Trend analysis of rainfall and temperature data for India

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This article aims to review studies pertaining to trends in rainfall, rainy days and temperature over India. Sen's non-parametric estimator of slope has been frequently used to estimate the magnitude of trend, whose statistical significance was assessed by the Mann–Kendall test. Spatial units for trend analysis vary from station data to sub-division to sub-basin/river basins. There are differences in the results of the various studies, and a clear and consistent picture of rainfall trend has not emerged. Although the different units (sub-basins or sub-divisions) may have a non-zero slope value, few values are statistically significant. In a study on basin-wise trend analysis, 15 basins had decreasing trend in annual rainfall; only one basin showed significant decreasing trend at 95% confidence level. Among six basins showing increasing trend, one basin showed significant positive trend. Most of the basins had the same direction of trend in rainfall and rainy days at the annual and seasonal scale.

Regarding trends in temperature, the mean maximum temperature series showed a rising trend at most of the stations; it showed a falling trend at some stations. The mean minimum temperature showed a rising as well as a falling trend. At most of the stations in the south, central and western parts of India a rising trend was found. Some stations located in the north and northeastern India showed a falling trend in annual mean temperature. Most of the data used in trend analysis pertained to the stations located in urban areas and these areas are sort of heat islands. This article also highlights the need of a network of baseline stations for climatic studies.

Keywords: Climate change, rainfall, trend, river basin, seasonal analysis, temperature data.

AGRICULTURE and related sectors, food security, and energy security of India are crucially dependent on the timely availability of adequate amount of water and a conducive climate. The rainfall received in an area is an important factor in determining the amount of water available to meet various demands, such as agricultural, industrial, domestic water supply and for hydroelectric power generation. Global climate changes may influence long-term rainfall patterns impacting the availability of water, along with the danger of increasing occurrences of droughts and floods. The southwest (SW) monsoon, which brings about 80% of the total precipitation over the country, is critical for the availability of freshwater for drinking and irrigation. Changes in climate over the Indian region, particularly the SW monsoon, would have a significant impact on agricultural production, water resources management and overall economy of the country. The heavy concentration of rainfall in the monsoon months (June–September) results in scarcity of water in many parts of the country during the non-monsoon periods.

In view of the above, a number of studies have attempted to investigate the trend of climatic variables for the country. These studies have looked at the trends on the country scale, regional scales and at the individual stations. This article gives an exhaustive coverage of the reported studies dealing with two variables which are critical in hydrologic studies: rainfall and temperature. Temperature and its changes impact a number of hydrological processes including rainfall and these processes, in turn, also impact temperature (e.g., cooling due to rain/snow).

Due to the uneven distribution of rainfall and the mismatch between water availability and demand, large storage reservoirs are required to redistribute the natural flow in accordance with the requirements of specific regions. The design of hydro-infrastructure is generally based on the assumption that climate is stationary[1]. Changes in rainfall due to global warming will influence the hydrological cycle and the pattern of stream-flows and demands (particularly agricultural), requiring a review of hydrologic design and management practices. Changes in run-off and its distribution will depend on likely future climate scenarios[2]. The trend analysis of rainfall, temperature and other climatic variables on different spatial scales will help in the construction of future climate scenarios. Using these water availability in different basins can be assessed in the context of future requirements.

River basins of India and their key features

In India, river basins having catchment areas exceeding 20,000 sq. km are classified as major basins. The country has 12 such basins whose total catchment area is 2.528 million sq. km. Among the major rivers, the Ganga–Brahmaputra–Meghna (Barak) system is the

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*For correspondence. (e-mail: s_k_jain@yahoo.com) largest. Three major basins, viz. Indus, Ganga and Brahmaputra are snow-fed, the remaining are purely rainfall-dependent. Seven other medium-sized basins of the Sabarmati, Mahi, Narmada and Tapi rivers flowing west and the Subarnarekha, Brahmani, Baitarani and Cauvery rivers flowing east together cover 15% of the total drainage area of India. The catchment area of medium rivers is about 0.25 million sq. km; Subarnarekha with catchment area of 19,000 sq. km is the largest among the medium rivers in the country. Major river basins of India are shown in Figure 1 and key features of the river basins are provided in Table 1.

An understanding of rainfall variability for the country is necessary to appreciate the impacts of climate change; it is also important for water management. The key rainfall statistics of different river basins is given in Table 1. The variability of rainfall and rainy days during winter, pre-monsoon and post-monsoon seasons is high. WFR2 basin receives the maximum mean annual rainfall, whereas Luni+ and Sabarmati basin receive the minimum mean annual rainfall. Regarding seasonal patterns, the maximum rainfall in the pre-monsoon season is received over Brahmaputra and Barak+ basins; in the monsoon season over WFR1; in the post-monsoon season over WFR2 and in winter season over Indus basin. There are large temporal variations in rainfall; expectedly, the coefficient of variation is the largest in arid regions and the smallest for rivers with high water yield.

Figure 2 shows the temporal variation of annual rainfall and annual rainy days for a few major river basins. Least square lines are also drawn in Figure 2 to illustrate a possible linear trend in the rainfall and rainy-day data. As seen from Figure 2, rainfall in the Brahmaputra and Godavari basins shows a decreasing trend, whereas in the Ganga and Krishna basins, no trend is seen. Similarly, rainy days indicate decreasing trend in the Brahmaputra and Godavari basins and increasing trend in three other river basins. Figure 2 also shows varying amounts of trend in rainfall and rainy days over different river basins.

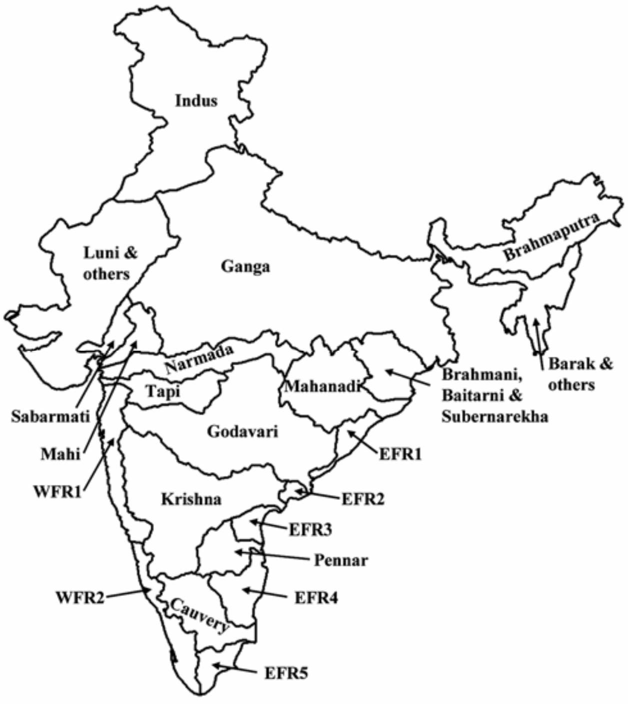

Figure 1. River basin map of India. EFR, East flowing rivers; WFR, West flowing rivers.

Trend analysis – general methodology

Trend analysis of a time series consists of the magnitude of trend and its statistical significance. Obviously, different workers have used different methodologies for trend detection. Kundzewicz[3] has discussed the change detection methodologies for hydrologic data.

In general, the magnitude of trend in a time series is determined either using regression analysis (parametric test) or using Sen's estimator method (non-parametric method)[4]. Both these methods assume a linear trend in the time series. Regression analysis is conducted with time as the independent variable and rainfall/temperature as the dependent variable. The regression analysis can be carried out directly on the time series or on the anomalies (i.e. deviation from mean). A linear equation, $y = mt + c$, defined by c (the intercept) and trend m (the slope), can be fitted by regression. The linear trend value represented by the slope of the simple least-square regression line provided the rate of rise/fall in the variable.

Sen's estimator has been widely used for determining the magnitude of trend in hydro-meteorological time series[5–7]. In this method, the slopes (T_i) of all data pairs are first calculated by

$$T_i = \frac{x_j - x_k}{j - k} \quad \text{for } i = 1, 2, \ldots, N, \tag{1}$$

where x_j and x_k are data values at time j and k $(j > k)$ respectively. The median of these N values of T_i is Sen's estimator of slope which is calculated as

$$\beta = \begin{cases} T_{\frac{N+1}{2}} & N \text{ is odd,} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & N \text{ is even.} \end{cases} \tag{2}$$

A positive value of β indicates an upward (increasing) trend and a negative value indicates a downward (decreasing) trend in the time series.

Significance of trend

To ascertain the presence of statistically significant trend in hydrologic climatic variables such as temperature and

Table 1. Details of river basins of India

River basin	Length of main river (km)	Catchment area (sq. km)	Average annual yield (km^3)	Annual precipitation		Seasonal precipitation (mm)			
				Mean (mm)	CV	Pre-monsoon	Monsoon	Post-monsoon	Winter
Ganga	2,525+	861,452+	525.02	1,051.2	0.13	56.4	898.3	57.9	38.5
Indus	1,114+	321,289+	73.31	1,097.1	0.18	248.3	538.5	63.8	246.5
Brahmaputra	916+	194,413+	537.32	2,589.2	0.14	537.9	1798.4	175.4	77.5
Barak and other rivers flowing into Barak (Barak+)	–	41,273	48.36	2,171.8	0.15	514.2	1413.7	195.4	48.6
Luni and others west-flowing rivers of Kutch and Saurashtra (Luni+)			15.10	397.0	0.35	13.8	360.8	16.0	6.3
Sabarmati	371	21,674	3.81	654.5	0.33	9.4	614.7	25.8	4.6
Mahi	583	34,842	11.02	1,002.6	0.32	7.8	948.2	40.9	5.7
Narmada	1,312	98,796	45.64	1,108.7	0.18	22.7	1006.2	47.9	31.9
Tapi	724	65,145	14.88	764.6	0.19	17.4	667.6	65.7	13.9
West-flowing river from Tapi to Tadri (WFR1)			87.41	2,872.0	0.15	65.0	2641.7	158.1	7.2
West-flowing river south of Tadri (WFR2)			113.53	3,107.0	0.16	355.6	2240.4	454.9	56.0
Brahmani, Baitarni and Subernarekha (BBS)		711,18	41.85	1,417.3	0.17	120.3	1146.7	111.1	39.3
Mahanadi	851	141,589	66.88	1,344.4	0.18	70.2	1144.2	99.2	30.8
Godavari	1,465	312,812	110.54	1,106.8	0.16	47.2	941.4	96.4	21.8
Krishna	1,401	258,948	78.12	838.1	0.14	70.0	619.1	137.0	12.0
Cauvery	800	81,155	21.36	1,031.7	0.17	157.9	485.4	304.4	83.9
Pennar	597	55,213	6.32	719.8	0.19	84.0	384.0	218.4	33.4
East-flowing river between Mahanadi and Godavari (EFR1)			22.52	1,183.0	0.19	120.6	786.5	245.6	30.3
East-flowing river between Godavari and Krishna (EFR2)				1,074.4	0.25	66.4	699.1	277.0	31.9
East-flowing river between Krishna and Pennar (EFR3)				784.3	0.28	86.6	358.2	295.1	44.4
East-flowing river between Pennar and Cauvery (EFR4)			16.46	1,002.4	0.16	98.5	423.4	370.0	110.5
East-flowing river south of Cauvery (EFR5)				973.9	0.15	169.8	297.5	376.3	130.3

Source: Publications of Central Water Commission; Jain *et al.*[80], and others.

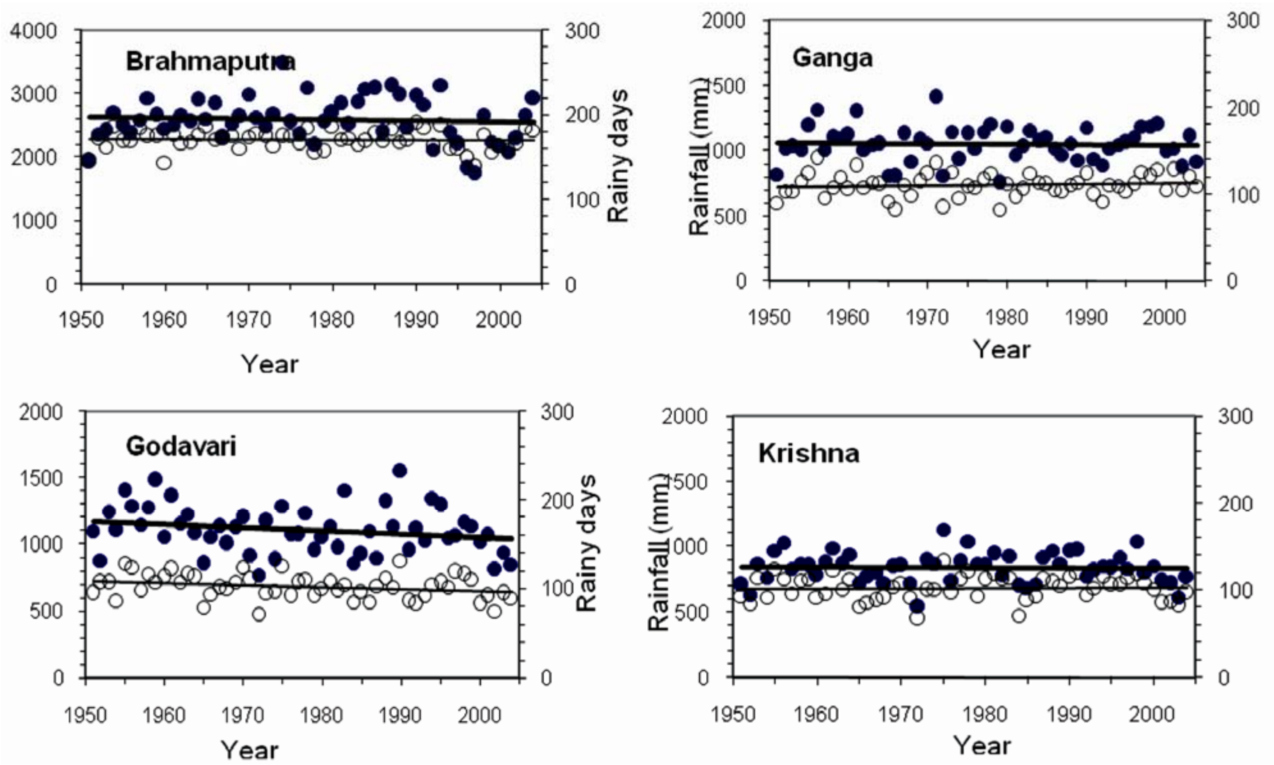

Figure 2. Temporal variation of annual rainfall and rainy days for four major river basins of India. Filled circles represent rainfall and empty circles represent rainy days. Thick and thin black lines are the linear trend lines in rainfall and rainy days respectively. Note that the y-axis scale for Brahmaputra River has a different scale.

precipitation with reference to climate change, non-parametric Mann–Kendall (MK) test has been employed[8–13]. The MK test checks the null hypothesis of no trend versus the alternative hypothesis of the existence of increasing or decreasing trend.

The statistics (S) is defined as[14]

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \operatorname{sgn}(x_j - x_i), \tag{3}$$

where N is the number of data points. Assuming $(x_j - x_i) = \theta$, the value of $\operatorname{sgn}(\theta)$ is computed as follows:

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta > 0 \\ -1 & \text{if } \theta > 0, \end{cases} \tag{4}$$

This statistics represents the number of positive differences minus the number of negative differences for all the differences considered. For large samples ($N > 10$), the test is conducted using a normal distribution[15], with the mean and the variance as follows:

$$E[S] = 0, \tag{5}$$

$$\operatorname{var}(S) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k (t_k - 1)(2t_k + 5)}{18}, \tag{6}$$

where n is the number of tied (zero difference between compared values) groups and t_k the number of data points in the kth tied group. The standard normal deviate (Z-statistics) is then computed as[16]

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\operatorname{var}(S)}} & \text{if } S < 0. \end{cases} \tag{7}$$

If the computed value of $|Z| > z_{\alpha/2}$, the null hypothesis (H_0) is rejected at α level of significance in a two-sided test. In this analysis, the null hypothesis was tested at 95% confidence level.

Studies of rainfall trends in India

Many studies have attempted to determine the trend in rainfall on both country and regional scales. Most of these deal with the analysis of annual and seasonal series of rainfall for some individual stations or groups of stations. Some past studies related to changes in rainfall over India have concluded that there is no clear trend in average annual rainfall over the country[17–22]. Though the monsoon rainfall in India exhibited no significant trend over a long period of time, particularly in the all-India scale, pockets of significant long-term rainfall changes were identified in some studies[22–26].

Parthasarathy and Dhar[27] found that the annual rainfall for the period 1901–1960 had a positive trend over Central India and the adjoining parts of the peninsula, and a decreasing trend over some parts of eastern India. A stable northeast monsoon rainfall was found over Tamil Nadu by Dhar *et al.*[28]. Pant and Hingane[29] found increasing trend in mean annual and SW monsoon rainfall over meteorological sub-divisions of Punjab, Haryana, west Rajasthan, east Rajasthan and west Madhya Pradesh during the period 1901–1982. Rupa Kumar *et al.*[30] reported that northeast peninsula, northeast India and northwest peninsula experienced a decreasing trend (ranged between –6% and –8% of the normal per 100 years) in the monsoon rainfall. But the west coast, central peninsula and northwest India experienced increasing trend (about 10–12% of the normal per 100 years) in monsoon rainfall.

Trends in monsoon rainfall in different sub-divisions and the whole of India were examined for the period 1871–1988 by Subbaramayya and Naidu[31]. Decreasing trends in the central and western Indian sub-divisions during the late 19th century and again in the 1960s were observed. The later trend was reversed in the early 1970s. Kothyari and Singh[32] found decreasing trend in monsoon rainfall and rainy days in the Ganga basin, and monsoon and annual rainfall over India starting around the second half of the 1960s. Singh and Sontakke[33] analysed rainfall data for the period 1829–1999 over the Indo-Gangetic Plains (IGP) and found significant increasing trend (170 mm/100 yrs) from 1900 in the summer monsoon rainfall over western IGP; non-significant decreasing trend (5 mm/100 yrs) from 1939 over central IGP and non-significant decreasing trend (50 mm/100 yrs) during 1900–1984 and non-significant increasing trend (480 mm/100 yrs) during 1984–1999 over eastern IGP.

Trend detection of rainfall for the period 1901–1984 at 11 stations in Himachal Pradesh indicated increasing trend in annual rainfall at 8 stations[24]. Further, eight other stations showed a decreasing trend in monsoon rainfall. The decreasing trend of annual and monsoon rainfall in Shimla was statistically significant at 95% confidence level. Ramesh and Goswami[34] analysed daily gridded observed rainfall data for the period 1951–2003 and found decreasing trends in both early and late monsoon rainfall and number of rainy days over India. Analysis of rainfall amount during different seasons indicated decreasing tendency in the summer monsoon rainfall over the Indian land mass and increasing trend in the rainfall during pre-monsoon and post-monsoon months[25]. Pattanaik[35] found decreasing trend in monsoon rainfall over northwest and central India during 1941–2002.

Trend analysis of rainfall data of 135 years (1871–2005) indicated no significant trend for annual, seasonal and monthly rainfall on an all-India basis[22]. Annual and monsoon rainfall decreased, and pre-monsoon, post-monsoon and winter rainfall increased over the years, with maximum increase in the pre-monsoon season. Monsoon months of June, July and September witnessed decreasing rainfall, whereas August showed increasing trend on an all-India basis. Further analysis on sub-divisional basis (30 sub-divisions) indicated that half of them have increasing trend in annual rainfall, but for only three sub-divisions, namely Haryana, Punjab and coastal Karnataka, this trend was statistically significant. Only the Chhattisgarh sub-division had significant decreasing trend out of the 15 sub-divisions showing decreasing trend in annual rainfall. All the five regions showed non-significant trend in annual, seasonal and monthly rainfall for most of the months.

Analysis of rainfall data at five stations (Srinagar, Kulgam, Handwara, Qazigund and Kukarnag) in the Kashmir Valley for the period 1903–1982 showed that the first three stations experienced a decreasing trend in annual rainfall; the largest decrease was for Kulgam (–20.16% of mean/100 yrs) and the smallest for Srinagar[26]. The decreasing trend in winter rainfall was statistically significant (95% confidence level) at Kulgam and Handwara, whereas none of the increasing trends in the pre-monsoon and post-monsoon season was significant. Srinagar and Handwara witnessed a decreasing (non-significant) trend in annual rainy days, whereas Kulgam experienced the opposite trend. All the stations experienced a decreasing trend in monsoon and winter rainy days. Qazigund and Kukarnag experienced decreasing annual rainfall, whereas Srinagar showed increasing annual rainfall during 1962–2002. Annual, pre-monsoon, post-monsoon and winter rainfall increased (non-significant), whereas monsoon rainfall decreased (non-significant) at Srinagar during the last century.

Studies of temporal variation in monthly, seasonal and annual rainfall over Kerala for 1871–2005 by Krishnakumar *et al*.[36] revealed significant decrease in SW monsoon rainfall, and an increase in post-monsoon season. Rainfall during winter and summer seasons showed insignificant increasing trend. Basistha *et al.*[37] analysed 80 years' (1901–1980) rainfall data from 30 rain gauge stations in the Indian Himalayas and found an increasing trend between 1901 and 1964, and a decreasing trend between 1965 and 1980. Pal and Al-Tabbaa[38] found decreasing trends in the spring and monsoon rainfall, and increasing trends in the autumn and winter rainfall over India during the period 1954–2003.

Rajeevan *et al.*[39] and Guhathakurta and Rajeevan[40] analysed a rainfall series created using a network of 1476

Table 2. Sen's estimator of slope for rainfall and rainy days*

Basin	Annual		Pre-monsoon		Monsoon		Post-monsoon		Winter	
	Rainfall (mm/yr)	Rainy days (days/yr)	Rainfall (mm/yr)	Rainy days (days/yr)	Rainfall (mm/yr)	Rainy days (days/yr)	Rainfall (mm/yr)	Rainy days (days/yr)	Rainfall (mm/yr)	Rainy days (days/yr)
Ganga	0.000	0.111	0.341	0.048	–0.302	0.000	–0.016	0.000	0.081	0.000
Indus	–1.825	–0.182	0.880	0.000	**–3.160**	–0.167	–0.261	–0.045	0.864	0.000
Brahmaputra	–0.442	–0.064	–1.935	–0.025	0.570	0.095	–0.057	–0.061	0.146	0.000
Barak+	2.662	–0.200	1.344	0.000	1.012	–0.111	0.191	–0.053	0.455	0.042
Luni+	–0.597	–0.104	0.109	0.000	–1.039	–0.125	0.028	0.000	0.057	0.000
Sabarmati	–0.990	–0.200	–0.006	0.000	–1.242	–0.231	0.013	0.000	–0.014	0.000
Mahi	–2.183	–0.138	0.003	0.000	–2.153	–0.139	0.000	0.000	0.000	0.000
Narmada	–2.409	–0.114	–0.030	0.000	–2.394	–0.067	0.097	0.000	0.030	0.000
Tapi	–1.387	–0.167	–0.073	0.000	–1.367	–0.139	0.379	0.030	0.000	0.000
WFR1	**–10.164**	–0.176	–0.318	–0.020	**–8.472**	–0.079	–0.515	**–0.111**	0.002	0.000
WFR2	–7.011	**–0.375**	**–2.482**	–0.152	–5.612	**–0.176**	0.926	–0.032	0.050	0.000
BBS	2.222	0.000	0.728	0.045	1.026	–0.034	–0.583	–0.079	0.056	0.000
Mahanadi	–2.905	0.053	0.172	0.029	–3.130	0.000	–0.091	0.000	0.127	0.000
Godavari	–2.727	**–0.276**	**–0.400**	0.000	–2.635	**–0.200**	0.209	–0.031	0.166	0.000
Krishna	–0.271	0.024	**–0.569**	0.000	–0.827	0.026	0.247	0.000	**0.155**	0.000
Cauvery	0.879	0.000	–0.563	0.000	0.075	0.028	**1.748**	0.050	0.024	0.000
Pennar	1.257	0.000	–0.398	–0.027	1.040	0.000	0.114	0.047	0.023	0.000
EFR1	–1.231	–0.190	0.418	0.053	–1.156	–0.167	–1.391	–0.091	0.386	0.034
EFR2	–0.442	–0.044	0.525	0.000	–1.722	–0.125	–0.136	0.000	**0.255**	0.000
EFR3	**4.928**	0.111	–0.630	–0.031	2.575	0.070	1.398	0.038	0.227	0.000
EFR4	0.445	–0.032	–0.345	–0.032	–0.214	–0.047	0.659	0.000	0.197	0.000
EFR5	–0.950	**–0.333**	–0.800	**–0.143**	–0.500	–0.125	0.491	0.000	–0.246	–0.032

*Bold values indicate statistical significance at 95% confidence level according to the Mann–Kendall test.

rain gauge stations for the period 1901–2003. It showed significant decreasing trend in the monsoon season for three sub-divisions (Jharkhand, Chhattisgarh and Kerala) and significant increasing trend over eight sub-divisions (Gangetic West Bengal, Western Uttar Pradesh, Jammu and Kashmir, Konkan and Goa, Madhya Maharashtra, Rayalseema, coastal Andhra Pradesh and North Interior Karnataka). Monthly, seasonal and annual precipitation of five meteorological sub-divisions of Central North East India showed a significant decreasing trend of 4.6 mm/yr for Jharkhand and 3.2 mm/day for Central North East India during the period 1889–2008 (ref. 41). During December, all the meteorological sub-divisions, except Jharkhand have shown a significant decreasing trend of rainfall in the recent past.

Some studies have investigated the trend and magnitude of variations in rainfall on the basin-scale. Mirza *et al.*[42] studied the changes over Ganges, Brahmaputra and Meghna basins and found that precipitation in the Ganges basin was by and large stable. One sub-division of the Brahmaputra basin showed a decreasing trend, whereas another showed an increasing trend. For Meghna basin, one sub-division showed decreasing trend and another showed increasing trend. Rao[43] did not find any significant trend in monsoon and annual rainfall over Mahanadi basin during the period 1901–1980. Ranade *et al.*[44] found no trend in the starting or ending date, duration and total rainfall of the hydrological wet season over different river basins of India. Using the data of 316 rain gauges, Singh *et al.*[45] found that annual rainfall over major basins in Central India (Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi) showed decreasing trend since the 1960s, whereas Indus, Ganga, Brahmaputra, Krishna and Cauvery basins showed an increasing trend.

Singh *et al.*[13] studied the changes in rainfall over the last century in nine river basins of northwest and Central India. The rate of change of rainfall in each of 43 stations was estimated by trend line slope and these point values were interpolated to get the spatial distribution of rainfall change over the study area. They found increasing trends in annual rainfall over eight river basins in the 2–19% range of the mean per 100 years.

Kumar and Jain[46] carried out a detailed analysis to determine the trends in rainfall amount and the number of rainy days in Indian river basins using daily gridded rainfall data at 1° × 1° resolution provided by the India Meteorological Department (IMD). The magnitude of trend in annual and seasonal rainfall and rainy days as determined by the Sen's estimator is given in Table 2. Six river basins had increasing trend in annual rainfall and 15 river basins had the opposite trend, whereas the Ganga basin had no trend. The increase in annual rainfall varied between 0.45 mm/yr (for EFR4 basin) and 4.93 mm/yr (for EFR3 basin); the decrease was maximum for WFR1 basin (–10.16 mm/yr) and minimum for Krishna basin (–0.27 mm/yr). Annual rainfall of only two basins showed

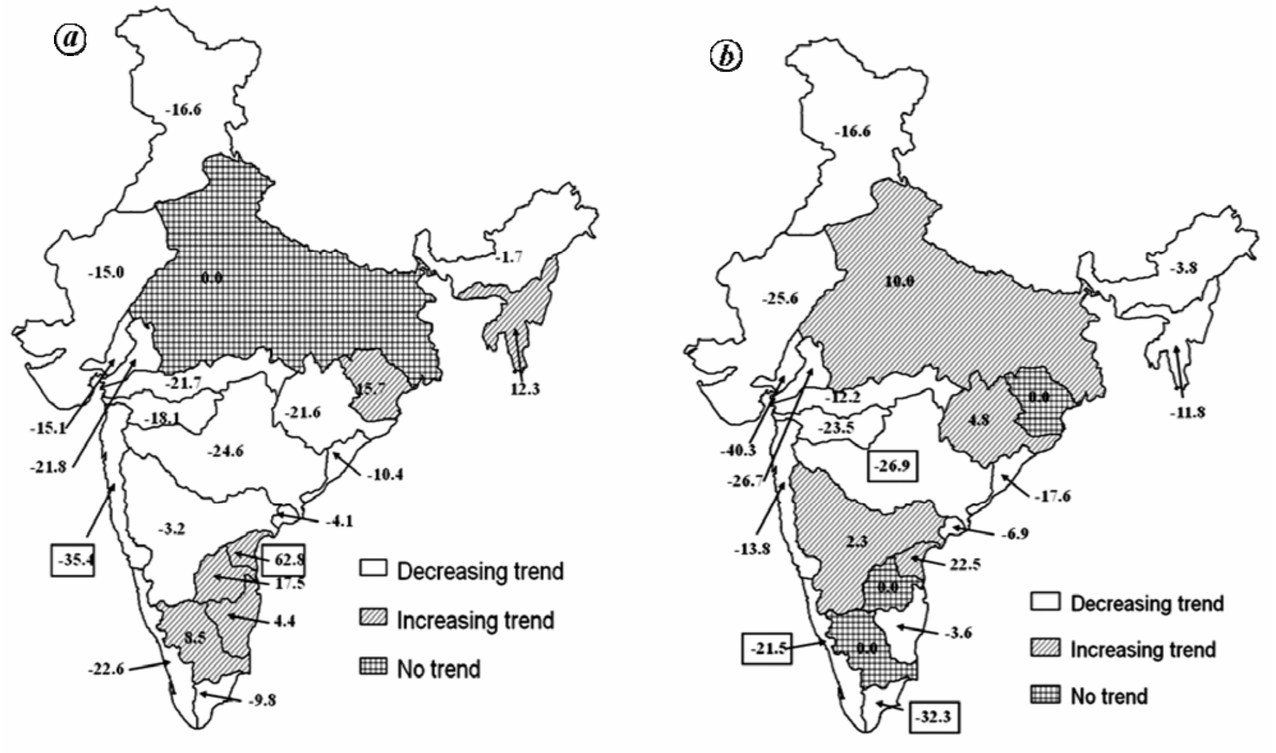

Figure 3. Trends and magnitude pertaining to rainfall changes for different river basins in India. Significant trends are displayed in boxes. ***a***, Annual rainfall (% of mean/100 yrs); ***b***, annual rainy days (% of mean/100 yrs).

significant trend and the trends for majority of the basins were non-significant. In the case of annual rainy days, 4 river basins showed increasing trend, 15 river basins showed decreasing trend and 3 showed no change. The maximum decrease was shown by WFR2. The increase in rainy days varied from 0.024 to 0.111 days/yr, with maximum increase in the Ganga and EFR3. The decreasing trend in annual rainy days in the Godavari, WFR2 and EFR5 river basins was statistically significant at 95% confidence level.

Analysis of seasonal trends showed that pre-monsoon rainfall increased over 9 river basins and decreased over 13; monsoon rainfall increased over 6 basins and decreased over 16; post-monsoon rainfall increased over 13 basins and decreased over 8; and winter rainfall increased over 18 basins and decreased over 2 of them. In the monsoon season, the maximum increase was of the order of 2.58 mm/yr for EFR3 and maximum decrease was for WFR1 (–8.47 mm/yr). The Ganga basin, with no change in annual rainfall, experienced a small decreasing trend in the monsoon and post-monsoon rainfall. There is some notion of weakening summer (SW) monsoon and strengthening in winter (NE) monsoon. Monsoon rainfall indicated negative significant trend in the Indus and WFR1 river basins. In the seasonal rainy days, 4 river basins each in the pre-monsoon, monsoon and post-monsoon season and 2 in the season experienced an increasing trend. Eleven river basins in the pre-monsoon, 3 in the monsoon, 10 in the post-monsoon and 19 in winter showed no change in the rainy days. In the monsoon season, the maximum increase in the number of rainy days was in the Brahmaputra basin (0.095 days/yr), whereas the maximum decrease was in the Sabarmati basin (–0.231 days/yr).

Trends and magnitude of changes in annual rainfall and rainy days in terms of percentage of mean per 100 years for basins are shown in Figure 3 (ref. 46). Direction of trend in rainfall and rainy days was found to be similar for most river basins. For annual data, Mahanadi and Krishna experienced decreasing trend in annual rainfall and increasing trend in rainy days, which means that droughts may become more recurrent in Krishna (a water-stressed basin)[46]. Barak+ and EFR4 have experienced increasing rainfall and decreasing rainy days, which implies that floods may become more intense. Similarly, in the monsoon season, Barak+ and BBS (positive trend in rainfall and negative in rainy days) and Krishna (negative trend in rainfall and positive trend in rainy days) experienced the opposite trend in rainfall and rainy days. Similar to annual data, these trends are non-significant.

Studies of extreme rainfall trends in India

Studies by various authors[25,47–53] show that, in general, the frequency of more intense rainfall events in many parts of Asia has increased whereas the number of rainy days and total annual precipitation has decreased. An increase in intense rainfall events leads to more severe floods and landslides.

Decreasing trends, particularly for stations in the hilly terrain, were found in annual extreme rainfall over Kerala[54]. Rakhecha and Soman[55] while analysing extreme events from 1 to 3 days duration for 316 stations across India for the period 1901–1980 found that increasing trends in these events were not statistically significant at most stations. They reported that 'the extreme rainfall series at stations over the west coast north of 12-degrees-N and at some stations to the east of the Western Ghats over the central parts of the peninsula showed a significant increasing trend at 95% level of confidence. Stations over the southern peninsula and over the lower Ganga valley have been found to exhibit a decreasing trend at the same level of significance.

Sen Roy and Balling[56] analysed daily rainfall data for 1910–2000 at 129 stations and found generally increasing trend in a contiguous region extending from the north-western Himalayas in Kashmir through most of the Deccan Plateau in the south and decreasing values in the eastern part of the Gangetic Plains and parts of Uttarakhand. Trends in extreme rainfall indices for the period 1901–2000 were examined for 100 stations over India by Joshi and Rajeevan[57]. Most of the extreme rainfall indices for the SW monsoon season and annual period showed significant positive trends over the west coast and northwestern parts of the peninsula. However, two hill stations (Shimla and Mahabaleshwar) showed decreasing trend in some of the extreme rainfall indices.

Using high resolution daily gridded rainfall data for the period 1951–2003, Goswami *et al.*[53] showed that there were significant rising trends in the frequency and magnitude of extreme rain events over central India during the monsoon season. They also found significant decreasing trend in the frequency of moderate events during the same period, thus leading to no significant trend in the mean rainfall. The results of this study were contradicted for some places when analysis was performed at a finer resolution (1° lat. × 1° long.) by Ghosh *et al.*[58].

Variability and long-term trends of extreme rainfall events over central India were examined by Rajeevan *et al.*[59] using 104 years (1901–2004) of high-resolution daily gridded rainfall data. They found statistically significant long-term trend of 6% per decade in the frequency of extreme rainfall events. According to them, the increasing trend of extreme rainfall events in the last five decades could be associated with the increasing trend of sea surface temperatures and surface latent heat flux over the tropical Indian Ocean.

Pal and Al-Tabbaa[60] studied the trends in seasonal rainfall extremes in Kerala, using gridded daily data for 1954–2003. They found winter and post-monsoon extreme rainfall having an increasing tendency with statistically significant changes in some regions and decreasing trends in spring seasonal extreme rainfall. Pal and Al-Tabbaa[61] also studied the changes in frequency and magnitudes of extreme monsoon rainfall deficiency and excess from 1871 to 2005 over 5 regions in India. The extreme monsoon seasonal precipitation exhibited a negative tendency leading to increasing frequency and magnitude of monsoon rainfall deficit and decreasing frequency and magnitude of monsoon rainfall excess.

The long-term trend in monsoon season extreme rainfall events for 1951–2005 was analysed by Pattanaik and Rajeevan[62]. The average frequency of extreme rainfall events along with the contribution of extreme rainfall events to the seasonal rainfall showed a significant increasing trend (above the 98% confidence level) over India during monsoon season and also during June and July. It was also found that the increasing trend of contribution from extreme rainfall events is balanced by a decreasing trend in low rainfall events.

Kothawale *et al.*[63] also studied the association between El Niño Southern Oscillation (ENSO) and monsoon rainfall over India and reported a strong association between El Niño events and deficient monsoon rainfall. Nearly 60% of major droughts over India have occurred in association with El Niño events. Strong association between monsoon droughts and El Niño events was noted by the authors. On the other hand, La Niña events were associated with more rainfall during monsoon and cooling. Earlier, Krishna Kumar *et al.*[64] had shown that the relation between the Indian monsoon and ENSO weakened in recent decades.

Studies of temperature trends in India

The surface temperatures over a given region vary seasonally and annually depending upon latitude, altitude and location with respect to geographical features such as a water body (river, lake or sea), mountains, etc. Probably one of the most widely quoted aspects of climatic change and the one that will have important ramifications on a range of sectors, including water is the significant increase in the global mean air temperature during the past century. Since the hydrologic cycle is a thermally driven system, rise in global temperature is likely to accelerate this cycle. Identification of the temperature trends and their projection has been the subject matter of a large number of studies.

Most of the temperature trend studies in India focus on the analysis of annual and seasonal temperature data for a single station or a group of stations. Such studies date back to at least 50 years. In one of the first studies, trends in the annual mean, maximum and minimum temperatures over the whole country were studied by Pramanik and Jagannathan[65], who did not find any general tendency for an increase or decrease in these temperatures. The study by Srivastava *et al.*[66] on decadal trends in climate over India gave the first indications that the diurnal asymmetry of temperature trends over India is quite different from that over many other parts of the globe. Pant and Kumar[67] analysed seasonal and annual air temperature series for 1881–1997 and showed that there is a significant warming trend of 0.57°C per 100 years. The magnitude of warming was higher in the post-monsoon and winter seasons. The monsoon temperature did not show a significant trend in any major part of the country, except for a significant negative trend over northwest India.

Mean annual temperature was found to be increasing over the west coast, interior peninsula, north central and northeastern regions of India along with the whole of India during the period 1901–1982 by Hingane *et al.*[68]. Pant and Hingane[29] found decreasing trend in mean annual surface air temperature for 1901–1982 over the northwest Indian region consisting of the meteorological sub-divisions of Punjab, Haryana, west Rajasthan, east Rajasthan and west Madhya Pradesh. Data from seven stations for 1901–1980 showed highly significant warming trend in the mean maximum, mean minimum and average mean temperatures of the Mahanadi river basin[43]. Trend analyses of maximum and minimum temperature data at 121 stations in India for 1901–1987 by Rupa Kumar *et al.*[69] showed increasing maximum temperature and trendless minimum temperature, resulting in rise in mean and diurnal range of temperature.

Kothyari and Singh[32] found increasing annual maximum temperature over the Ganga basin and increasing average annual temperature for India starting around the second half of 1960s. The annual surface air temperature in IGP showed significant rising trend (0.53°C/100-yrs) during 1875–1958 and significant decreasing trend (–0.93°C/100-yrs) during 1958–1997 (ref. 33). Sinha Ray and De[21] summarized information on trends in the occurrence of extreme events over India. An increasing trend of 0.35°C over the last 100 years was observed in the temperature records. Extreme maximum and minimum temperatures showed an increasing trend in the south and a decreasing trend in the north. Temporal variation in the temperature over Pune city during the period 1901–2000 revealed significant decrease in mean annual and mean maximum temperature[70]. Winter season experienced decrease in temperature, whereas monsoon season temperature was found to be increasing.

Arora *et al.*[71] analysed a series of annual and seasonal mean temperature, annual mean maximum temperature and annual mean minimum temperature using the data from 125 stations distributed throughout India. For annual series, mean maximum temperature showed a rising trend at 63 stations and a falling trend at 8 stations. The mean minimum temperature showed a rising trend at 33 stations and a falling trend at 31 stations. In the mean temperature series, a rising trend was observed at 53 stations and a falling trend at 17 stations. Most of the stations in the south, central and western parts of India showed a rising trend and some stations in the north and northeastern parts showed a falling trend in annual mean temperature. In the winter season, a rising trend in mean temperature was observed at 39 stations and a falling trend at 19 stations. Most of the stations in the coastal and southern areas showed an increasing trend, whereas a falling trend was exhibited by some stations in the north, central and eastern India. The mean pre-monsoon temperature showed a rising trend at 35 stations and a falling trend at 23 stations. Most of the stations in the eastern region and in the foothills of the Himalayas showed a falling trend. For the mean monsoon temperature series, 27 stations showed a rising trend and 18 stations a falling trend. In the mean post-monsoon temperature series, 59 stations showed a rising trend and six a falling trend. A rising trend dominates all over India in this season.

Arora *et al.*[71] also found that the percentage of significant trends was high and there is a rising trend in most cases, except for temperatures for mean pre-monsoon, mean monsoon, pre-monsoon mean minimum and monsoon mean minimum. There was an increase of 0.42°C $(100\ \text{year})^{-1}$ in the annual mean temperature, 0.92°C $(100\ \text{year})^{-1}$ in the mean maximum temperature and 0.09°C $(100\ \text{year})^{-1}$ in the mean minimum temperature. Averaged for all seasons, there was a rise of 1.1°C $(100\ \text{year})^{-1}$ in mean winter temperature, 0.94°C $(100\ \text{year})^{-1}$ in mean post-monsoon temperature, and a fall of –0.40°C $(100\ \text{year})^{-1}$ in mean pre-monsoon temperature.

Atmospheric surface temperature in India has increased in the last century by about 1°C and 1.1°C during winter and post-monsoon months respectively. Also, decrease in the minimum temperature during summer monsoon and its increase during post-monsoon months have created a large difference of about 0.8°C in the seasonal temperature anomalies. Opposite phases of increase and decrease in the minimum temperatures in the southern and northern regions, respectively, have been noticed in the interannual variability. In north India, the minimum temperature showed a sharp decrease between 1955 and 1972, and then a sharp increase. But in south India, the minimum temperature showed a steady increase[25].

Bhutiyani *et al.*[72] found increasing trend in maximum, minimum, mean and diurnal temperature range over the northwestern Himalayan region during the 20th century. Frequency of occurrence of hot days and hot nights showed widespread increasing trend, whereas that of cold days and cold nights showed widespread decreasing trend during the period 1970–2005 over India as a whole and seven homogeneous regions[63]. The frequency of occurrence of hot days was found to have significantly increased over the east coast, west coast and interior peninsula, whereas that of cold days showed significant decreasing trend over Western Himalaya and the west coast. The three regions, east coast, west coast and northwest, showed significant increasing trend in the frequency of hot nights.

Trends in annual and seasonal temperatures in the four most populated cities of India – Delhi, Kolkata, Mumbai and Chennai showed positive change with different rates in different seasons[73]. The maximum temperature at Mumbai during winter and monsoon was significantly increasing, whereas minimum temperature showed significant decrease. The remaining cities recorded significant increase in minimum temperature during winter. Analysis of maximum, minimum and mean temperatures; diurnal temperature range; and sunshine duration in eight sites in North East India by Jhajharia and Singh[74] showed decreasing trends in diurnal temperature range corresponding to annual, seasonal (pre-monsoon and monsoon) and monthly (September) timescales at three sites. Diurnal temperature range increases were also observed at three other sites in the monsoon and post-monsoon seasons as well as in June, October and December. Temperature remained practically trendless in winter and pre-monsoon season and increased in the monsoon and post-monsoon seasons over NE India. Decreasing trends in sunshine duration were observed mainly on annual, seasonal (winter and pre-monsoon) and monthly (January–March) timescales.

Maximum temperature showed significant rising trend of 0.008°C/yr during monsoon season; 0.014°C/yr during post-monsoon season and 0.008°C/yr in the annual maximum temperature during the period 1914–2003 for Central Northeast India[41]. Minimum temperature showed significant rising trend of 0.012°C/yr during post-monsoon season and significant falling trend of 0.002°C/yr during monsoon season. Studies of the long-term trends and variations of the monthly maximum and minimum temperatures in various climatological regions in India by Pal and Al-Tabbaa[75] showed increasing monthly maximum temperature, though unevenly, over the last century. Minimum temperature changes were found more variable than maximum temperature changes, both temporally and spatially, with results of lesser significance.

The monthly maximum and minimum temperature data from 121 stations well distributed over the country for the period 1901–2007 were used by Kothawale *et al.*[76] and from these data, they computed seasonal and annual trends in surface air temperature over the country and seven homogeneous regions (western Himalaya, northwest, north-central, northeast, east coast, west coast and interior peninsula) during three periods: 1901–2007, 1971–2007 and 1998–2007. Key findings of this comprehensive study are described here.

(i) Annual mean (average of maximum and minimum), maximum and minimum temperatures showed significant warming trends of 0.51, 0.72 and 0.27°C $(100\ \text{year})^{-1}$, respectively, during 1901–2007. The temperature has increased gradually and continuously over this period. This warming was mainly due to increasing temperatures in the winter and post-monsoon seasons. During the three decades from 1971 to 2007, annual mean temperature increased by 0.20°C per decade due to significant increases in both maximum and minimum temperatures. Also, increase in minimum temperature was much steeper than the maximum temperature. On the whole, winter and summer monsoon temperatures showed a significant increasing trend over almost the entire country, whereas post-monsoon temperatures significantly increased over relatively smaller number of regions.

(ii) On larger spatially aggregated scales, the temperature trends in India were found to be quite consistent and in agreement with global and hemispheric trends. However, on smaller regional scales and for different subperiods, trends were not always consistent with Indian aggregated temperatures. Further, the trends were also influenced by the variability of rainfall in the monsoon and post-monsoon seasons. It was opined that the recent temperature changes in some parts of the country may also be due to the relative influence of greenhouse gases and aerosols.

(iii) Accelerated warming was observed during 1971–2007 and this was attributed mainly to intense warming in the decade 1998–2007. During 1998–2007, maximum temperature was significantly higher compared to the long-term (1901–2007) mean throughout India, with a stagnated trend during this period, whereas minimum temperature showed an increasing trend, almost equal to that observed during 1971–2007. It is pertinent to note that recently, the year 2010 has been reported to rank in the top three warmest years since the beginning of instrumental climate records in 1850, according to data sources compiled by the World Meteorological Organization (WMO).

(iv) On the seasonal scale, maximum temperature has significantly increased in all seasons during the period 1901–2007. On this scale, pronounced warming trends in mean temperature were observed in two seasons – winter and monsoon. However, for the recent period only, winter and post-monsoon temperatures showed significant warming trends and the other seasons showed a warming tendency (trend not significant). In contrast, minimum temperature showed a significant warming trend in most seasons during 1971–2007.

(v) The global mean annual and seasonal (DJF, MAM, JJAS and ON) temperatures have significantly increased by 0.82°C, 0.89°C, 0.94°C, 0.72°C and 0.76°C per 100 years, respectively, during the period 1901–2007. Indian mean annual and seasonal temperatures also showed a significant warming trend in all seasons. The magnitude of the warming trend of winter and post-monsoon seasons was almost the same for these two areas, whereas pre-monsoon and monsoon temperature trends for India were half that of the global trend (Figure 4).

Kothawale and Rupa Kumar[77] had shown a strong negative simultaneous correlation between Indian monsoon mean surface temperature and monsoon rainfall. Kothawale *et al.*[63] concluded that on interannual time

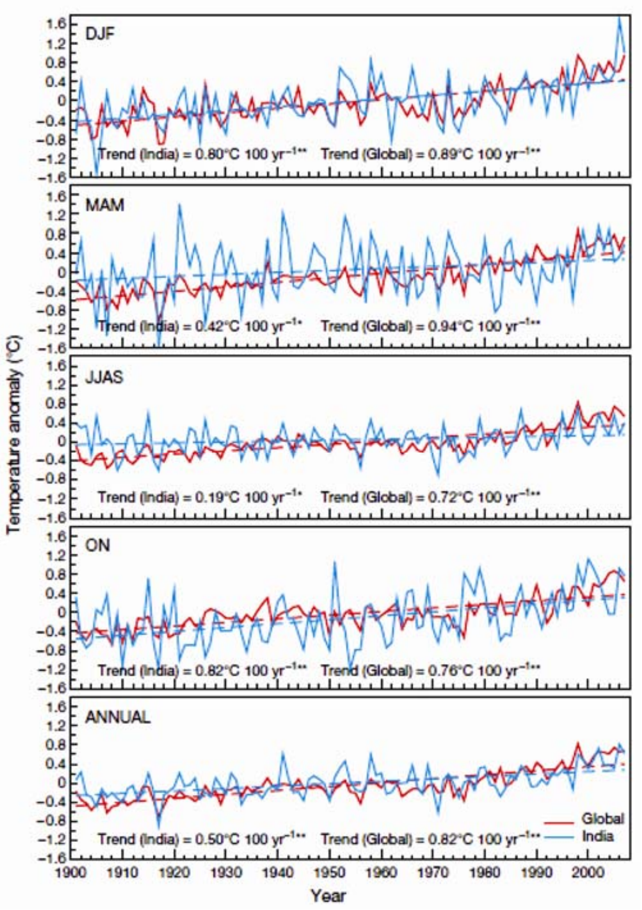

Figure 4. Global (red) and Indian (blue) annual and seasonal mean temperature variations during 1901–2007. $*p < 0.05$; $**p < 0.01$. DJF, Previous year December–February; MAM, pre-monsoon March–May; JJAS, monsoon June–September; ON, post-monsoon October–November (Source: Kothawale *et al.*[63]).

scales, Indian mean temperatures are strongly correlated with SST in the eastern Pacific and the equatorial Indian Ocean. A strong interannual link between Indian temperatures and Indian Ocean SST was found. ENSO was found to be impacting Indian temperatures significantly. The composite maximum temperature anomalies of El Niño years were statistically significant and positive during monsoon and post-monsoon seasons over large areas of the country and the composite anomalies of La Niña years were almost opposite to El Niño years. Interestingly, the year 2010 was special for climate scientists since El Niño conditions prevailed in the tropical Pacific for the first four months but it quickly changed and a La Niña pattern had emerged by June.

Concluding remarks

An understanding of the spatial and temporal distribution and changing patterns in rainfall is a basic and important requirement for the planning and management of water resources. Expectedly, the river-basin rainfall trends show a large variability. In a recent study, 6 river basins have shown increasing trend in annual rainfall in the 0.27–10.16 mm/yr range whereas 15 river basins have shown decreasing annual rainfall in the 0.45–4.93 mm/yr range. Further, 4 river basins have shown increasing trend in rainy days and 15 river basins have shown the opposite trend. Seasonal analysis shows that in the pre-monsoon season, rainfall increased over nine river basins and rainy days increased in four river basins; in the monsoon season, rainfall increased over six river basins and rainy days in four river basins; in the post-monsoon season, rainfall increased over 13 river basins and rainy days on four river basins and in the winter season, rainfall increased over 18 river basins and rainy days increased over 2 river basins. Rainfall decreased in 13 river basins in the pre-monsoon season, in 16 basins in the monsoon and in 8 basins in the post-monsoon. Some of these are major and water-deficit basins. Majority of river basins in the pre-monsoon, post-monsoon and winter season have shown no change in rainy days. Further, majority of the basins show neither increasing nor decreasing significant trend in seasonal rainfall and rainy days. Absence of significant change in the number of rainy days shows that at present there is no clear-cut indication of any major change in rainfall intensities. Temperature data, however, show nearly monotonous rising trends although the behaviour of the maximum and the minimum temperature at different locations is different.

In trend analysis studies, the results significantly depend upon the period of data and the stations whose data are used. There is another observation that most of the data used in trend detection pertain to the stations that are located in urban areas and these areas are a sort of heat islands. Thus, the study of trends using this data may not be the correct depiction of the reality and this aspect needs to be addressed. These concerns, in fact, highlight the importance of identifying a network of baseline stations for change detection studies. Countries, such as the USA, have identified such networks. Existing stations with long series of good quality will be the obvious candidates for the baseline network and it will be necessary to add new stations so that the whole country is properly represented. More studies to detect teleconnections between Indian rainfall and temperatures and ENSO/SST are also needed.

In a major exercise, an assessment of impact of climate change in the 2030s on four key sectors of the Indian economy, namely agriculture, water, natural ecosystems and biodiversity, and health in four climate sensitive regions of India, namely the Himalayan region, the Western Ghats, the coastal areas and the northeastern region has been carried out by the Ministry of Environment and Forests, GoI[78]. There is a need of an integrated nationwide program of change detection, impact assessment, and adaptation and mitigation.

Finally, while interpreting the results of trend analysis, the observations of Cohn and Lins[79] are worth repeating:

'that reported trends are real yet insignificant indicates a worrisome possibility: natural climatic excursions may be much larger than we imagine. So large, perhaps, that they render insignificant the changes, human-induced or otherwise, observed during the past century'.

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