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Trends and Periodicities of Rainfall Over India

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ABSTRACT—Trends and periodicities in the annual rainfall of India were studied using data for 48 stations having record lengths of over 70 yr. Increasing or decreasing rainfall tendencies were found over large continuous areas in India. These trends, however, are not significant over all the stations in the areas but only at a few places distributed at random. Wherever a trend is significant, it has persistance or a periodicity of more than 40 yr. Quasi-biennial oscillation (QBO) is exhibited at several stations in the areas of increasing or decreasing trend. Similarly, the 11-yr cycle (solar cycle) is also exhibited in both areas. The QBO and the solar cycle are both present at only three stations, however. This casts a serious doubt on whether or not there is any physical relation between the QBO and the solar cycle, at least for rainfall.

1. INTRODUCTION

Much work has been done in various countries on trends and fluctuations of rainfall and temperature, notably by Reynolds (1953), Kraus (1960), Willett (1950), and Callendar (1961). Angell et al. (1966) observed quasi-biennial oscillations (QBO) in the tropospheric zonal winds of the Tropics and subtropics, and Landsberg et al. (1963) found evidence of QBO in the surface temperature in many parts of the world. Pramanik and Jagannathan (1953) found systematic variations in the annual rainfall over certain parts of India. Koteswaram and Alvi (1969) and Bhargava and Bansal (1969) reported a QBO in the southwest monsoon/annual rainfall over some stations on the west coast of south India. Jagannathan and Bhalme (1973) showed that rainfall in India during the monsoon season (June to September) has oscillations corresponding to the sunspot cycle. Further, they have found that the QBO is significantly present in some of the parameters. Their study, however, was restricted to the monsoon season alone and that too was based on pentad rainfall. Here, we propose to examine the oscillations, if any, in the annual rainfall and to study their nature. For this purpose a network of 48 stations having long-period homogeneous rainfall data has been selected (table 1). The annual rainfall, A_0, is taken for computational convenience as equal to $\Sigma R_i/12$, where R_i is the monthly rainfall.

2. PERSISTENCE

The various alternatives to randomness have the common property of low-frequency variation, which introduces positive serial correlation at small lags. To calculate the lag-one serial correlation, we used the following formula:

$$r_1=\frac{(N-1)\sum_{i=1}^{N-1} x_i x_{i+1}-\left(\sum_{i=1}^{N-1} x_i\right)\left(\sum_{i=2}^{N} x_i\right)}{\sqrt{\left[(N-1)\sum_{i=1}^{N-1} x_i^2-\left(\sum_{i=1}^{N-1} x_i\right)^2\right]\left[(N-1)\sum_{i=2}^{N} x_i^2-\left(\sum_{i=2}^{N} x_i^2\right)^2\right]}}. \quad (1)$$

The significance of the lag-one correlation, r_1, is tested using the one-tail 95-percent significance point of the Gaussian distribution (WMO 1966). The test value $(r_1)_t$ is computed from

$$(r_1)_t=\frac{-1+t_g\sqrt{N-2}}{N-1} \quad (2)$$

where t_g is the value of the standard deviate in the Gaussian distribution corresponding to the desired level of significance. The r_1 values for all the stations are given in table 2.

Gilman et al. (1963) have given the method of finding the persistence of the first-order, linear Markov process, which is a dominant form of trend. Accordingly, the serial correlations at lag two and lag three were compared with r_1^2 and r_1^3, respectively. When r_1 was negative, it was tested against the two-tailed value and interpreted as indicative of marked high-frequency oscillations. The significant values are indicated in table 2. They show that the sample values of r_1 are positive and significantly greater than the test value (at 95 percent) at Trivandrum, Fort Cochin, Akola, Veraval, Sagar, and Shillong with the values of r_2 and r_3 equal to or greater than r_1^2 and r_1^3, respectively. This indicates Markov linear-type persistence at these stations. The r_1 is also significant at Daltonganj, Allahabad, and Darjeeling, but the values of r_2 and r_3 are less than r_1^2 and r_1^3, respectively, indicating that the persistence is not linear. At Bangalore and Darbhanga, r_1 is significantly negative, indicating the presence of high-frequency oscillations.

3. TREND

The Mann-Kendall rank statistic has been suggested as a powerful test (Kendall and Stuart 1961) when the most likely alternative to randomness is linear or nonlinear trend. The statistic τ is computed from

$$\tau=\frac{4\Sigma n_i}{N(N-1)}-1 \tag{3}$$

where n_i is the number of values larger than the ith value in the series subsequent to its position in the time series. The test statistic $(\tau)_t$ is

$$(\tau)_t=\pm t_g\sqrt{\frac{4N+10}{9N(N-1)}} \tag{4}$$

where t_g is the value of t at the probability point in the Gaussian distribution appropriate to the two-tailed test. Table 3 gives the Mann-Kendall rank statistic values significant at 95 and 99 percent. A positive value indicates that the trend is one of increasing tendency while a negative value indicates a decreasing tendency. This test has been applied to all the series irrespective of whether or not the first test indicated a trend. We found a significant increasing trend at Trivandrum, Fort Cochin, Bellary, Belgaum, Masulipatnam, Bombay, Veraval, Indore, and Leh, and significant decreasing trend at Darjeeling and Simla. The rest of the stations do not exhibit significant trends.

4. LOW-PASS FILTER

To understand the nature of this trend, we subjected the series to a "low-pass filter" (WMO 1966), thus supressing the high-frequency oscillations. The weights used were the nine ordinates of the Gaussian probability curve (0.01, 0.05, 0.12, 0.20, 0.24, 0.20, 0.12, 0.05, and 0.01). The response curve of the Gaussian low-pass filter has a response function that is equal to unity at infinite wavelengths; it then tails off asymptotically to zero with decreasing wavelength. The response is approximately

$$R(f)=\exp[-2\pi^2\sigma_g f^2] \tag{5}$$

where σ_g is the appropriate standard deviation (i.e., $6\sigma_g=$ 10 yr). The trend is not linear but oscillatory, consisting of periods of more than 10 yr in duration. A few filtered series along with the unfiltered series are shown as examples in figure 1.

TABLE 1.—*Rainfall data used in this study*

Station symbol	Name of station	Period of data	Station symbol	Name of station	Period of data
TRV*	Trivandrum	1890-1967	AHM	Ahmadabad	1869-1967
PBN	Pamban	1893-1967	SGR	Sagar	1871-1967
F.CHN	Fort Cochin	1864-1967	DTG	Daltanganj	1893-1967
KDK	Kodaikanal	1901-1967	DMK	Dumka	1883-1967
MNG	Mangalore	1864-1967	SLC	Silchar	1869-1967
BNG	Bangalore	1837-1967	KTA	Kotah	1869-1967
MDS	Madras	1813-1967	ALB	Allahabad	1845-1967
BLY	Bellary	1859-1967	SHL	Shillong	1867-1967
BLG	Belgaum	1856-1967	PTN	Patna	1868-1967
MPT	Masulipatnam	1863-1967	DBN	Darbhanga	1875-1967
HYD	Hyderabad	1893-1967	GHT	Gauhati	1849-1967
VSK	Visakhapatnam	1866-1967	JDP	Jodhpur	1897-1967
PNA	Poona	1856-1967	JSM	Jaisalmer	1883-1967
BMB	Bombay	1847-1967	JPR	Jaipur	1875-1967
JGD	Jagdalpur	1910-1967	DJG	Darjeeling	1868-1967
AKL	Akola	1870-1967	AGR	Agra	1862-1967
CTK	Cuttack	1867-1967	DBH	Dibrugarh	1902-1967
VVL	Veraval	1893-1967	BKR	Bikaner	1878-1967
NGP	Nagpur	1855-1967	DLH	New Delhi	1875-1967
SBP	Sambalpur	1867-1967	MKS	Mukteswar	1898-1967
SGR	Sagar Island	1869-1967	LDN	Ludhiana	1868-1967
DWK	Dwarka	1901-1967	SML	Simla	1862-1967
CAL	Calcutta	1829-1967	SRN	Srinagar	1893-1967
IND	Indore	1877-1967	LEH	Leh	1876-1967

*Stations as listed run from southern India to northern India in figure 2.

TABLE 2.—*Lag-one serial correlation*, r_1

Name of station	r_1	Name of station	r_1
Trivandrum	+0.208*	Ahmadabad	+0.092
Pamban	−.122	Sagar	+.264*
Fort Cochin	+.170*	Daltonganj	+.188†
Kodaikanal	−.087	Dumka	−.072
Mangalore	−.018	Silchar	+.029
Bangalore	−.231†	Kotah	+.125
Madras	+.084	Allahabad	+.303†
Bellary	+.054	Patna	+.101
Belgaum	+.110	Shillong	+.209*
Masulipatnam	+.146	Darbhanga	−.173†
Hyderabad	+.068	Gauhati	−.003
Visakhapatnam	−.018	Jodhpur	+.119
Poona	+.103	Jaisalmer	−.005
Bombay	+.008	Jaipur	−.007
Jagdalpur	+.098	Agra	−.047
Akola	+.177*	Darjeeling	+.255†
Cuttack	−.016	Dibrugarh	+.062
Veraval	+.232*	Bikaner	+.029
Nagpur	+.098	New Delhi	+.114
Sambalpur	+.100	Mukteswar	−.072
Sagar Island	+.079	Ludhiana	−.114
Dwarka	−.028	Simla	+.144
Calcutta	−.004	Srinagar	−.083
Indore	+.101	Leh	+.109

*Significant Markov linear persistence at 95 percent.
†Significant correlation coefficient at 95 percent.

5. POWER SPECTRUM ANALYSIS

Having found these oscillations in the annual rainfall, we now wish to see if there are any cycles. To do this, we conducted a power spectrum analysis of the time series of the mean annual rainfall for all stations. Tukey's (1950) procedure for computing power spectra has been followed. To achieve satisfactory resolution in the spectrum, we chose a maximum lag, m, as large as possible but not exceeding one-third of the total number of years of the record involved in the analysis. To reduce the chances of picking up a high power, we conducted the analysis sepa-

TABLE 3.—*Mann-Kendall rank statistic,* τ

Name of station	τ	Name of station	τ
Trivandrum	+0. 211*	Ahmadabad	+0. 037
Pamban	−. 034	Sagar	+. 080
Fort Cochin	+. 185*	Daltonganj	+. 051
Kodaikanal	−. 020	Dumka	−. 001
Mangalore	+. 078	Silchar	+. 081
Bangalore	+. 023	Kotah	+. 079
Madras	+. 033	Allahabad	+. 027
Bellary	+. 181*	Patna	−. 050
Belgaum	+. 232*	Shillong	+. 071
Masulipatnam	+. 143†	Darbhanga	−. 014
Hyderabad	+. 044	Gauhati	−. 022
Visakhapatnam	−. 104	Jodhpur	+. 145
Poona	+. 040	Jaisalmer	−. 048
Bombay	+. 149†	Jaipur	+. 012
Jagdalpur	−. 102	Agra	+. 127
Akola	+. 074	Darjeeling	−. 197*
Cuttack	−. 002	Dibrugrah	−. 117
Veraval	+. 304*	Bikaner	−. 010
Nagpur	+. 056	New Delhi	+. 077
Sambalpur	+. 069	Mukteswar	+. 001
Sagar Island	+. 057	Ludhiana	+. 067
Dwarka	+. 113	Simla	−. 225*
Calcutta	−. 088	Srinagar	+. 020
Indore	+. 159†	Leh	+. 204*

*Significant value at 99-percent level
†Significant value at 95-percent level

rately with five or six different maximum lags that might have arisen due to "aliasing effect" consistent with the above restrictions. The null hypothesis for this purpose was considered in accordance with whether or not the series revealed any persistence. If the persistence was of the Markov linear-type, the appropriate red noise spectrum and the associated 99-, 95-, and 90-percent limits were calculated, and the individual peaks were tested with reference to these limits. If the lag-one correlation was significantly greater in magnitude than zero but higher lag correlation did not taper off exponentially, the spectral estimates in the first half were tested with reference to the red noise spectrum and the rest against white noise. In the absence of any persistence, the spectral estimates were tested against the white noise spectrum.

Significant periods (at 99-, 95-, 90-percent levels) revealed by the spectral analysis are given in table 4. This table shows low-frequency oscillations (more than 40 yr) at Belgaum, Bombay, Akola, Veraval, Nagpur, Indore, Sagar, Dumka, Allahabad, Agra, Simla, and Leh. Cycles of nearly 11 yr are seen at Madras, Jagdalpur, Silchar, Kotah, Allahabad, Jodhpur, Darjeeling, and New Delhi. Figure 2 shows these stations and also those that have exhibited trends.

A quasi-biennial oscillation is observed at Bangalore, Madras, Bombay, Jagdalpur, Dumka, Silchar, Darbhanga, Jaipur, Agra, Bikaner, Ludhiana, and Srinagar. It is important to note that of all the stations having nearly 11-yr cycles, only Madras, Jagdalpur, and Silchar have ex-

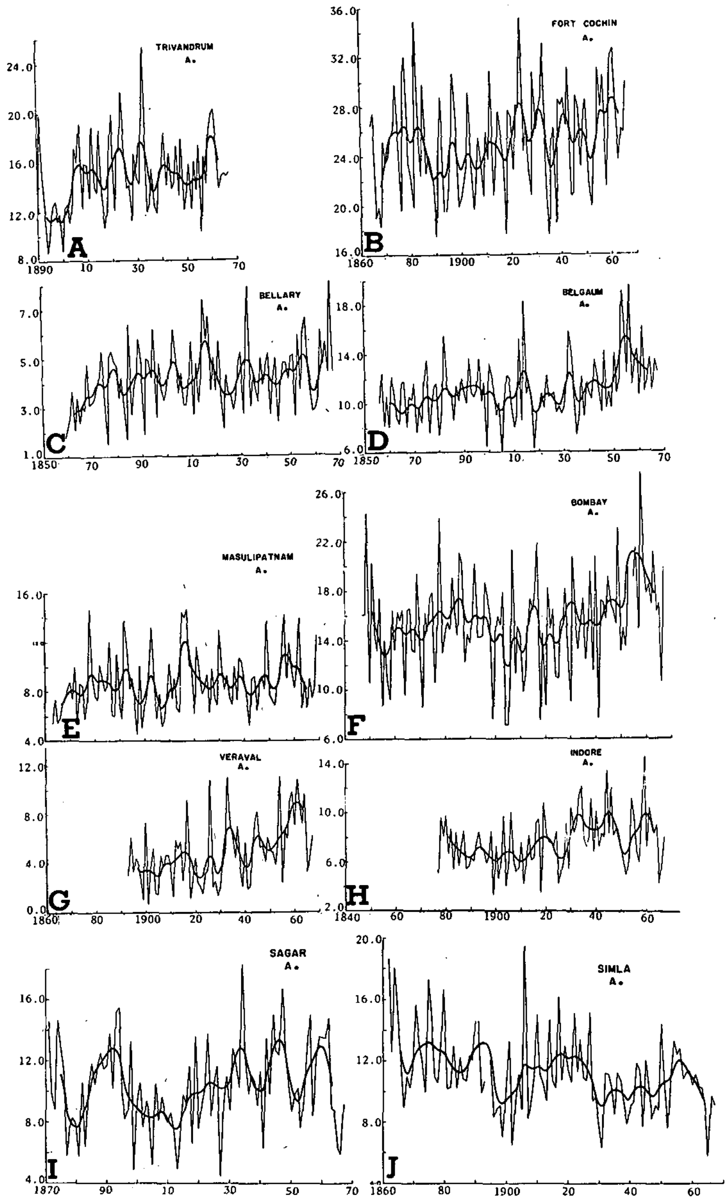

FIGURE 1.—Examples of filtered (10-yr weighted moving average, thick curve) and unfiltered (thin curve) values of rainfall showing increasing trends (A, B, C, D, E, F, G, H), decreasing trends (J), and no significant trend (I).

hibited QBO (fig. 2). QBO, it may be pointed out, is often considered as part of the solar cycle (nearly 11 yr) which in turn is intimately related to the ultraviolet emission (Shapiro and Ward 1962, Staley 1963).

6. CONCLUSION AND REMARKS

This study shows that the areas having increasing and decreasing trend in the annual rainfall are practically contiguous. However, this trend is not significant over all the stations in the area but only at a few places distributed at random. Wherever this trend is significant, it has persistence or a periodicity of more than 40 yr. QBO is exhibited at several stations in the areas of increasing and

TABLE 4.—*Power spectrum results*

Name of station	Class interval of significant periods (yr)	Name of station	Class interval of significant periods (yr)
Trivandrum	– –	Indore	∞– 88.0†
Pamban	6.7– 5.8		17.6– 12.5†
	5.8– 5.1†	Ahmadabad	18.8– 12.2
Fort Cochin	4.6– 4.1		4.8– 4.5
	3.5– 3.2	Sagar	44.0– 26.4
Kodaikanal	4.1– 3.5*		14.6– 12.0†
Mangalore	– –	Daltonganj	29.3– 12.5†
Bangalore	5.6– 5.3	Dumka	44.0– 26.4
	3.2– 3.0		2.9– 2.6*
	2.2– 2.0	Silchar	12.0– 8.8**
Madras	35.2– 25.1		2.8– 2.2**
	13.5– 11.7	Kotah	12.5– 8.0*
	2.4– 2.3**		8.0– 6.7
	2.3– 2.2	Allahabad	44.0– 26.4
Bellary	– –		26.4– 18.8*
Belgaum	∞–132.0*		12.0– 7.7†
	132.0– 44.0	Patna	4.1– 3.8
Masulipatnam	8.0– 6.7	Shillong	– –
Hyderabad	– –	Darbhanga	4.0– 3.5*
Visakhapatnam	4.0– 3.7		2.3– 2.1†
Poona	4.8– 4.2*	Gauhati	3.3– 3.0†
Bombay	∞– 44.0†	Jodhpur	12.5– 8.0†
	4.8– 4.5†	Jaisalmer	3.2– 2.8
	2.4– 2.2†	Jaipur	14.6– 12.0
Jagdalpur	12.5– 9.7		2.4– 2.2
	9.7– 8.0*	Agra	∞– 44.0
	2.5– 2.3		3.2– 2.6*
Akola	44.0– 26.4†	Darjeeling	14.6– 10.1†
	26.4– 18.8	Dibrugrah	29.3– 17.6
Cuttack	8.8– 7.7	Bikaner	14.6– 12.0
	3.7– 3.3		8.8– 7.7
Varaval	∞– 88.0		2.4– 2.3
Nagpur	132.0– 26.4	New Delhi	12.0– 10.1†
Sambalpur	10.5– 7.7		7.7– 6.9
	3.0– 2.9	Mukteswar	– –
Sagar Island	4.8– 4.5†	Ludhiana	8.8– 6.9†
	3.3– 3.0		2.9– 2.4†
Dwarka	– –	Simla	∞–132.0†
Calcutta	4.2– 4.0		132.0– 44.0
	4.0– 3.9*	Srinagar	8.0– 6.7
	3.3– 3.2		2.3– 2.1
		Leh	44.0– 26.4

*Significant at 99-percent level
†Significant at 95-percent level

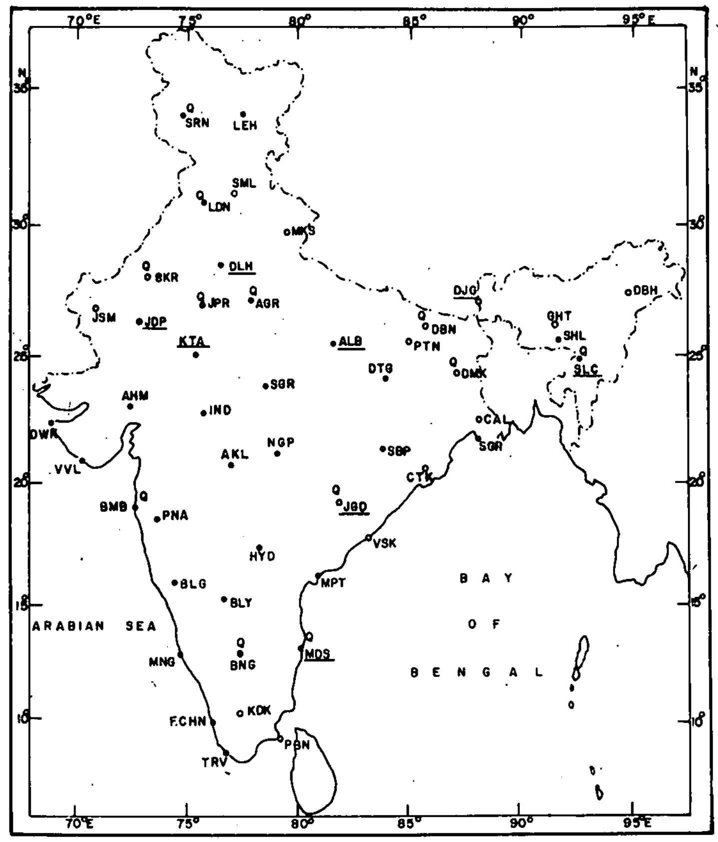

FIGURE 2.—Observing stations from which rainfall data were used. Here, (●) indicates increasing trend, (○) indicates decreasing trend, Q indicates QBO, and underscore indicates 11-yr cycle. (Note that all stations indicate either an increasing or decreasing trend; those with *significant* trends are named in section 3.)

decreasing trend. Similarly, the 11-yr cycle (solar cycle) is also exhibited in both these areas. However, both the QBO and 11-yr cycle are present at three stations only. This is an important feature that has to be seriously considered when we seek a physical explanation for the QBO in the rainfall. Presently, QBO in any meteorological parameter is generally believed to be intimately connected with the solar cycle. If the solar phenomena are responsible for the QBO, we should reasonably expect the solar cycle also at the same place. Since this association is absent at certain stations we have studied, it is rather difficult for us to visualize at present how the solar cycle and QBO are related.

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CORRECTION NOTICE

Vol. 101, No. 2, Feb. 1973, p. 140, left col: the reference to Deland, Raymond J. (**1972*b***) should read Deland, Raymond J., "Traveling Planetary-Scale Temperature Waves in the Stratosphere," *TR* No. 72–5, NSF Grant GA–25820, Geophysical Sciences Laboratory, New York University, Bronx, N.Y., Aug. **1972*b***, 63 pp.