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CONSTRUCTION AND ANALYSIS OF ALL-INDIA SUMMER MONSOON RAINFALL SERIES FOR THE LONGEST INSTRUMENTAL PERIOD : 1813-1991

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CONSTRUCTION AND ANALYSIS OF ALL-INDIA SUMMER MONSOON RAINFALL SERIES FOR THE LONGEST INSTRUMENTAL PERIOD : 1813-1991

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ABSTRACT

The all-India summer monsoon rainfall series for the longest instrumental period of 1813-1991 (179 yrs) has been constructed using a progressively increasing station density upto the year 1870, and fixed thereafter at a uniformly distributed 36 stations. The statistical scheme employed accounts for the increasing variance contributed to the all-India series by the increasing number of rain-gauges during the period 1813-1870.

The constructed rainfall series displayed homogeneous characteristics with some significant periodicities ranging between 2 and 3 yrs. Two periods of about forty years of increasing rainfall tendency (1848-86, 1904-45) were observed, and the deficient rainfall years were found mainly clustered in three different epochs (1838-68, 1899-1920 and 1965-87). An interesting outcome of this study is that a reliable estimate of the summer monsoon rainfall over India can be obtained by using only 36 observations.

1. INTRODUCTION

The Asian summer monsoon as a component of the global circulation system profoundly influences the climate of the Indian subcontinent. Due to major contribution to the annual rainfall and large spatial and temporal anomalies in its occurrence it plays an important role in the agricultural economy of the country. In view of its regional and global importance the construction and examination of Indian monsoon rainfall series has been the principal target of numerous studies. Blanford (1886) first studied the Indian rainfall using instrumental records for the period 1867-1885 based on 500 stations. Walker (1910) examined the monsoon rainfall of British India by taking into consideration variable network of raingauges (maximum upto 2000) for the 68 year period (1841-1908) and observed disastrously low rainfall period of 18 yrs during 1843-1860. His studies (Walker; 1914 and 1922) confirmed that vagaries in Indian monsoon rainfall are interlinked with changes in the pressure distribution over the large portions of the earth's surface and stressed the need for study of the global patterns in detail for forecasting the regional conditions. Parthasarathy and Mooley (1978) and Mooley and Parthasarathy (1979) have attempted to construct the summer monsoon rainfall series for the entire country for the period 1841-1977 and shown that the number of bad monsoon years in a five year period are distributed according to a poisson probability law.

Several noteworthy studies about Indian monsoon rainfall include Sankaranarayanan (1933), Rao and Jagannathan (1963), Banerjee and Raman (1976), Parthasarathy and Dhar (1975, 1976), Flohn (1976), Bhalme and Mooley (1980), Thapliyal (1990). However, in all these studies the monsoon rainfall series for the country as a whole have been discussed with varying network of raingauges and are confined to a particular period of records. Taking into consideration all these drawbacks, Mooley and Parthasarathy (1984) have prepared the time series of Indian monsoon rainfall for a long period of 108 yrs from 1871-1978 with a fixed 306 raingauge stations which was later extended upto the year 1984 by Parthasarathy et al. (1987). This series is widely refered and used by many scientists and named as all-India summer monsoon rainfall series. It is denoted here as AISMR-306. As the series is based on a fixed number (306) of well spread raingauge stations it has been extensively used as the representative of all India scale.

For the period prior to 1871 the instrumental rainfall records are available, but the geographical coverage slowly decreases as one goes back in time. The first rainfall observation in India started at Madras from 1792. Some of the available isolated annual rainfall figures for Nungambakkam of Madras observatory (Pogson, 1879) are 1678.9 mm (1803), 789.9 mm (1804), 792.5 mm (1805), 1562.1 mm (1806), 363.2 mm (1807), and 1008.4 mm (1811). The continuous monthly rainfall records at Madras are however, available from the year 1813. Some other important stations for which early monthly rainfall records are available are Bombay (1817), Bangalore (1835), Shimoga (1835), Patna (1842), etc. In absence of any other alternative, it is imperative that these early observations of rainfall record which are historically important are made use of for practical purposes.

In the present study a statistical scheme has been developed for the construction of all-India summer monsoon rainfall series from the earliest possible year of instrumental data with a limited number of selected stations. The longest instrumental all-India summer monsoon rainfall series has thus been constructed for the continuous period of 179 years of rainfall records.

Thus making use of the reliable rainfall records of earlier years it is possible to extend the continuous all-India rainfall series back in time by 58 years from the year 1871 while retaining the characteristics of the all-India series for all climatological purposes. Further, the updating of all-India monsoon rainfall series immediately after the monsoon season, which is an urgent need of atmospheric scientists and planners, is possible due to limited number of observations involved in the preparation of the series. In the context of long-term climatic changes and low frequency variations of rainfall time series a detailed statistical analysis of this extended series is of great importance. This reconstructed long period rainfall series will be useful for long-term social and economic planning and also to verify the expected probabilities and recurrence periods of major anomalies in rainfall amounts such as droughts and floods. This data can be used for cross comparison with the climatological data prior to established observational period obtained from the sources such as tree rings (Parker, 1986), micro-organisms in the sea core samples along the Indian coastal regions (Nigam, 1988), lake sediments (Singh et al., 1974), polynological data (Gupta and Sharma, 1988), ice cores (Thompson et al., 1989), etc.

2. RAINGAUGE NETWORK AND ANALYSIS OF DATA

2.1 Selection of the raingauge network

Processed monthly rainfall data of 306 stations for the period 1871-1984 were obtained from Dr. B. Parthasarathy. Details of preparation of this data set are given in Parthasarathy (1984). Prior to 1871 the data of selected stations have been taken from the India Meteorological Department Memoirs, Vol. XIV by Eliot (1902). After 1871, though a large number of stations are available, timely updating of representative all-India rainfall series is a difficult task, if too many stations are considered. Therefore, stations for constructing the all-India monsoon rainfall series for the longest possible period of 1813-1991 have been selected with the following criteria,

i) the stations should have long and continuous monthly rainfall records,

ii) the stations should be well spread over the country, giving good spatial representation,

iii) the data series of the added stations should make some positive contribution to the variance explained of the all-India summer monsoon rainfall series prepared by Mooley and Parthasarathy (1984) using data of 306 stations (hereafter referred to as AISMR-306), and

iv) rainfall data at the selected stations should be readily available immediately after the monsoon season for easy updating of the all-India series.

With the above criteria the selected station network increases with time. Starting with lone station Madras in the year 1813, the number of stations progressively increased to two (Madras and Bombay) in 1817, three (Madras, Bombay and Bangalore) in 1835, to 36 in 1871 and remained fixed 36 later. These stations are given in Table-1 in the sequence of their selection alongwith the geographical details. Location of the stations is shown in Fig.1. The gaps in the data for the period 1857-1860, when meteorological observations were in suspension over northern India (Patna, Ferozepur, Gorakhpur) due to mutiny with British Empire and missing monthly data for some other stations prior to 1871 have been interpolated by the ratio method as suggested by Rainbird (1967). A nearby station showing the highest correlation coefficient with the station having missing data is used for interpolation. Details of these data gaps, which are about 2% of the total number of monthly rainfall values involved, are given by Sontakke (1990). Rainfall data for 36 selected stations for the period 1985-1991 have been collected from the relevant records of the India Meteorological Department, Pune.

2.2 Statistical analysis of monsoon rainfall series of individual stations

The homogeneity, randomness and normality of the 36 selected individual series are tested using standard statistical techniques and basic statistical characteristics are examined in order to see the nature of these series.

There was no uniform system of raingauges and observational standards for early periods especially before the year 1865 (I.M.D., 1976). It is, therefore, felt necessary to examine the continuity of rainfall data for the early period with the data added afterwards. The Swed and Eisenhart Run test (WMO, 1966a) has been applied for this purpose for all the data series from available period to 1991 which suggested that all the data series are homogeneous. It can thus be inferred that all the data from earlier period to present belong to the same population.

Persistence of the series is tested by calculating auto-correlation coefficients (CCs) upto three lags. It is seen that lag 1 CC is not significant (at 5% level) for all the stations. The auto-correlations at lag 2 for three stations (Shimoga, Gorakhpur, Jabalpur) and at lag 3 for three stations (Shimoga, Delhi and Gorakhpur) are significant at 5% level. In general, it can be stated that the summer monsoon rainfall series for most of the stations are free from persistence.

To see whether non-randomness is present in any of the series the Mann-Kendall Rank statistic test (WMO, 1966b) is applied and three stations namely Bombay, Shimoga and Patiala showed increasing trend significant at 5% level. Nature of the frequency distribution is tested by χ^2 test. Ninety percent of the stations are normally distributed except Deesa, Bikaner and Bangalore. The main statistical parameters mean, standard deviation and coefficient of variation alongwith highest and lowest rainfall amounts of the 36 stations are given in Table-2. In general the selected stations are well representative of the subdivisions in which they are located (Parthasarathy, et al., 1987).

Time series plots of the 12 stations having long monsoon rainfall series are presented in Figs. 2 & 3. The standardized values based on common period 1871-1991 are presented and the corresponding actual values and percentage of normal are shown on parallel scales. By careful visual inspection it can be seen that all the series are continuous without any abrupt change suggesting that they are homogeneous. In order to see the rainfall fluctuations in a low frequency mode individual series have been smoothed by a 5-point binomial filter in the following manner (see Tyson et al, 1975 and WMO, 1966a).

$$Y(1) = 0.54\ X(1) + 0.46\ X(2);$$

$$Y(N) = 0.54\ X(N) + 0.46\ X(N-1)$$

$$Y(2) = 0.25\ X(1) + 0.50\ X(2) + 0.25\ X(3);$$

$$Y(N-1) = 0.25\ X(N) + 0.50\ X(N-1) + 0.25\ X(N-2)$$

For $i = 3$ to $N-2$,

$$Y(i) = 0.06\ X(i-2) + 0.25\ X(i-1) + 0.38\ X(i) + 0.25\ X(i+1) + 0.06\ X(i+2)$$

where Xs are the actual values, Ys filtered values and N number of observations. The small periods of different length of increasing and decreasing tendency are observed by 5-point binomial low pass filtered curves at individual stations.

3. CONSTRUCTION OF THE ALL-INDIA SUMMER MONSOON RAINFALL SERIES

The 36 stations selected from different parts of the country for construction of all-India monsoon rainfall series constitute a network with number of data points increasing with time till all the 36 selected stations have been incorporated by the year 1871. Starting from one station in 1813 to 36 stations in 1871 thirteen steps are identified in the increasing rate of raingauge density in the selected network (for details see Table-3). The process of constructing an all-India summer monsoon rainfall series based on these stations is also carried out accordingly in 13 stages. The AISMR-306 (1871-1984) is used as the yardstick in this construction process. Our aim is to use the regression method for construction and extension of rainfall series backward with less number of stations and not for its prediction. Therefore, full length of the common period is used for regression analysis which gives more stable and consistent estimation.

The mean monsoonal rainfall series of stations in each group from A to M and AISMR-306 are correlated for the common period 1871-1984. The CC increased from 0.396 with a single station Madras in group A to 0.956 with 36 stations in the last group M (see Table 4). Thirteen regression equations have been developed one for each of the groups from A to M, between AISMR-306 and mean monsoon rainfall of stations in the respective group. Table-4 gives the CC values, the regression equations and variance explained for the individual group. The first group A is having regression equation AISMR = 749.41 + $0.26\bar{R}_A$, where $\bar{R}_A$ is the Madras monsoon rainfall. The AISMR for the period 1813-1816 are estimated from this equation. Similarly further AISMR are estimated from 12 regression equations developed for the purpose for the respective periods. The last equation AISMR = 175.29 + 0.85 $\bar{R}_M$, where $\bar{R}_M$ is the mean monsoon rainfall of 36 stations in group M, is used to estimate AISMR values for the period 1871-1991 (AISMR-36). The stepwise increase in CC and stations for different periods and the constructed all-India rainfall series from 1813-1991 are shown in Fig.4 which clearly shows that the construction of the series comprises of two parts. In first part the backward extension of the all-India monsoon rainfall series from 1813-1870 where 12 regression equations for increasing network of data points were used. Secondly, the series from 1871-1991 is reconstructed with 36 fixed stations, instead of 306 stations in the original series. Therefore, these two parts are separately discussed below.

i) Period from 1813-1870

The variance explained by the 12 regression equations used to estimate the all-India monsoon rainfall from 1813-1870 varies from 16% to 83%. Use and analysis of this series will, therefore, pose serious statistical problems. To bring the entire series to a consistent level of variation (1871-1984), the rainfall amount for the years before 1871 is corrected as suggested by Klein et al. (1959).

The 13 different series of AISMR based on 13 regression equations are calculated for the common period 1871-1984. The standard deviation of these 13 series increases from 33.07 mm to 79.85 mm (Table-4). The estimated AISMR values for the period 1813-1870 with first 12 regression equations developed for 12 different groups are then standardized with respective mean and standard deviation for that group based on the period 1871-1984. For example, estimated AISMR values from 1813-1816 are based on equation AISMR = 749.41 + $0.26\bar{R}_M$ and AISMR series with this equation for 1871-1984 period has mean 851.9 mm and S.D. 33.07. Therefore, for the years 1813-1816 the estimated AISMR values are standardized with mean 851.9 mm and S.D. 33.07. In the same way AISMR values for the whole period 1813-1870 are standardized with mean and S.D. of the respective AISMR series for the period 1871-1984.

In order to bring different estimated values to the same base they have been inflated to the variance level of the Eq. 13 which explains 91% variance of the AISMR-306. The mean and S.D. of the 13th series with 36 stations are 851.9 mm and 79.85 mm respectively. From standardized values for the period 1813-1870 the actual AISMR values are obtained by using this mean and S.D. This has brought the explained variance of the total series from 1813-1991 to a single level of 91% and, therefore it can be used for continuous analysis. One must take note of the CC values while making use of rainfall figures for the particular period.

ii) Period from 1871-1991

All-India summer monsoon rainfall is reproduced here with the rainfall data of 36 stations instead of 306 stations in the original series where CC between the original AISMR-306 and AISMR-36 for the regressed period 1871-1984 is 0.956.

Table 5 shows the statistical properties of these two series for the common period 1871-1984. It is seen that they are in close agreement. The mean and S.D. of the constructed series is 851.9 mm and 79.9 mm respectively.

The aptness of regression model is tested by calculating error statistics. The standard error of estimate is 24.5 mm. The autocorrelation of first three lags (0.042, 0.081 and -0.016) of error series shows that it is free from persistence. The Chi-square test of normality ($\chi^2 = 4.25$ for 7 d.f.)

shows that it is Gaussian distributed. Fisher's coefficient $g_1/SE(g_1)$ and $g_2/SE(g_2)$ are -1.059 and -1.109 respectively.

The scatter diagram for the period 1871-1984 is plotted alongwith the fitted line in Fig. 5. The deficient and excess monsoon rainfall years of the AISMR-306 series are shown separately.

The 11, 21 and 31 year sliding CCs between AISMR-306 and AISMR-36 are plotted in Fig. 6. The CC values are highly significant for all the lengths and periods at 0.1% levels except on few occasions for 11-year sliding period which shows that this regression model is fit for all the periods considered. It is seen that stability and consistency of the CC values increases with sliding length and explains the existence of the close reltionships between the series.

4. ANALYSIS OF THE ALL-INDIA SUMMER MONSOON RAINFALL SERIES 1813-1991

The longest series of All-India monsoon rainfall for a period of 179 years is subjected to different statistical techniques in order to understand its behaviour on different time scales. In addition to interannual variability aspect this series is appropriate for the analysis on decadal scale due to its coverage of 18 decades. The rainfall values from 1813-1991 are given in Table-6.

The mean All-India rainfall for the period 1813-1991 is 846.9 mm with a standard deviation of 79.7 mm and coefficient of variation 9.4%. The median is 854.4 mm. The Swed and Eisenhart's run test shows that the series is homogeneous. The first three auto-correlation coefficients (-0.057, 0.014 and 0.043) are statistically insignificant, indicating the absence of persistence.

The highest value which occurred in the year 1961 is 1021.5mm and is 21% above the mean value. The lowest which occurred in the year 1877 is 621.0 mm and is 27% below the mean value. The percentile values show that the deviation from median is more on the lower side than the higher side of the percentile.

The Chi-square test by dividing the data into 10 equal probability class intervals (Cochran, 1952) is applied for normality test. The test statistic is 13.68 which shows that the series is distributed normally (5% value is 14.10). The more stringent test of Fisher's statistic shows that $g_1/SE(g_1)$ is -2.43 and $g_2/SE(g_2)$ is -0.44. Thus the series is left skewed. In general the monsoon rainfall series over India is taken as normally distributed for practical purposes but to be more precise its negative skewness is worth noting. The statistical properties of All-India monsoon rainfall for the period 1813-1991 are given in Table-5.

Decadal mean and CV values for 18 decades (the first decade comprise only 8 values from 1813-1820) are calculated and presented in Fig. 7 and tabulated in Table-7. Lowest CV values of 4% and 6% are observed during the decades 1881-90 and 1941-50. Mean rainfall for these decades is much higher than the average. For the three continuous decades 1921-30, 1931-40 and 1941-50 rainfall has been above normal and stable when C.V. values are lower 5, 7 & 6% respectively. During the current period from

1961 onwards decadal C.V. values are continuously on higher side of the long-term mean (11, 12 & 10%).

Decadal average values show continuous increase from the decades 1841-50 to 1881-90 and again from 1901-10 upto 1941-50 and interestingly the two periods are of 40 years duration. Cramers t_k value (WMO, 1966a) shows that decadal averages are not significantly high or low than the overall mean.

The Mann-Kendall rank statistic shows that the series is not having any trend when 179 years of continuous period is taken into consideration. But, when the test is applied for two equal parts of 89 years the series from 1813-1901 and 1902-1990, it is seen that for 1902-1990 period there is an increasing trend marginally significant at 10% level (τ = 0.1205 and τ_t = 0.1203). This is an interesting observation which may perhaps indicate that the slight increase in rainfall in the current century may be following the recent global warming trend.

To analyse the variability of rainfall in subperiods of few decades (which are normally referred as epochs) the rainfall series is smoothed by using a cubic spline curve fit (Pant et al., 1988). The smoothed cubic spline of 50% variance reduction frequency values at 10, 20 & 30 years are computed and plotted in Fig 8. The large fluctuations at 10 year cubic spline curve suggest the strong role played by decadal scale variability. The 20 year spline curve starts showing up the prominence of major climatic episodes and the picture with 30 year spline becomes clear with well marked periods. The five distinct epochs are identified of contrasting characteristics out of which three are of excess rainfall namely 1815-33, 1875-94 and 1932-64 whereas two epochs from 1834-74 and 1895-1931 are of deficient rainfall. The two periods of increasing tendency from 1848 to 1886 (39 years) and 1904-1945 (41 years) are noticed.

The autocorrelation values upto 60 lags (1/3 length of the series) are calculated but none of them are statistically significant. The lag correlation upto 40 lags is calculated by dividing the series into two equal parts. For second half from 1902-1990 values at lag 14 and lag 32 are significant at 5% level. For more detailed analysis the power spectrum analysis by Schickendanz and Bowen (1975) is applied. The normalised smooth spectral estimates have been calculated and are plotted in Fig. 9 for total length and for two equal parts. For total length three cycle between 2 to 3 years (2.87, 2.83, 2.78) are significant at 5% levels and three cycles between 2 to 3 years (2.40, 2.37, 2.34) are significant at 10% level. For first half 4.89 years cycle is significant and two cycles between 2 to 3 years (2.93, 2.84) are significant at 10% level. For second half 8.00, 7.33 and 2.44 year cycle are significant at 10% level. The periodicities in these ranges observed in the rainfall series by many researchers earlier are said to be associated with QBO and ENSO phenomena.

5. INTERANNUAL VARIABILITY AND RAINFALL EXTREMES.

The percentage departure of rainfall from long term mean of 179 years for each year is computed for the period 1813-1991. Excess and deficient rainfall years are classified with the margin ±10 percent departure from the mean value respectively. The percentage departure from mean values are plotted in Fig. 10. The corresponding standardised and actual rainfall values are also shown side by side on parallel scale. There are 22 excess and 31 deficient years in the series. Five excess and four deficient rainfall years are observed during the period 1813-1843 in which the series is based on few number of raingauges. The historical documents by Mitra (1978), Ghosh (1944), Loveday (1914), Masefield (1963), Ray (1901), Walford (1878) and Indian famine commission (1880, 1898, 1901) about Indian famines have supported these deficient rainfall years identified here and described the areal extent of droughts in these years which is discussed in detail in Sontakke (1990). From 1844 the series prepared by (Mooley and Parthasarathy 1979) closely agrees with our series. However, it should be borne in mind that the period from 1813-1843, though is representative of All-India rainfall is not perfect for quantitative analysis.

In general it is seen that frequency of occurrence and intensity of deficient rainfall years is high compared to excess rainfall years. The 31 occurrences of deficient rainfall years in time span of 179 years of the study suggests prominent clustering in varying time scales. The empirical probabilities for total period and for three identified periods of frequent deficient rainfall years is shown below with number of deficient rainfall years.

Period	No. of yrs.	Deficient rain-fall years	Empirical probability
1813-1991	178	31	0.18
1838-68	31	9	0.29
1899-1920	21	8	0.38
1965-87	23	7	0.30

First two periods of frequent deficient years namely 1838-68 and 1899-1920 are followed by good rainfall periods. Therefore, we can hope of good rainfall period after the present bad epoch.

6. CONCLUSIONS

i] The 179 years longest Indian monsoon rainfall series based on instrumental records starting from the year of the first systematically observed weather records in the subcontinent shows that basic characteristics of the rainfall in this large continental region have been stable.

ii] All-India rainfall series is in the statistical limits of normal distribution for practical purposes but its negative skewness is worth noting.

iii] Three excess (1815-33, 1875-94 and 1932-64) and two deficient (1834-74 and 1895-1931) rainfall epochs are noticed. Two periods of increasing tendency are observed from 1848 to 1886 (39 yrs) and 1904-45 (41 yrs).

iv] On interannual scale All-India monsoon rainfall has varied from +21% to -27% of the long term mean. The deficient rainfall years are mainly clustered in three time periods from 1838-68, 1899-1920 and 1965-87.

v] Spectrum analysis has broughtout 2 to 3 years cycle throughout the period but other cycles are of temporary nature.

vi] The important finding of this study is that 36 stations selected are sufficient enough to estimate the All-India rainfall for practical purposes.

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LEGENDS OF FIGURES

Fig. 1 : Location of thirty six selected raingauge stations over India for this study.

Fig. 2 : Actual, standardised and percentage of normal of the summer monsoon rainfall series for six, chosen stations from the earliest available year through 1991. Continuous curve denotes a 5-point binomial low-pass filtered values.

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Fig. 5 : Scatter diagram of All-India monsoon rainfall based on 306 stations versus mean monsoon rainfall for 36 selected stations for the period 1871-1984.

Fig. 6 : Variation in the correlation coefficient between All-India summer monsoon rainfall (AISMR-306) and the summer monsoon rainfall of 36 stations for the 11, 21 and 31-yr sliding window-width over the period 1871-1984.

Fig. 7 : Decadal averages and coefficient of variations of All-India summer monsoon rainfall (AISMR-36) for the period 1813-1990.

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Fig. 10 : Percentage departure of All-India summer monsoon rainfall (AISMR-36) over the period 1813-1991. Actual and standardised scales are also marked on the diagram. Continuous curve denotes a 5-point binomial low-pass filtered values.

Table 1 : Details of 36 selected stations over India

S. No.	Name of the station	Symbol	Index No.	Location latitude °N	Location longitude °E	Height amsl in mts.	Year of Start	Length of record
1.	Madras (Nungabakkam)	MDS	43278	13 04	80 15	06	1813	179
2.	Bombay (Colaba)	BMB	43057	18 54	72 49	11	1817	175
3.	Bangalore	BNG	43295	12 58	77 35	921	1835	157
4.	Shimoga	SMG	43258	13 56	75 38	571	1837	155
5.	Patna	PTN	42491	25 30	85 15	52	1842	150
6.	Hyderabad	HYD	43129	17 27	78 28	545	1843	149
7.	Delhi	DLH	42182	28 35	77 12	216	1844	148
8.	Ferozepur	FZP	42096	30 55	74 40	200	1844	148
9.	Gorakhpur	GRK	42379	26 45	83 25	78	1844	148
10.	Jabalpur	JBP	42675	23 10	79 57	393	1844	148
11.	Puri	PRI	43053	19 48	85 49	06	1848	144
12.	Nagpur/ Mayo Hosp.	NGP	42866	21 06	79 03	310	1854	138
13.	Deesa	DSA	42539	24 12	72 12	136	1856	136
14.	Pune	PNE	43063	18 32	73 51	559	1856	136
15.	Amraoti	AMT	42937	20 56	77 47	370	1860	132
16.	Bareilly	BRL	42189	28 22	79 24	173	1860	132
17.	Varanasi	VNS	42483	25 18	83 01	76	1860	132
18.	Raipur	RPR	42875	21 14	81 39	298	1864	128
19.	Seoni	SNI	42771	22 05	79 33	610	1864	128
20.	Sambalpur	SBP	42883	21 28	83 58	148	1867	125
21.	Anantpur	ANT	43237	14 41	77 37	350	1871	121
22.	Calcutta (Alipore)	CAL	42807	22 32	88 20	06	1871	121
23.	Thiruvanantha-puram	TRV	43371	8 29	76 57	64	1871	121
24.	Kanpur	KNP	42366	26 26	80 22	126	1871	121
25.	Guwahati	GWT	42410	26 06	91 35	54	1871	121
26.	Jaipur	JPR	42348	26 49	75 48	390	1871	121
27.	Ujjain	UJN	42662	23 11	75 47	527	1871	121
28.	Porbandar	PBD	42830	21 37	69 38	12	1871	121
29.	Jodhpur	JDP	42339	26 18	73 01	217	1871	121
30.	Kotah	KTA	42451	25 11	75 51	257	1871	121
31.	Baroda	BRD	42747	22 47	73 18	34	1871	121
32.	Patiala	PTL	42101	30 20	76 28	251	1871	121
33.	Udaipur	UDP	42543	24 35	73 42	582	1871	121
34.	Jalgaon	JLG	42851	23 03	75 34	201	1871	121
35.	Bikaner	BKR	42165	28 00	73 18	224	1871	121
36.	Daltonganj	DTG	42587	24 03	84 04	221	1871	121

Table 2 : Statistical properties of monsoon rainfall series for 36 stations from earliest available year to 1991

S. No.	Station	Period of data	Mean (mm)	Std.Dev. (mm)	C.V. (%)	Median (mm)	Highest Rainfall (mm)	Lowest Rainfal (mm)
1.	Madras	1813-1991	392	132	33.8	383	860	97
2.	Bombay	1817-1991	1836	471	25.6	1809	3423	584
3.	Bangalore	1835-1991	497	145	29.2	473	437	194
4.	Shimoga	1837-1991	524	162	30.9	510	1160	127
5.	Patna	1842-1991	977	283	29.0	979	1892	398
6.	Hyderabad	1843-1991	587	164	27.9	548	1079	258
7.	Delhi	1844-1991	597	225	37.7	599	1421	967
8.	Ferozepur	1844-1991	375	186	49.6	342	1038	48
9.	Gorakhpur	1844-1991	1078	298	27.6	1051	1731	376
10.	Jabalpur	1844-1991	1244	323	25.9	1237	2260	414
11.	Puri	1848-1991	987	259	26.3	992	1793	454
12.	Nagpur/ Mayo Hosp.	1854-1991	1015	230	23.0	500	1548	336
13.	Deesa	1856-1991	572	283	49.4	518	1416	29
14.	Pune	1856-1991	529	172	33.0	379	1207	106
15.	Amraoti	1860-1991	733	208	28.0	503	1303	271
16.	Bareilly	1860-1991	949	318	33.0	919	1916	188
17.	Varanasi	1860-1991	910	249	27.0	888	1857	395
18.	Raipur	1864-1991	1147	287	25.0	1137	2051	532
19.	Seoni	1864-1991	1185	284	24.0	1149	2608	557
20.	Sambalpur	1871-1991	1426	316	22.0	1432	2309	765
21.	Anantpur	1871-1991	315	130	42.0	296	686	63
22.	Calcutta		1226	267	21.7	1181	205	689
23.	Thiruvanantha-puram	1871-1991	803	256	31.9	777	1779	356
24.	Kanpur	1871-1991	708	229	32.4	696	1353	145
25.	Guwahati	1871-1991	1079	225	20.9	1059	1565	605
26.	Jaipur	1871-1991	564	229	40.6	546	1312	93
27.	Ujjain	1871-1991	842	253	30.0	832	1797	357
28.	Porbandar	1871-1991	534	301	56.5	493	1849	32
29.	Jodhpur	1871-1991	329	167	50.8	307	884	24
30.	Kotah	1871-1991	709	254	35.9	656	1332	151
31.	Baroda	1871-1991	859	324	37.7	849	1850	125
32.	Patiala	1871-1991	574	215	37.4	534	1423	119
33.	Udaipur	1871-1991	585	200	34.1	584	1075	82
34.	Jalgaon	1871-1991	695	187	26.9	693	1156	185
35.	Bikaner	1871-1991	244	121	49.5	231	621	29
36.	Daltonganj	1871-1991	1013	249	24.6	1004	1751	482

Table 3 : Details of stations considered during different sub-periods between 1813-1991 for constructing the All-India summer monsoon rainfall series

Sr. No.	Period	Group	Name of Station(s) included during the course of the period	No.of stns. utilised
1.	1813-1816	A	Madras	1
2.	1817-1834	B	Gr.A and Bombay	2
3.	1835-1836	C	Gr.B and Bangalore	3
4.	1837-1841	D	Gr.C and Shimoga	4
5.	1842	E	Gr.D and Patna	5
6.	1843	F	Gr.E and Hyderabad	6
7.	1844-1847	G	Gr.F and Delhi, Ferozepur Gorakhpur and Jabalpur	10
8.	1848-1853	H	Gr.G and Puri	11
9.	1854-1855	I	Gr.H and Nagpur	12
10.	1856-1859	J	Gr.I and Deesa & Puri	14
11.	1860-1863	K	Gr.J and Amraoti, Bareilly and Varanasi	17
12.	1864-1870	L	Gr.K and Raipur and Seoni	19
13.	1871-1991	M	Gr.L and Sambalpur, Anantapur, Jaipur, Ujjain, Porbandar, Jodhpur, Kotah, Baroda, Patiala, Udaipur, Jalgaon, Bikaner, Daltonganj, Calcutta, Thiruvananthapuram, Kanpur and Guwahati	36

Table 4 : Regression equations and correlation coefficients for different sub-periods during 1813-1991 used to construct the All-India summer monsoon rainfall series ($\bar{R}_A$ ..... $\bar{R}_M$ indicates the mean monsoonal rainfall in each group from A to M.)

S. No.	Period	Regression equation used to estimate All-India rainfall	Correlation Coefficient with AISMR-306	Variance explained (percent)	S.D. for the estimated series (1871-1984)
1.	1813-1816	$AISMR = 749.41 + 0.26\bar{R}_A$	0.3959	16	33.07
2.	1817-1834	$AISMR = 685.45 + 0.15\bar{R}_B$	0.4858	24	40.59
3.	1835-1836	$AISMR = 662.86 + 0.21\bar{R}_C$	0.4972	25	41.54
4.	1837-1841	$AISMR = 633.55 + 0.27\bar{R}_D$	0.5200	27	43.44
5.	1841	$AISMR = 556.36 + 0.35\bar{R}_E$	0.5469	30	45.69
6.	1843	$AISMR = 526.46 + 0.40\bar{R}_F$	0.5949	35	49.70
7.	1844-1847	$AISMR = 333.51 + 0.64\bar{R}_G$	0.8068	65	67.41
8.	1848-1853	$AISMR = 301.76 + 0.66\bar{R}_H$	0.8188	67	68.41
9.	1854-1855	$AISMR = 265.87 + 0.69\bar{R}_I$	0.8481	72	70.86
10.	1856-1859	$AISMR = 263.54 + 0.73\bar{R}_J$	0.8853	78	73.96
11.	1860-1863	$AISMR = 265.21 + 0.72\bar{R}_K$	0.9049	82	75.59
12.	1864-1870	$AISMR = 247.50 + 0.71\bar{R}_L$	0.9134	83	76.31
13.	1871-1991	$AISMR = 175.29 + 0.85\bar{R}_M$	0.9558	91	79.85

Table 5 : Statistical properties of the AISMR-306 (1871-1984), the AISMR-36 (1871-1984) and the AISMR-36 (1813-1991)

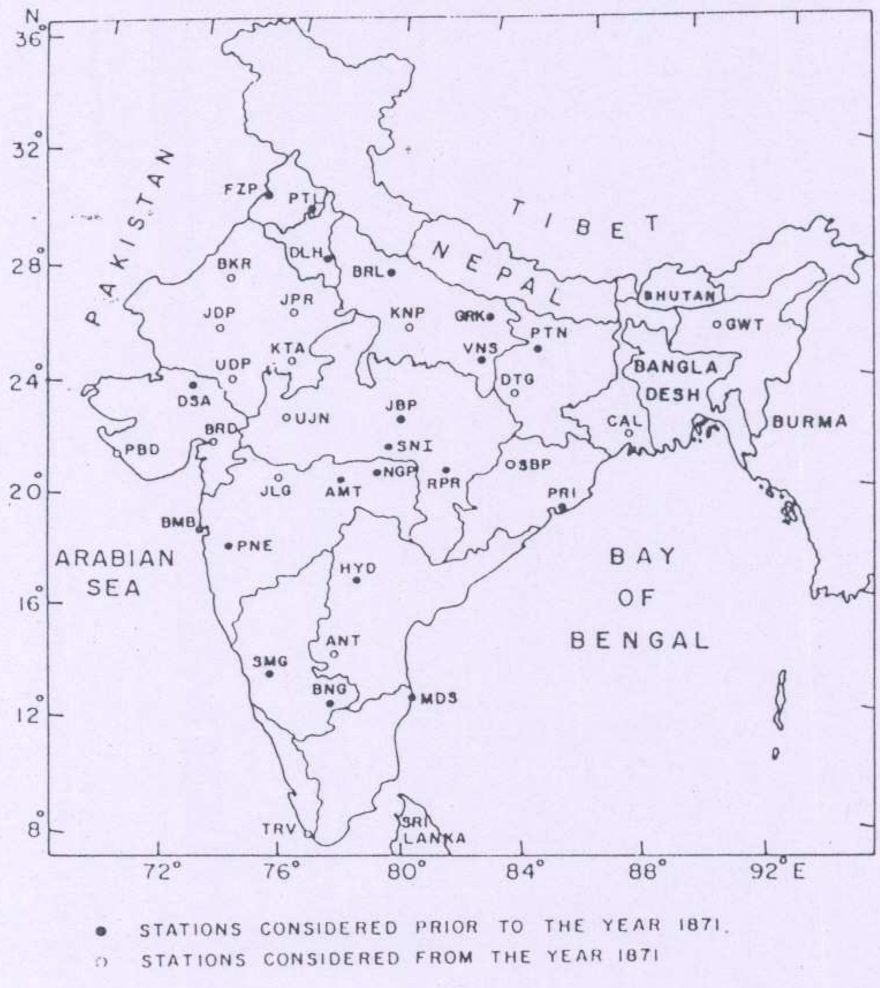
S.No.	Statistical parameter	AISMR-306 (1871-1984)	AISMR-36 (1871-1984)	AISMR-3 (1813-19
1.	Mean (mm)	851.9	851.9	846.9
2.	Standard deviation (mm)	83.5	79.8	79.7
3.	Coefficient of Variation(%)	9.8	9.4	9.4
4.	Mean deviation (mm)	66.4	63.4	63.2
5.	Mean variability	7.8	7.4	7.5
6.	Coeff. skewness (g_1)	-0.61	-0.64	-0.44
7.	Coeff. kurtosis (g_2)	0.11	0.12	-0.16
8.	$g_1/SE(g_1)$	-2.70	-2.85	-2.43
9.	$g_2/SE(g_2)$	0.25	0.27	-0.44
10.	Chi-square (10 classes)	8.3	12.5	13.68
11.	Median (mm)	864.6	863.6	854.4
12.	Lower quartile (mm)	798.1	802.6	800.4
13.	Upper quartile (mm)	907.9	909.2	907.0
14.	Lowest value (mm)	603.7	621.0	621.0
15.	Percentage of mean	70.9	72.9	73.3
16.	Year of occurrence	1877	1877	1877
17.	Highest value (mm)	1017.0	1021.5	1021.5
18.	Percentage of mean	119.4	119.9	120.6
19.	Year of occurrence	1961	1961	1961
20.	Range (mm)	413.5	400.5	400.5
21.	Auto-correlation			
	upto 3 lags (r_1)	-0.14	-0.10	-0.06
	(r_2)	0.05	0.03	0.01
	(r_3)	0.11	0.11	0.04
22.	No. of runs above and below the median	57	57	89

Table 6 : All-India summer monsoon rainfall (AISMR-36) (in mm) from 1813 to 1991

Decade	Year ——> 0	1	2	3	4	5	6	7	8	9
1810	–	–	–	718	842	766	920	959	910	887
1820	850	880	985	801	657	852	891	878	1017	806
1830	856	984	843	841	842	834	903	769	720	871
1840	808	826	938	706	744	746	924	853	756	857
1850	796	791	916	805	939	726	827	768	756	848
1860	836	944	831	901	701	838	841	841	700	860
1870	884	856	910	789	944	937	778	621	917	918
1880	811	894	887	827	954	836	863	904	833	908
1890	867	849	966	902	924	801	858	854	866	635
1900	916	728	753	831	739	715	847	800	884	902
1910	887	708	822	803	900	814	949	995	669	891
1920	749	864	900	845	876	825	862	816	743	792
1930	806	909	797	996	888	827	889	863	860	778
1940	838	745	914	866	921	918	900	922	854	917
1950	878	683	782	892	903	914	955	755	907	908
1960	850	1021	824	850	926	717	751	875	766	834
1970	976	924	667	938	747	965	871	932	910	720
1980	887	887	773	941	840	830	752	701	966	856
1990	914	874	822	882	981					

Table 7 : Decadal statistics of the All-India summer monsoon rainfall (AISMR-36) for the period 1813-1990

S.No.	Period	Mean (mm)	Std.Dev. (mm)	C.V. (%)	Cramers' t-value
1	1813-1820	856.4	75.7	8.8	0.365
2	1821-1830	862.3	94.8	11.0	0.649
3	1831-1840	841.4	67.8	8.1	-0.200
4	1841-1850	814.6	75.0	9.2	-1.293
5	1851-1860	821.3	64.3	7.8	-1.021
6	1861-1870	834.1	74.4	8.9	-0.498
7	1871-1880	848.0	95.9	11.3	0.070
8	1881-1890	877.2	38.0	4.3	1.261
9	1891-1900	857.2	86.2	10.1	0.443
10	1901-1910	808.7	67.6	8.4	-1.540
11	1911-1920	830.0	99.2	11.9	-0.664
12	1921-1930	833.0	43.9	5.3	-0.542
13	1931-1940	864.5	58.8	6.8	0.739
14	1941-1950	883.5	51.8	5.9	1.522
15	1951-1960	854.8	82.3	9.6	0.346
16	1961-1970	854.1	93.3	10.9	0.315
17	1971-1980	856.2	99.5	11.6	0.401
18	1981-1990	845.9	80.9	9.6	-0.357



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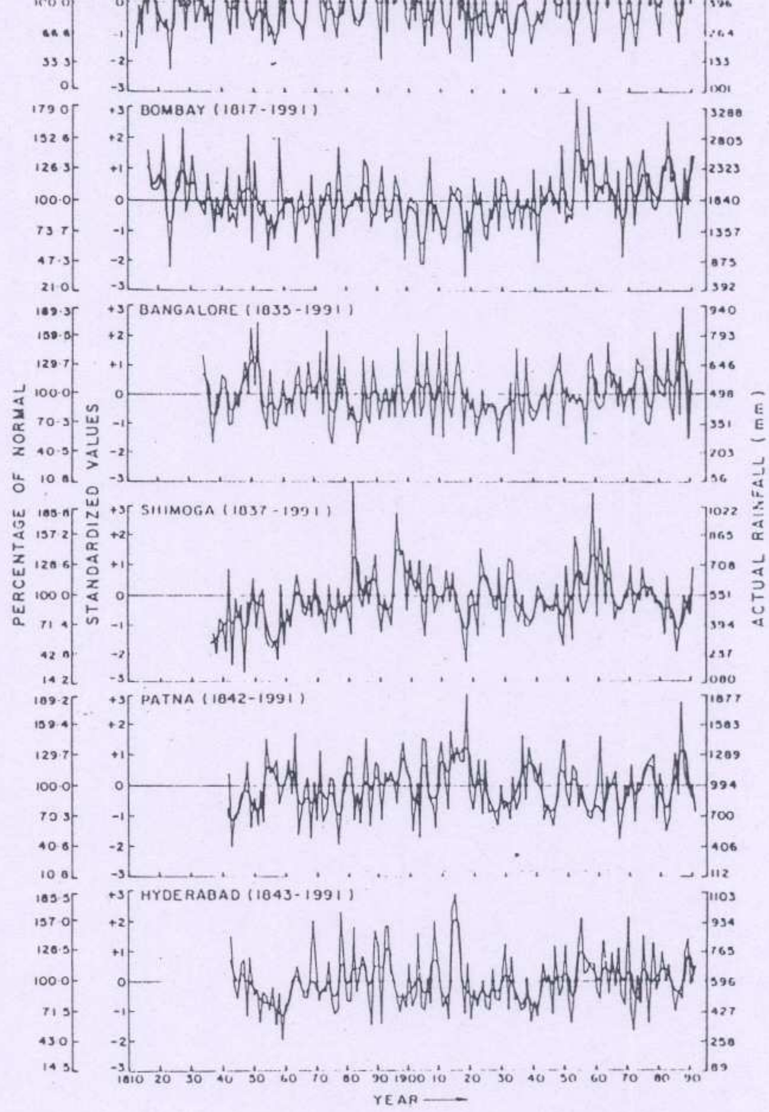

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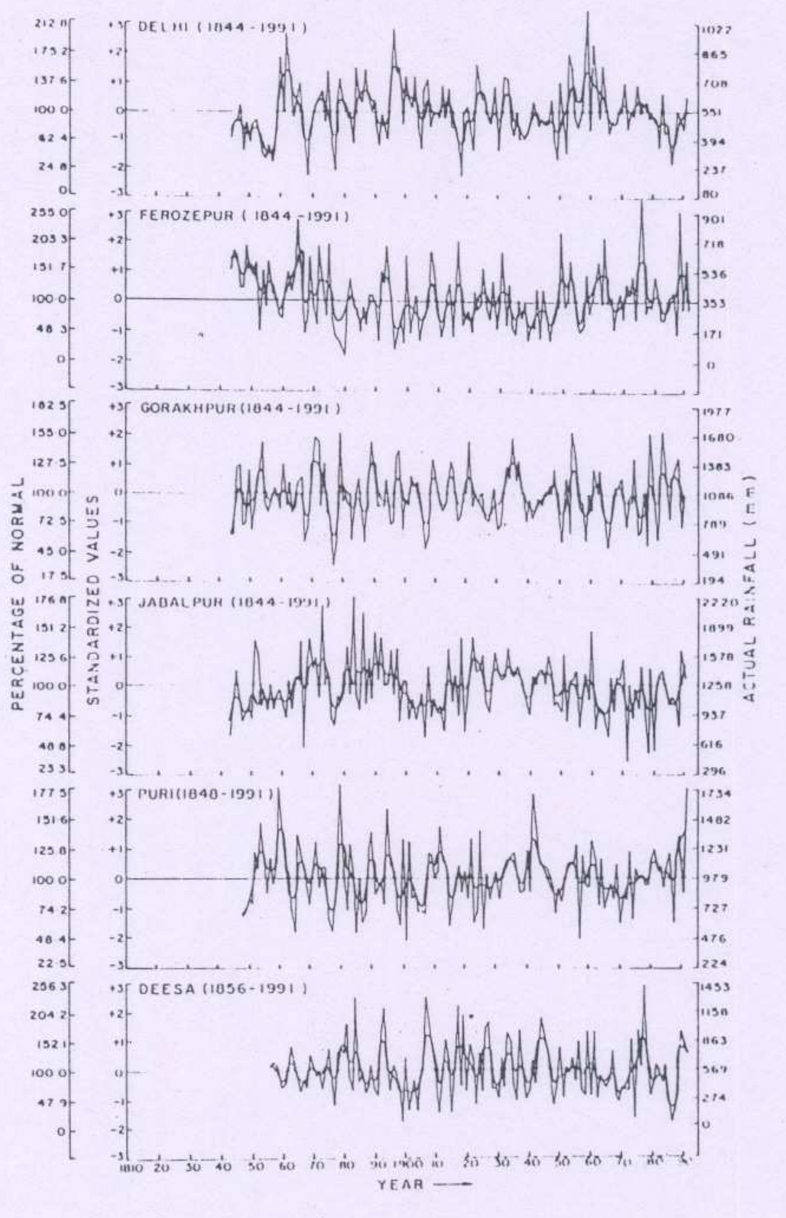

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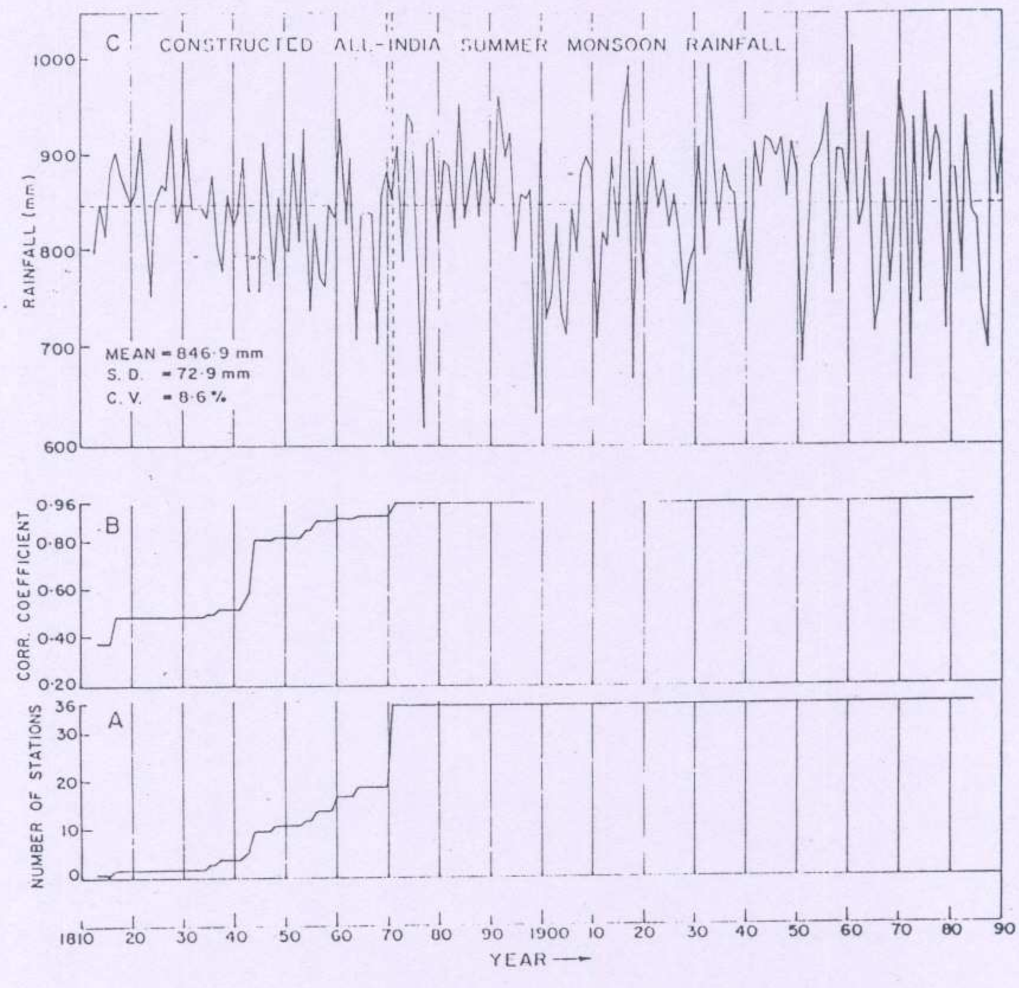

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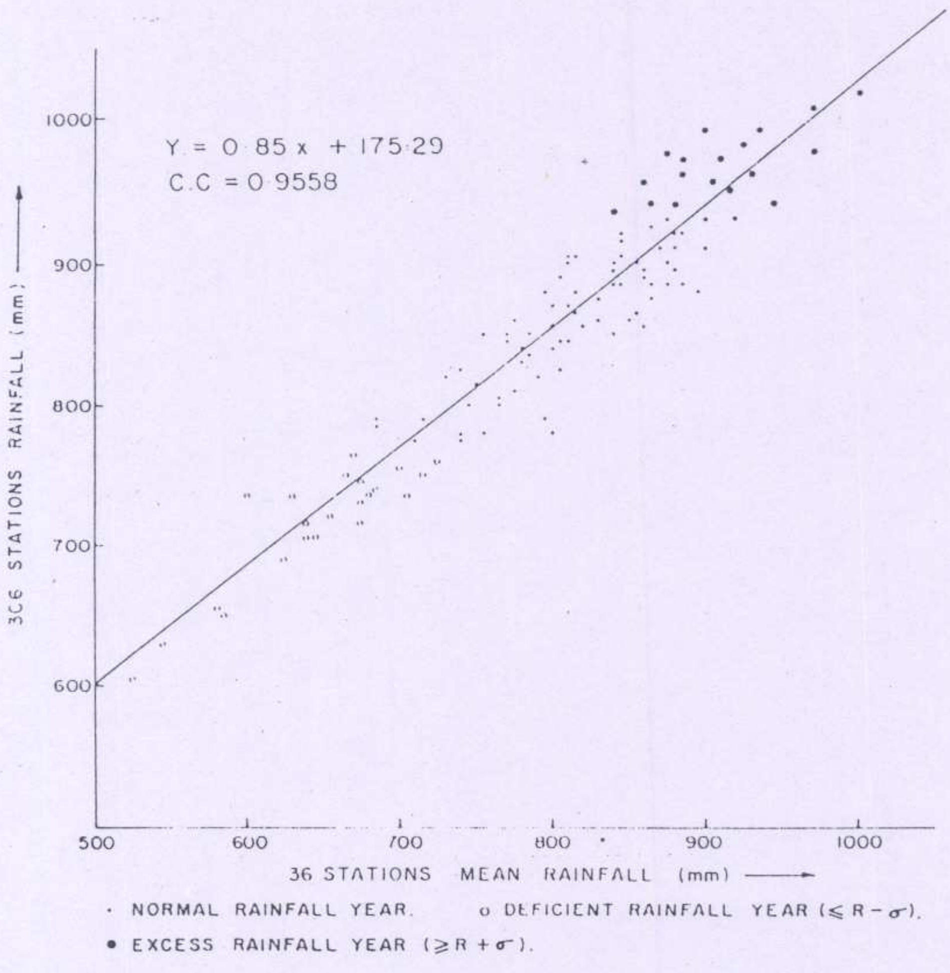

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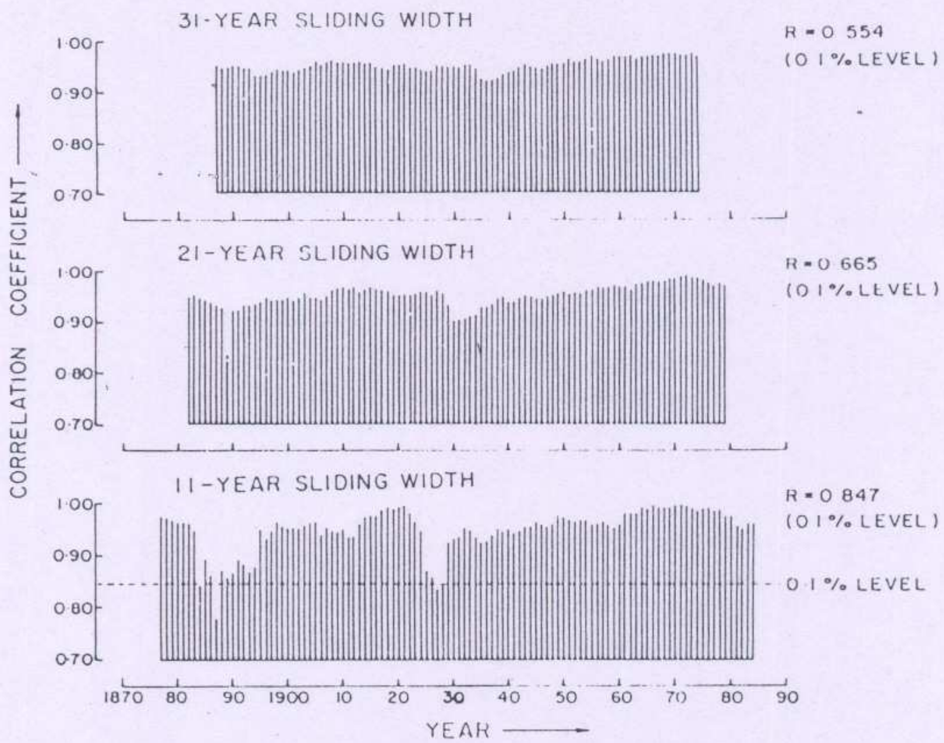

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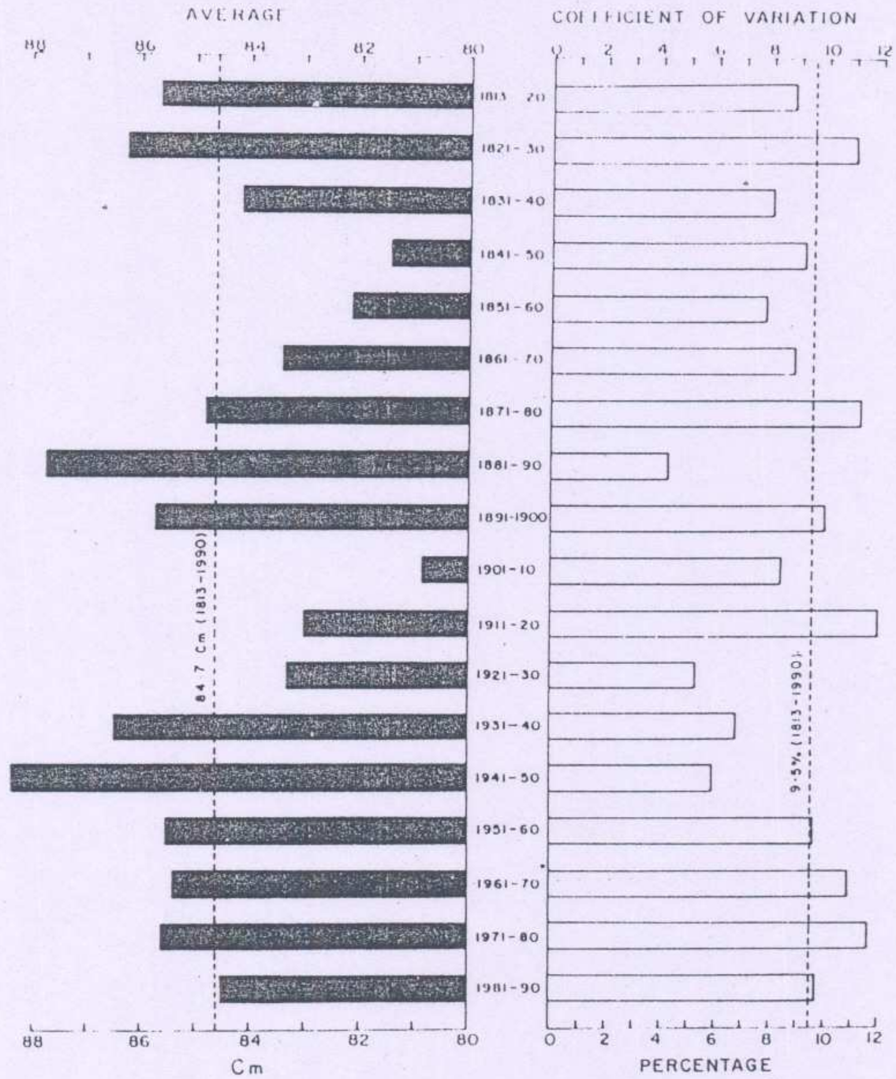

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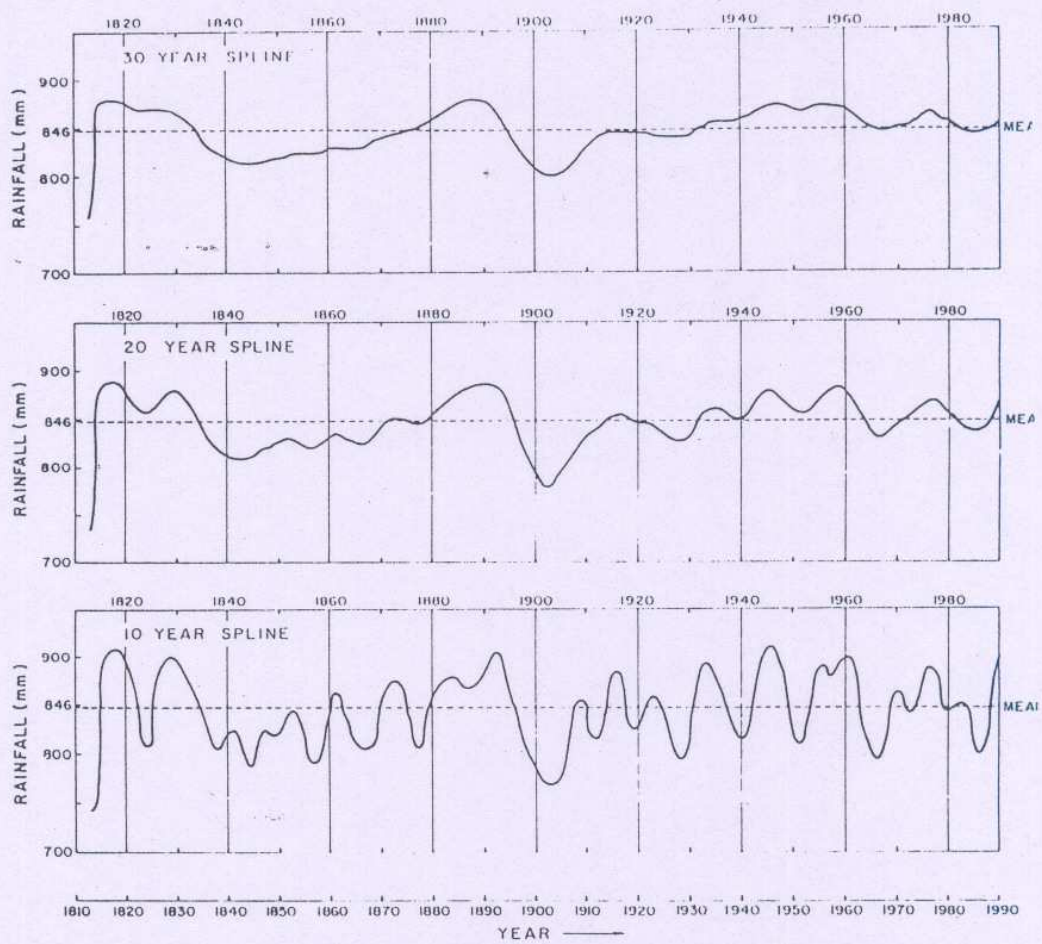

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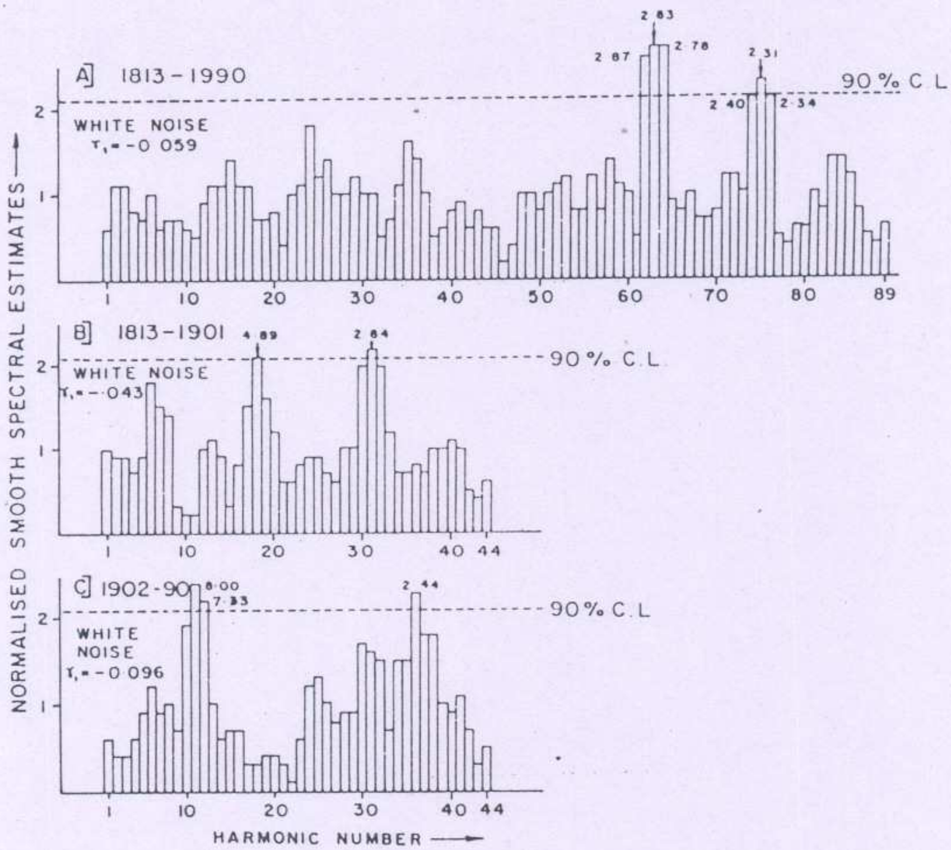

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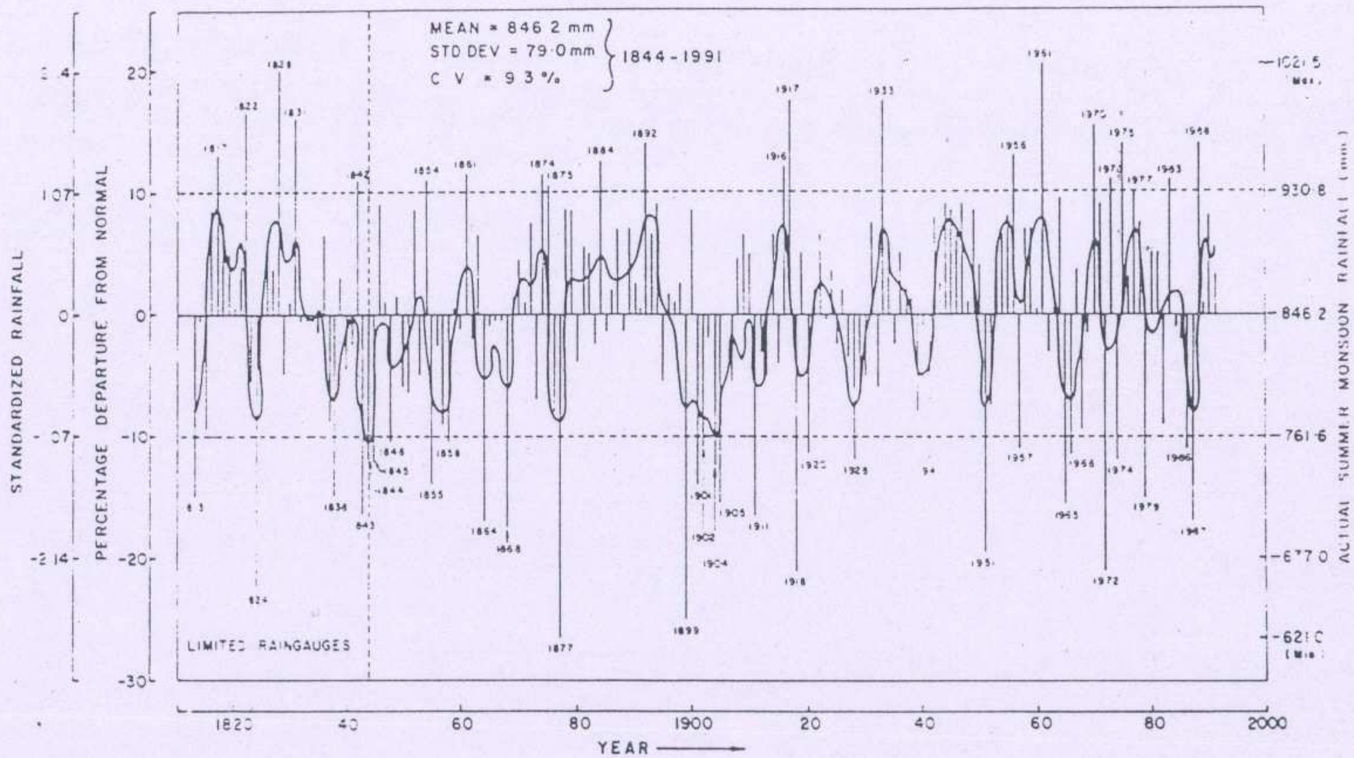

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