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Spatial analysis of Indian summer monsoon rainfall

Markand Oza and C.M. Kishtawal
Space Applications Centre, ISRO, Ahmedabad – 380 015
Email: markand@sac.isro.gov.in; cmk307@rediffmail.com

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Abstract: Changing rainfall has significant effect on water resources, agricultural output and hence economy. To understand the variability in rainfall, a spatio-temporal analysis of Indian summer monsoon rainfall was taken up. The objective for the present analysis was to identify trends in amount of Indian summer monsoon at various spatial scales. Daily gridded rainfall data (1^0 X 1^0 spatial resolution) for the period 1951-2010 corresponding to monsoon season and monthly rainfall data at meteorological sub-division level for 1901 - 2010 were analysed. From the gridded data, a series of rainfall at agroclimatic regions was constructed. The analysis was based on linear trend analysis. Both parametric and non-parametric methods were used. From statistical analysis of data it was concluded that there is a decreasing trend in all-India Indian summer monsoon rainfall. Northeast India is one big cluster having highly decreasing trend. Also, there is a strong agreement between gridded and meteorological subdivision based rainfall.

Keywords: IMD Gridded data, Meteorological sub-division, Agroclimatic zone, Rainfall, Indian summer monsoon, Trend analysis

1. Introduction

Water is a precious natural resource and most of the water is received in the form of rainfall. Declining rainfall has adverse effect on water resources, agricultural output and economy. It is well realized that natural climate variability (e.g. decadal changes in circulation) and human induced (e.g. land cover and emissions of green house gases) changes alter the rainfall patterns. The contribution and effects of these factors are difficult to quantify and vary in time and space (IPCC, 2007). The rainfall has important socioeconomic implications over the Indian subcontinent (Fein and Stephens, 1987). Therefore it is of interest to study changing patterns of rainfall in spatio-temporal domain to identify areas undergoing rapid changes.

The monsoon season follows intense heat of the summer months in the Indian subcontinent which becomes hot and draws moist winds from the oceans. This causes a reversal of the winds over the region which is called the onset of monsoon (Das, 1984; Gadgil, 2007). The monsoon season in India typically begins in late May/early June. It advances gradually and covers the Indian land mass by June-end / July. After mid-August the Indian summer monsoon undergoes a gradual decaying phase and withdrawal of monsoon begins. By September, the monsoon season in India ends. India Meteorological Department (IMD) defines a four month period from June to September as Indian summer monsoon (ISM) period (Attri and Tyagi, 2010). About 75% of the annual rainfall is received during a short span of these four months.

ISM is a well studied phenomenon. Mooley and Parthasarathy (1984) and Parthasarathy *et al.* (1991) analysed long term rainfall datasets over the Indian subcontinent and found epochal variations in the ISM rainfall. Krishna Kumar et al. (1999) related amount of ISM rainfall with El Nino – Southern Oscillation (ENSO) and found that above average rainfall was coinciding with cold phase and below average rainfall with warm phase on ENSO. Gadgil et al. (2004) related extremes of ISM with ENSO and equatorial Indian Ocean oscillation. Sahai et al. (2003) related ISM to sea surface temperature. Rajeevan et al. (2010) studied active and break cycles of ISM.

In spite of its regularity, ISM exhibits large variability in different space and time scales. The most important parameter which has drawn attention of meteorologists is the amount of rainfall during ISM season. The spatial scales of rainfall variability cover a wide range starting from the scale as small as a single rain-gauge site to as big as a continent. Analyzing 100 years of surface rain gauge observations, Srivastava et al. (1992) showed that the mean monsoon seasonal rainfall has not changed significantly in the past century. However, Goswami et al. (2006), by performing analysis over central India, concluded that there are significant changes in the heavy rainfall trends. Such contradicting conclusions indicate heterogeneity on ISM rainfall in spatial domain. The time-scale varies from daily to interannual to decadal scales, centuries and even millennia (Pai and Rajeevan, 2007). In the present study, spatio-temporal analysis of ISM rainfall has been considered.

2. Data used

Spatio-temporal analysis of rainfall over India was performed with a view to identifying trends in amount of ISM in various regions of India. Two sets of rainfall data were used for the present study as shown in Table 1. The first set of data, high resolution (1^0 x 1^0) daily gridded rainfall dataset, has been prepared by IMD. IMD prepares a consistent set of gridded data based on station data. The grid-point analysis of rainfall is prepared by using Shepard's interpolation method (Shepard, 1968) over the Indian subcontinent (6.5^0 N to 37.5^0 N, 66.5^0 E to 101.5^0 E). Shepard's method is based on the weights that not only depend on the distance between the station and the grid point but also considers the directional effects. Standard quality controls are performed before carrying out the interpolation analysis. Due to averaging, the gridded rainfall data are smoother compared to individual station data. A detailed description of the preparation of this gridded dataset, is discussed in Rajeevan et al. (2005, 2006). The second data set was taken from monthly rainfall at meteorological subdivisions (MSBD) of India as available at www.tropmet.res.in.

Table 1: Description of data used

Data characteristic	Set 1	Set 2
Variable	Rainfall	Rainfall
Frequency	Daily	Monthly
Format	.grd	Table (ascii)
Duration	1951-2010	1901-2010
Resolution	1^0 x 1^0	Meteorological subdivision
Source	India Meteorological Department – New Delhi	www.tropmet.res.in

3. Methods

The data were available in ".grd" format which were imported in a digital image processing compatible format. There were 365 / 366 layers / year, each giving daily rainfall for a 1^0 x 1^0 grid cell. A subset corresponding to 122 day period representing ISM period was extracted for further analysis. Accumulated rainfall for this period is computed. This is done for each of the years under consideration. The data were exported to ascii format for further processing in a spreadsheet.

It is very common to analyse 30 – year moving average, called climatic series, to study long-term behavior of meteorological data (Mazumdar et al., 2001; Arguez and Vose, 2011; www.ncdc.noaa.gov.oa/climate/normals/usnormals.hml; www.wmo.int/pages/themes/climate/climate_data_and_products.php; www.metoffice.gov.uk/climate/uk/averages; WMO, 1989). Basically, it performs low pass filtering in time domain. By doing this smoothing, the year-to-year variations get suppressed and dominant behavior, if any, emerges. A 30-year moving average was computed to represent climatic conditions.

For detecting trend in the smoothed data series, parametric and non-parametric approaches were employed. In parametric approach, a least square linear trend of the form "a + b* year" was fitted for each cell. The parameters of the fit such as coefficients, their standard errors, R^2 value, F-statistic were also computed. If there is increasing trend in the climatic series, then the slope coefficient should be positive and statistically significant. Conversely, for decreasing trend in behavior of a variable the slope value should be negative. The values of slopes were brought back to image format for visualization and analysis.

It may be pertinent to note that most of the parametric methods are based on assumption of normality and are very sensitive to extreme values. Therefore, non-parametric methods, which are distribution free, were applied at agroclimatic scale. In the present study, we have used Mann-Kendall test (Gilbert, 1987) which is based on order (or rank) rather than magnitude of measurement. This is a non-parametric test to detect presence of trend in time series data (of length n) and test statistic S is calculated as

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k);$$

where,

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases}$$

The mean and variance of S, under the assumption of null hypothesis (no trend in time series data), are given by

$$E(S) = 0$$

$$Var(S) = \begin{cases} \dfrac{\left\{ n(n-1)(2n+5) - \sum_{j=1}^{p} t_j(t_j-1)(2t_j+5) \right\}}{18} & \text{if ties} \\ \dfrac{\{n(n-1)(2n+5)\}}{18} & \text{no ties} \end{cases}$$

For n >10, z = (S-1) / √[Var(S)] if S >0
= (S+1) / √[Var(S)] if S <0
provides critical values.

It may be noticed that it is the distribution-free (hence robust), positive (negative) value of S indicates increasing (decreasing) trend but gives only direction (not magnitude) of trend.

The data at 1^0 x 1^0 give detail at fine scale. For checking consistency and correctness of gridded data, the data may be required at coarser scales. Policy makers require information at agro-climatic levels (AGCL). India is divided into 15 agro-climatic regions (Planning Commission, 1989) on the basis of commonality of factors like soil type, rainfall, temperature and water resources. To arrive at the value of ISM rainfall at coarser scale (of MSBD or AGCL) gridded data over India for each ISM period were intersected with a vector layer containing these boundaries. Since area within a 1^0 x 1^0 cells are not equal, areas of each grid cell was computed and area weighted average ISM rainfall was computed to represent ISM rainfall for that region. This was done for each of the 60-year data. A 30-year moving average and linear trend fitting was followed as in previous case.

For dataset 2, monthly rainfall corresponding to four ISM months, available at www.tropmet.res.in, at meteorological subdivision (MSBD) were summed. MSBD 1 (Andaman and Nicobar Islands) had data missing for 1941 – 1945 and MSBD 2 (Arunachal Pradesh) had missing data for 1901-15, 1950, 1954-56 and 1971. Hence, data corresponding to these two MSBDs were not analysed any further. For the remaining 34 MSBDs, accumulated ISM rainfall was derived from the monthly rainfall. A 30-year moving average was computed and linear trend was fitted.

4. Results

The outcome and interpretation of analysis of data at various scales and their comparison is reported in the following sub-sections.

4.1 Grid-wise anlysis

There are 332 1^0 x 1^0 cells over Indian landmass. Table 2 gives frequency distribution of cell-wise slope coefficient. The values of slope were categorized into five levels as shown in column 1; number of cells satisfying the criteria and shown in column 2. Column 2 also gives break up of statistically significant and non-significant number of cells (based on t-statistic) of these. Column 3 provides proportion of Indian landmass cells falling under each slope category.

Table 2: Frequency distribution of grid-wise slope coefficient for 30-year moving average rainfall

Slope Range	*Frequency* (Siginificant / non-significant)	*Percent*
<-2	100 (99/01)	30.12
-2 to -1	34 (31/03)	10.24
-1 to 0	42 (15/27)	12.65
0 to 1	49 (22/27)	14.76
1 to 2	26 (24/02)	7.83
>2	81 (80/01)	24.4
Total	332(271/61)	100

From table 2, it can be seen that out of 332 grids, 156 grids had positive slopes (indicating increasing tendency of rainfall pattern) compared to 176 grids which had negative slopes. The mean value of slopes was -0.631. Also, notice that as absolute value of slope increases, the proportion of significant slope values increases as could be expected. Spatial distribution of grid-wise slope pattern is shown in fig. 1. The graph of area-weighted all-India rainfall as a function of time is shown in fig. 2. The value of slope was -0.695 (with t-value of -6.1), which is statistically highly significant, indicating decreasing trend in all India rainfall pattern.

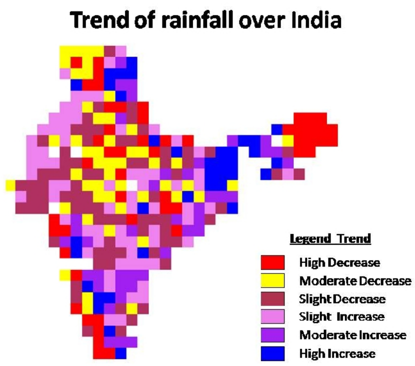

Figure 1: Spatial distribution of least-square fitted slope values

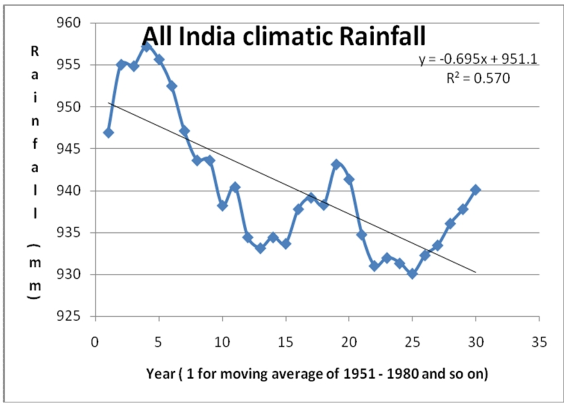

Figure 2: All India area-weighted 30-year moving average rainfall

4.2 Meteorological subdivision-wise analysis

Data of MSBD 1 and 2 were not analysed as the data set was not complete. MSBD 1 had data missing for 1941 – 1945 whereas MSBD 2 had missing data for 1901-15, 1950, 1954-56 and 1971. So the analysis is done for remaining 34 MSBDs. The data are analysed for 4 months (June, July, August and September) and total of these four months. As with gridded data, a series of moving average of 30-years was prepared and a least square linear trend model was fitted to such a smoothed series. of 34 x 4 = 136 monthly series, the slopes for 29 series were statistically significant with 13 having positive slopes and 16 having negative slopes (Table 3). MSBD 33 (North interior Karnataka) had positive slope for 2 months (Jun and Aug). MSBDs 4 (Manipur, Mizoram, Nagaland and Tripura in NE) and 15 (Himachal Pradesh) had 3 months having negative slope whereas 12 (Uttaranchal) had 2 months having negative slopes and remaining two months showing lack of trend.

From table 3, it can be seen that MSBD 8 had two statistically significant trends (one positive and one negative). Ten MSBD (3, 6, 13, 14, 17, 25, 26, 29, 30 and 32) had one month with positive trend where as seven MSBD (5, 9, 16, 20, 24, 31 and 34) had one month having negative trend. Twelve MSBD (7, 10, 11, 18, 19, 21, 22, 23, 27, 28, 35 and 36) did not have any month showing trend (either positive or negative). It can be seen that first ten of these MSBDs cover states of Orissa, Uttar Pradesh, areas in East Rajasthan, West Madhya Pradesh, Gujarat, Chhatisgarh and coastal Andhra Pradesh. Spatially, they form inverted "U" belt starting from Gujarat going to (West and East) Uttar Pradesh and falling to coastal Andhra Pradesh. The last two represent Kerala and Lakshadeep islands.

Analysing total south-west monsoon rainfall (last column of table 3), it is observed that 9 MSBD had statistically significant trend (4 increasing and 5 decreasing). As could be expected, MSBDs having multiple months of similar trend, the ISM rainfall also retained the pattern. MSBD 33 had positive trend and MSBD 4, 12 and 15 had negative trend. Figure 3 shows the slope patterns of ISM rainfall over study years. It can be seen that MSBD 4, 5, 12, 15 and 20 have dominant negative slopes indicating tendency for decreased rainfall over the years. The MSBD 5, 12 and 15 are dominantly mountainous region in the Himalayas. MSBD 14 has a positive trend and is located south-west of MSBD 15 and west of MSBD 12, both having decreasing pattern of rainfall. Similarly, MSBD 6 is having increasing trend and is located west of MSBD 4 and south of MSBD 5, both having decreasing pattern of ISM rainfall. MSBD 32 and 33 also have increasing ISM rainfall.

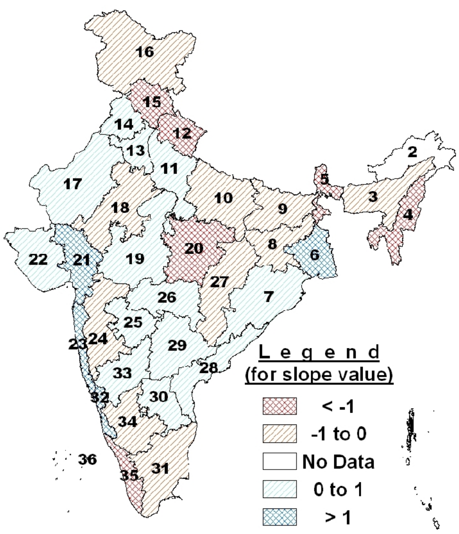

Figure 3: The slope patterns of total Indian summer monsoon (ISM) rainfall during study years at meteorological sub-division (MSBD) level

4.3 Analysis at Agroclimatic Zones

Moving to coarser level, the analysis was performed at AGCL scale also. Spatial extent of agroclimatic regions of India, as defined by Planning Commission of India, is shown in fig. 4. As mentioned earlier, ISM rainfall at AGCL was derived from gridded data. At this scale, both (parametric and non-parametric) methods were used and compared. It can be seen that AGCL 15 is composed of small islands of Andaman, Nicobar and Lakshadeep. The land portion over representative 1^0 x 1^0 would be very less. It was not analysed as the gridded data were not available over this region. Analysis was performed for the remaining 14 AGCLs. The outcome of analysis is summarized in Table 4. Perusal of Table 4 reveals that three AGCLs (1, 7 and 13) did not show any statistically significant trend in parametric procedure. There were four AGCLs (3, 4, 10 and 11) with positive slope values where as remaining seven AGCLs had significantly negative trend in ISM rainfall. The spatial representation is shown in figure 4. As regards comparison of parametric and non-parametric methods, it can be seen from table 4 that in 12 cases there is agreement between the decisions of parametric and non-parametric approaches. In the remaining two cases, one method indicated significance and the other did not. The two methods did not show contradicting decision (one increasing and another decreasing). Thus it can be concluded that there is good agreement the two approaches.

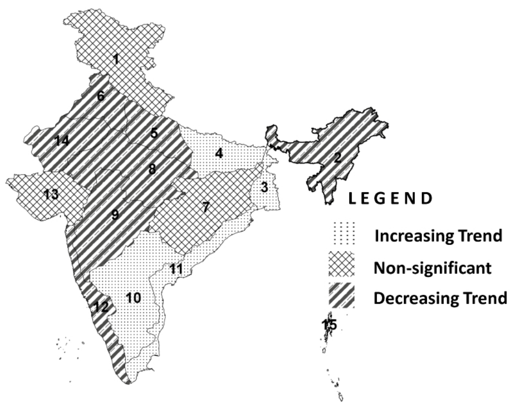

Figure 4: The trend patterns of Indian summer monsoon (ISM) rainfall over agro-climatic (AGCL) regions

4.4 Comparison of all-India rainfall derived from gridded rainfall and MSBD data

It may be of interest to compare the all-India rainfall patterns as obtained by two methods, namely gridded rainfall and MSBD based. Since the geographic area of each MSBD is known, it was possible to calculate area weighted all India rainfall. However, since MSBD 1 and 2 were not analysed, it is not proper to compare the values of rainfall. But the correlation coefficient is a sound indicator to judge the consistency of all India rainfall derived from these two methods. This is shown in fig 5. The correlation is positive and strong (r = 0.86), as could be expected. However, high deviation for 2005 rainfall needs to be investigated.

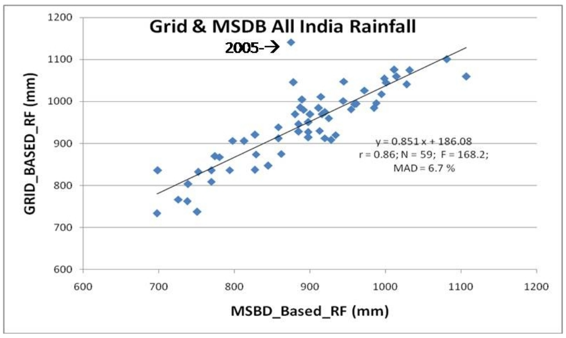

Figure 5: Scatter plot of all India rainfall by two methods, namely gridded data and MSBD data for common year

4.5 Analysis in neighbouring regions (including oceanic area)

With a view to relating spatio-temporal changes in ISM over Indian land mass to adjoining region, analysis region was extended to include neighboring region including ocean. CMAP (CPC Merged Analysis of Precipitation) data were used for the same. CMAP provides merged dataset of precipitation derived from satellite, rain gauge measured and forecast from numerical weather prediction models (Xie and Arkin, 1996; 1997). The data set is available over entire earth surface at 2.5 deg x 2.5 deg resolution on monthly scale from 1979 to 2011. A subset of the data set over Indian region (5^0 – 35^0 N and 65^0 – 100^0 E) for ISM season was extracted and analysed. Since the length of data series is just 33, no smoothing / filtering was performed. The locations of statistically significant relationships and their values of slope are shown in fig 6. It can be seen that besides a cluster of decreasing patterns in Northeast, a bigger cluster of deceasing rainfall patterns was observed in Bay of Bengal.

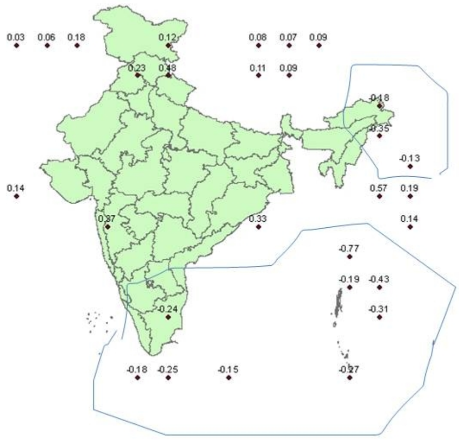

Figure 6: Locations and values of statistically significant ISM rainfall trend values based on 1979 - 2011 analysis of CMAP data over Indian region (5^0 – 35^0 N and 65^0 – 100^0 E)

5. Discussions

The above results indicate over-all decreasing amount of rainfall. However, this need not be looked in isolation. Parallel to the changes in the monsoon rainfall, the regional land use has also been changing (Pielke et al., 2003, 2007). The land use change over India in the recent decades has primarily occurred in terms of urbanization (Kishtawal et al., 2009). Due to creation of irrigation systems in first few five-year plans of independent India, significant changes have taken place. The moisture regime has altered and area under agriculture has increased. This has also led to intensive agriculture. Studies have shown that temperature regimes of the pre- and post- agricultural green revolution have different characteristics (Roy et al., 2007). Such land cover transformation can produce significant changes in the future climate and could affect monsoon circulation (Feddema et al., 2005). Douglas et al. (2006, 2009) have shown that agricultural irrigation can impact regional evapotranspiration, surface radiative balance and mesoscale rainfall over the Indian monsoon region. Similarly, there would be effect of solar and greenhouse gas forcing (Meehl, 2003). The impact of land use land cover changes such as urbanization and intensification of agriculture on rainfall, though difficult to quantify, needs to be taken up.

6. Conclusions

From the present study, it can be concluded that based on the analysis of last 60 years of gridded data, there is a statistically significant decreasing trend in all India ISM rainfall. Northeast India is one big cluster having highly decreasing trend. From the analysis of MSBD data over 110 years, a very significant decreasing trend in MSBD 4, 5, 12 and 15 and increasing trend in MSBD 6 and 33 was noticeable. The correlation coefficient between all India rainfall by gridded data and MSBD based data is positive and strong. However, high disagreement for 2005 rainfall needs to be investigated.

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Table 3: Value of slope coefficient for 30-year moving monthly average and ISM rainfall at meteorological sub-division (MSBD) level. (Values in bold indicate statistically significant at 5 % level)

MSDB	Nomenclature	June	July	Aug	Sept	ISM
3	Assam & Meghalaya	-0.084	**0.68**	-0.455	-0.28	-0.138
4	Nagaland, Manipur, Mizoram, Tripura	**-1.051**	-0.644	**-1.2**	**-0.901**	**-3.797**
5	Sub-Himalayan West Bengal & Sikkim	**-1.638**	0.374	-0.892	-0.47	**-2.626**
6	Gangetic West Bengal	0.043	0.367	0.112	**1.073**	**1.596**
7	Orissa	0.085	0.048	0.344	0.045	0.522
8	Jharkhand	0.092	-0.22	**-0.576**	**0.478**	-0.226
9	Bihar	-0.052	0.569	**-0.55**	-0.045	-0.078
10	East Uttar Pradesh	0.27	-0.142	-0.468	0.064	-0.277
11	West Uttar Pradesh	0.126	0.083	0.105	-0.043	0.271
12	Uttarakhand	-0.123	**-0.893**	**-1.389**	-0.158	**-2.563**
13	Haryana, Chandigarh & Delhi	**0.283**	0.231	0.39	-0.126	0.779
14	Punjab	**0.33**	0.434	0.176	0.006	**0.946**
15	Himachal Prradesh	0.111	**-2.869**	**-4.113**	**-0.802**	**-7.673**
16	Jammu & Kashmir	0.156	-0.279	**-0.588**	-0.165	-0.876
17	West Rajasthan	**0.189**	0.272	-0.13	-0.07	0.26
18	East Rajasthan	0.125	-0.11	0.065	-0.177	-0.097
19	West Madhya Pradesh	0.057	-0.232	0.424	-0.003	0.246
20	East Madhya Pradesh	0.019	**-0.78**	-0.39	-0.155	**-1.306**
21	Gujarat region, DD & NH	0.324	-0.23	0.823	0.097	1.014
22	Saurashtra, Katchh, Diu	0.387	-0.123	0.434	0.06	0.758
23	Konkan, Goa	1.049	-0.438	1.174	0.25	2.034
24	Madhya Maharashtra	0.051	**-0.768**	0.038	0.084	-0.594
25	Marathwada	-0.062	0.071	**0.595**	-0.387	0.217
26	Vidarbha	0.003	-0.248	**0.62**	-0.237	0.137
27	Chhatisgarh	-0.079	-0.323	-0.375	-0.132	-0.908
28	Coastal Andhra Pradesh	0.044	0.16	0.243	0.012	0.459
29	Telangana	-0.001	0.312	**0.879**	-0.256	0.934
30	Rayalseema	**0.233**	0.004	0.285	0.045	0.568
31	Tamilnadu, Poducherry	**-0.162**	0.072	-0.191	-0.021	-0.301
32	Coastal Karnataka	1.194	-0.438	**1.976**	0.431	**3.163**
33	North Interior Karnataka	**0.343**	-0.075	**0.38**	0.295	**0.943**
34	South interior Karnataka	-0.011	**-0.719**	0.086	0.22	-0.425
35	Kerala	-0.964	-1.141	-0.288	0.283	-2.11
36	Lakshadeep	-0.156	0.145	0.122	0.146	0.258

Table 4: Value of slope coefficient along with R2 and F value for 30-year moving average ISM rainfall at agro-climatic region (AGCL) level

		PARAMETRIC METHOD				NON-PARAMETRIC METHOD	
AGCL	**Region**	**Slope**	**R^2**	**F**	**Remarks**	**Z-value**	**Remarks**
1	Western Himalayan	-0.53	0.04	1.11	NS	0.07	NS
2	Eastern Himalayan	-4.64	0.44	22.6	Negative	-3.88	Negative
3	Lower Gangatic Plains	4.94	0.93	378.5	Positive	6.66	Positive
4	Middle Gangatic Plains	1.28	0.6	43.69	Positive	4.62	Positive
5	Upper Gangatic Plains	-1.64	0.79	108.5	Negative	-5.74	Negative
6	Trans Gangatic Plains	-1.03	0.55	34.81	Negative	-4.49	Negative
7	Eastern Plateaus & Hills	0.4	0.12	4.09	NS	2.24	Positive
8	Central Plateau & hills	-1.39	0.62	47.64	Negative	-4.69	Negative
9	Western Plateau & hills	-0.97	0.35	15.5	Negative	-2.92	Negative
10	Southern Plateau & Hills	0.9	0.3	12.37	Positive	1.94	NS
11	East coast Plains & hills	1.01	0.41	20.18	Positive	2.28	Positive
12	West coast Plains & Hills	-2	0.41	20.5	Negative	-3.13	Negative
13	Gujarat Plains & Hills	-0.64	0.1	3.14	NS	-0.24	NS
14	Western Dry	-0.42	0.17	5.76	Negative	-2.11	Negative
15	The Islands	No-data					

NS indicates statistically non-significant.