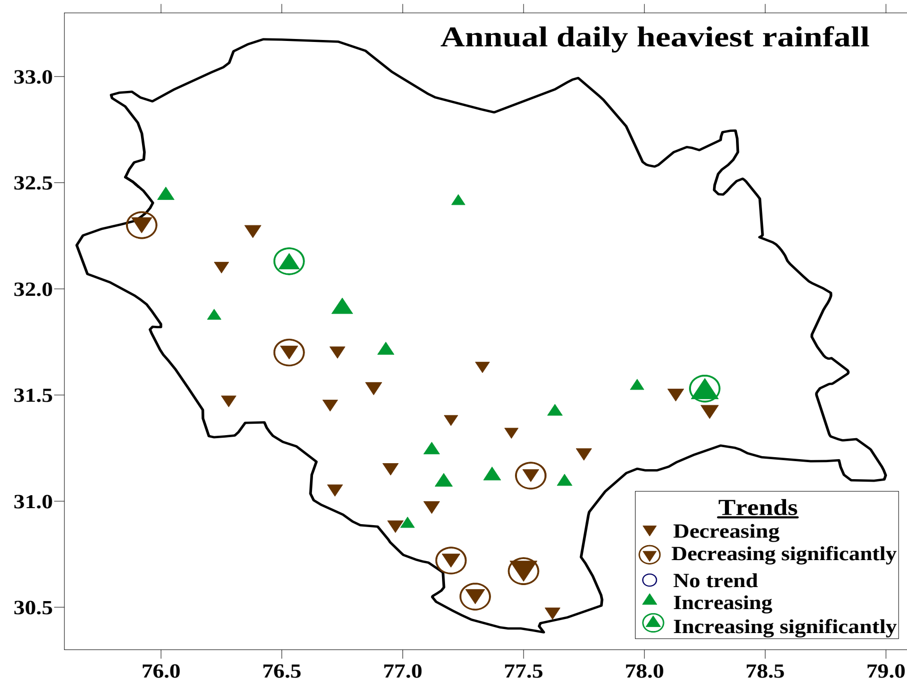


Fig. 10. Spatial variations in annual daily heaviest rainfall for stations in Himachal Pradesh during 1951-2005. Trends significant at 95% level of significance are shown by an outer circle

Himachal Pradesh during the study period 1951-2005. Since this season has the maximum contribution to the annual total, the decrease in rainfall is noteworthy and a cause of concern. Out of 37 stations, 31 are showing decreasing trends, 5 are showing increasing trends and one station is showing no trend in monsoon rainfall as given in Table 4. The spatial pattern of monsoon rainfall trends in the state suggest decrease in almost all parts except extreme north where it is having non-significant increasing trend as shown in Fig. 8(a). The significant decreasing trends in monsoon season rainfall are spatially coherent in south and central parts of Himachal Pradesh. Stations showing significant decreasing trends are Arki (-5.87 mm/year), Banjar (Saraj) (-1.52 mm/year), Dharampur (-6.25 mm/year), Karsog (-3.34 mm/year), Kotkhai (-5.46 mm/year), Pachhad (-8.43 mm/year), Renuka (Rainka) (-21.81 mm/year), Sangla (-1.56 mm/year), Sarkaghat (-9.48 mm/year), Shimla (-3.71 mm/year) and Sundernagar (-6.06 mm/year). Monsoon rainy days are decreasing at 27 stations, increasing at 5 stations, while 5 stations are showing no trend as given in Table 4. The spatial pattern of monsoon rainy days trends in the state suggest decrease in almost all parts as shown in Fig. 8(b). The decreasing trends are significant at Arki (-0.17 days/year), Dharampur (-0.22 days/year), Kotkhai (-0.17 days/year), Pachhad (-0.30 days/year), Renuka (Rainka) (-0.33 days/year), Sangla (-0.13 days/year), Shimla (-0.17 days/year), Sundernagar (-0.28 days/year) and Suni (Seoni) (-0.12 days/year). If the widespread decreasing trends in rainfall and rainy days persist in future also, it will adversely impact agriculture and horticulture in the state.

4.4.5. *Post monsoon*

Trend analysis of post monsoon rainfall reveals decreasing trends at 34 stations while 3 stations have no trend as given in Table 4. The spatial patterns of post monsoon rainfall trends suggest decrease in almost all parts of Himachal Pradesh as shown in Fig. 9(a). Stations showing significant decreasing trends are Banjar (Saraj) (-0.61 mm/year), Kangra (-0.81 mm/year), Kasauli (-0.78 mm/year), Koksar (-0.89 mm/year), Kotkhai (-0.51 mm/year), Nurpur (-0.73 mm/year) and Sangla (-0.47 mm/year). No station is showing increasing trend in post monsoon rainfall. Post monsoon season rainy days trends are decreasing at 23 stations, while 14 stations are showing no trend as given in Table 4. The spatial patterns of post monsoon rainy days trends suggest decrease in almost all parts of Himachal Pradesh as shown in Fig. 9(b). The decreasing trends of post monsoon rainy days are significant at Banjar (Saraj) (-0.03 days/year), Kandaghat (-0.05 days/year), Kasauli (-0.06 days/year), Koksar (-0.06 days/year), Nurpur (-0.03 days/year), Palampur (-0.03 days/year), Paonta (-0.03 days/year) and Sundernagar (-0.04 days/year).

4.5. *Annual daily heaviest rainfall trends*

Trend analysis of annual daily heaviest rainfall at all 37 stations in Himachal Pradesh during the period 1951-2005 is given in Table 5. Out of 37 stations, 23 are showing decreasing trends, while 14 are showing increasing trends. The spatial patterns of annual daily heaviest rainfall trends suggest decrease in south and central parts and increase in west, east and north parts of Himachal Pradesh as shown in Fig. 10. The decreasing trends in annual daily heaviest rainfall are significant at Hamirpur (-0.68 mm/year), Kotkhai (-0.46 mm/year), Nahan (-0.95 mm/year), Nurpur (-1.17 mm/year), Pachhad (-0.72 mm/year) and Renuka (Rainka) (-2.28 mm/year). Annual daily heaviest rainfall is significantly increasing in eastern part of Himachal Pradesh at Chini (Kalpa) (+1.68 mm/year) and western part of the state at Palampur (+0.91 mm/year). In mountainous regions, the precipitation patterns are influenced by the irregular topography leading to extreme precipitation on many occasions.

5. Discussion

The global surface warming is taking place at the rate of 0.74 ± 0.18 °C (IPCC, 2007) and for the Indian region (south Asia), the IPCC has projected 0.5 to 1.2 °C rise in temperature by the year 2020. Mountains cover close to 20 per cent 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, 2001; Beniston, 2003). The middle and high mountain ranges in Himalayas are more sensitive to climate change due to their physiographic characteristics (Shrestha *et al*., 1999). Altitude, latitude, continentality and topography influence climates in mountainous regions (Barry, 1992). Since mountainous and hilly regions are particularly sensitive to change, they have a special role in showing the effects of climate change. The state of Himachal Pradesh exhibits considerable variation in the distribution of temperature and rainfall due to the varying aspects like topography and altitudes (SCCAP, 2012). Analysis of temperature trends in the Himalayas and its vicinity shows that temperature increases are greater in the uplands than the lowlands (Shrestha *et al*., 1999; Dash *et al*., 2007; Bhutiyani *et al*., 2007). Studies have also shown that average air temperatures are rising in Himachal Pradesh in all seasons and the rise in temperature with respect to 1970s is in the range between 1.5 °C to 2.8 °C (SCCAP, 2012). Changes in precipitation are one of the expected impacts of global warming. Variability of precipitation in Himalayas is closely related to the variation in temperature with precipitation decreasing with increase in temperatures (Duan and Yao, 2003). Temperature and precipitation in the form of rainfall and snow largely determine the hydrological cycle, including surface runoff. Changes in these parameters will thus impact freshwater supplies from mountain areas and have implications for water availability in the lowlands.

Analysis of rainfall and rainy days in Himachal Pradesh shows that there is a general decline in rainfall and rainy days in all periods, except in summer season during 1951-2005. Out of 37 stations under study, annual rainfall and rainy days have declined at 84% and 76% of the stations respectively. The seasonal rainfall for winter, summer, monsoon and post monsoon has declined at 46%, 27%, 84% and 91% of the stations respectively. Similarly, seasonal rainy days for winter, summer, monsoon and post monsoon has declined at 38%, 16%, 73% and 62% of the stations respectively. Summer season rainfall and rainy days in Himachal Pradesh are increasing at 73% and 49% of the stations respectively during 1951-2005. Shimla, the capital city of Himachal Pradesh is showing significant decrease in rainfall in monsoon and significant increase in winter and summer seasons. Bhan and Singh (2011) have also reported decreasing trends in snowfall in winter months at Shimla during 1992-2011. Annual daily heaviest rainfall is decreasing at 62% stations and increasing at 38% of the station in Himachal Pradesh during the study period. Majority of stations showing significant decrease in daily heaviest rainfall are located in the Shivaliks (Hamirpur, Nurpur, Nahan, Renuka (Rainka), Kotkhai and Pachhad). With 93% of the population depending directly upon agriculture and horticulture, decline in rainfall in the state will severely impact large number of population. Stations showing significant increasing trends in annual daily heaviest rainfall are Palampur (+0.91 mm/year) in western part and Chini Kalpa (+1.68 mm/year) in the eastern part of the middle Himalayas. Prasad and Rana (2010) have also found increase in rainfall and decrease in rainy days at Palampur during monsoon suggesting rise in heavy precipitation. Also similar to trends obtained in this study, decrease in rainfall is reported in central Himalayas (Tibet, China) by Duan and Yao (2003).

Climate warming observed over the past several decades is consistently associated with changes in parts of the hydrological cycle and hydrological systems such as changing precipitation patterns, widespread melting of snow and ice, increasing atmospheric water vapour and changes in soil moisture in many parts of the world (*e.g.*, Beniston, 2003; Shrestha *et al*., 2000). In Himachal Pradesh, evidence of global warming could be clearly deciphered by changes like receding snowfall in the Himalayas, retreating glaciers (Bhagat *et al*., 2004), drying up of perennial hill springs, shifting of temperate fruit belt upward (Rana *et al*., 2009), productivity of apples, shifting and shortening of rabi season, disrupted rainfall pattern and more severe incidences of diseases and pests over crops and forest trees. Examining the response of monsoon precipitation in Himalayas to the global warming, Duan *et al*. (2006) has attributed decrease in precipitation to the decrease in thermal contrast between the Tibetan Plateau and the tropical Indian Ocean.

The growth of Himachal Pradesh economy is still determined by the trend in agricultural and horticultural production as it has a significant share in the total domestic product. Also agriculture and horticulture sector alone provides direct employment to 71% of people of the state. But due to lack of irrigation facilities, the agricultural and horticultural production to a large extent still depends on timely rainfall and weather conditions. Due to growth in population in the state, increase in per capita demand of fresh water, urbanization, agricultural and industrial demand, the problems of fresh water scarcity are going to become acute in the near future. Even though the state is extremely rich in hydro electric resources, the decline in rainfall will affect the river discharge which will have adverse impact on various major, medium, small and mini/micro hydel projects on the five river basins. Therefore, the changing patterns of rainfall in the state requires urgent attention and renewed efforts for adaptation to climate change, as it will affect the agriculture, horticulture and tourism which are the main contributors to the economy of the state.

6. Conclusions

Analysis of annual and seasonal rainfall data indicates a broad pattern of decrease in annual, winter, monsoon and post monsoon rainfall and an increase in the summer rainfall in Himachal Pradesh during the study period 1951-2005. The main results of this study are summarized below:

(*i*) The spatial patterns of mean annual rainfall and rainy days in Himachal Pradesh indicates regions of highest (lowest) rainfall and rainy days in the western (eastern) part of the state. Long-term mean annual rainfall is highest at Dharamsala (2923.4 mm) and lowest in Sangla (757.3 mm).

(*ii*) The state averaged monthly rainfall in Himachal Pradesh is highest in July (345.1 mm) and lowest in November (14.1 mm) contributing 25% and 1% respectively to the annual mean of 1353.4 mm for the long-term period 1951-2005. Seasonally, monsoon rainfall is contributing highest (70 %) followed by winter (14%) and summer (13%) seasons to the annual mean rainfall in the state indicating rainfall in all seasons in Himachal Pradesh. However, with lowest mean and highest coefficient of variation (117%), post monsoon season rainfall has highest inter-annual variability.

(*iii*) State averaged monthly rainfall is decreasing significantly for January (-0.61 mm/year), July (-1.83 mm/year), August (-1.49 mm/year) and October (-0.90 mm/year). Similar to rainfall, state averaged monthly rainy days are significantly decreasing for January, July, August and October. Annually, rainfall and rainy days are showing significantly decreasing trends by -4.58 mm/year and -0.13 days/year respectively. On seasonal scale, rainfall and rainy days are showing significantly decreasing trends for monsoon (-3.68 mm/year and -0.09 days/year respectively) and post monsoon (-0.98 mm/year and -0.03 days/year respectively).

(*iv*) With 86% of the stations showing decrease in rainfall, the spatial patterns of annual rainfall trends in Himachal Pradesh indicate a general decrease in rainfall and rainy days during 1951-2005. The stations showing significant decreasing trends in rainfall and rainy days are spatially coherent in southern parts of the state, particularly in the Shivaliks and the middle Himalaya. Seasonally, monsoon and post monsoon rainfall is showing decrease at 84% and 92% of the stations while summer rainfall is showing increasing trends at 73% of the stations during the study period.

(*v*) Spatial patterns of monsoon rainfall and rainy days indicate significant decrease in southern and eastern parts of Himachal Pradesh, particularly in the Shivaliks and the middle Himalayas. Stations showing significant increasing trends in summer rainfall and rainy days are spatially coherent in the Shivaliks and the middle Himalaya.

(*vi*) The annual daily heaviest rainfall is showing significantly decreasing trends in the southern Himachal Pradesh in the Shivaliks (Hamirpur, Kotkhai, Nahan, Nurpur, Renuka (Rainka) and Pachhad. Stations showing significant increasing trends in daily rainfall are located in middle Himalayas (Chini (Kalpa) and Palampur).

With very high variations of topography and rainfall across the state, projection of future climate trends will be especially difficult for Himachal Pradesh. If the widespread decreasing trends in rainfall and rainy days obtained in this study persist in future also, it will adversely impact the economy of this hilly state.

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