Mausam, (1985), **36**, 4, 479-490

551.577.22 : 519.251·7

Time series analyses of annual rainfall over India

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(*Received 20 November 1981*)

सार — भारत के कई स्थानों पर स्थित 23 स्टेशनों के 100 वर्ष से भी अधिक वर्ष की उपलब्ध वर्षा श्रृंखलाएं निम्न पारक फिल्टरों की विभिन्न किस्मों द्वारा जांची गई हैं। इनका उद्देश्य इन श्रृंखलाओं की प्रवृति तथा आवृतिता नापना है। इनमें से कुछ श्रृंखलाओं द्वारा दिखाई गई अवधि प्रवृति की सूर्यकलंक संख्या द्वारा दिखाई गई एक अन्य प्रवृति से तुलना की गई। इस प्रवृति की श्रृंखला को (1940 तथा इससे आगे) उसी प्रकार के निम्न पारक फिल्टरों से उपचारित किया गया था। वर्षा श्रृंखलाओं में से आवृतिता तलाशने के लिये इन श्रृंखलाओं के बन्ड पास फिल्टर तथा पावर स्पैक्ट्रम विश्लेषण द्वारा उपचार किया गया था। ऐसा देखा गया है कि त्रिवेन्द्रम के उत्तर में पश्चिमी समुद्री तट की वर्षा ने तथा सूर्यकलंक चक्रों ने शताब्दी के आरंभ से सातवें दशक तक बढ़ते क्रम की प्रवृति दिखाई है। इसमें वेरावल, बम्बई, रत्नागिरी तथा वेंगुरला की प्रवृतियां सांख्यिकीय रूप से बहुत महत्व पूर्ण है। अध्ययन के अन्य परिणाम उपसंहार में दिए गए ह।

ABSTRACT. The available rainfall series extending to more than 100 years for 23 stations representing different parts of India have been examined with different types of low pass filters in order to find out trends and periodicities in these series. The long period trend shown by some of the series has been compared with that shown by sunspot numbers the series of which from 1940 onwards was treated with the same low pass filter. The rainfall series have also been treated with band pass filter and power spectrum analysis for finding out of periodicities in them. It is seen that rainfall of west coast stations north of Trivandrum as well as the sunspot cycles have shown an increasing trend from the beginning of the century till the sixties, the trends for Veraval, Bombay, Ratnagiri and Vengurla being statistically significant. Other results of the study have been given in the conclusion.

1. Introduction

With recurrent floods and droughts occurring over different parts of the country, the question of periodicities and trends of rainfalls, if any, over different parts of India has assumed great importance. The problem has been studied by Indian and other meteorologists for over four decades. The earlier methods (Pramanik and Jagannathan 1953, Rao and Jagannathan 1963) were fitting orthogonal polynomials upto the 5th degree and ordinary moving averages mostly of 10-year period to the rainfall series. The general conclusion was that neither the annual nor seasonal rainfall showed any significant trends. Kraus (1955) showed with the help of residual mass curves that when the annual records of Madras are broken down into seasons, it is seen that the October-December rains constituting about 60% of the stations rainfall have shown a tendency to increase in the present century. In recent years two powerful methods of detecting these parameters have been developed (*i*) the numerical filter, and (*ii*) the power spectrum analysis (WMO 1966). Bhargava and Bansal (1969) analysed power spectra of rainfall records at a few stations and found a quasi-biennial oscillation at Bombay (Colaba). The authors made a detailed analysis of rainfall records of 23 representative stations of different parts of India and preliminary results were given in two earlier publications (Koteswaram and Alvi 1969 and 1970). Bhalme (1975) has shown the fluctuations in the pattern of distribution of southwest monsoon rainfall over Rajasthan and their association with sunspot cycle. Dhar and Parthasarathy (1974) have also shown with the study of 1901-70 data of about 3000 stations in India the presence of 2.3 to 2.5 years cycle and a weak cycle of about 10 to 15 years. Raghavendra (1974) has shown increasing rainfall trend over the west coast sub-division of Maharashtra north of Latitude 15 deg. N, confirming earlier findings by Koteswaram and Alvi at individual raingauge stations along the west coast. Bhalme and Mooley (1981) recently found a 22-year cycle in the Flood Area Index (FAI) for India nearly in phase with the double (Hale) sunspot cycle.

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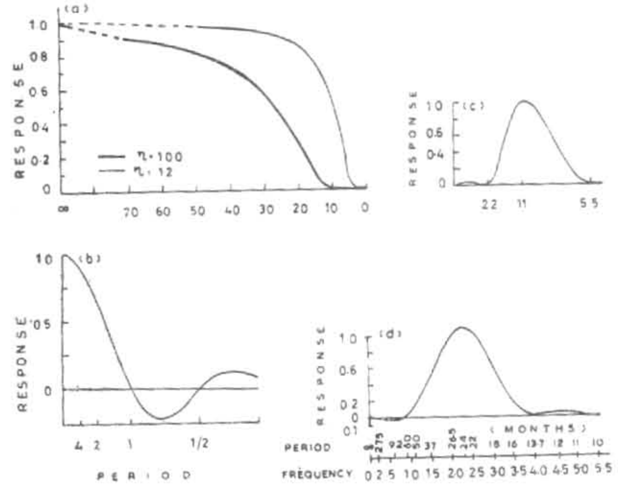


Figs. 1. (a-d)

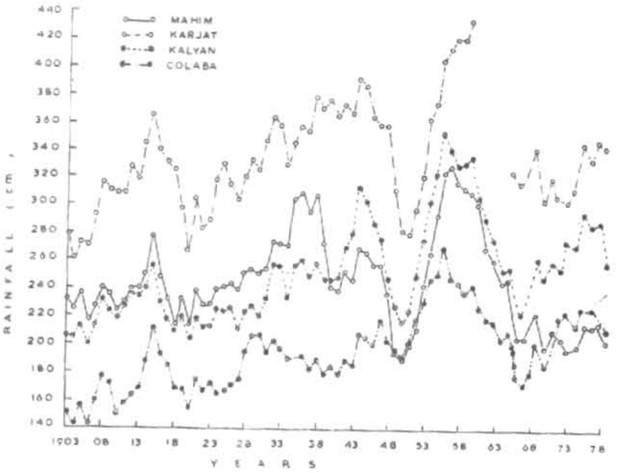


Fig. 2. Five year ordinary moving averages of annual rainfall for Bombay (Colaba) & neighbouring stations

In this paper we present detailed results for the following 23 stations representing various parts of India :

West coast — Veraval, Bombay (Colaba), Ratnagiri, Vengurla, Mangalore, Cochin, Trivandrum.

Peninsula — Nagpur, Pune, Belgaum, Hyderabad, Bangalore.

East coast — Visakhapatnam, Madras.

NE India — Calcutta, Gaya, Tezpur.

NW India — Amritsar, Delhi, Lucknow, Jodhpur, Bikaner, Ahmedabad.

Some of the results and discussions in this paper were previously published in *Idojaras* (1970), Hungary. Since the earlier paper was communicated to the 75 Anniversary Volume of *Idojaras* in response to an invitation extended to one of the authors (P. Koteswaram) by the Hungarian Meteorological Society at that time and is not readily available in Indian Libraries for reference, the authors have felt it necessary to repeat some of the material in the earlier paper for the sake of completeness of the present article.

2. Data used and analysis techniques

The rainfall records of most of these stations extend for periods exceeding 100 years. Actual durations are mentioned in individual cases. The rainfall records are quite reliable as the stations have been maintained by the India Meteorological Department since its inception in 1875 and by the Meteorological Reporters of the concerned Presidencies earlier. The statistical analysis techniques used are the following :

(*i*) 5 and 10 years moving averages,

(*ii*) Low pass filter with 9 effective weights,

(*iii*) Low pass filter with 31 effective weights,

(*iv*) Band pass filters,

(*v*) Power spectrum.

Details of these methods are well known and have been described in WMO Tech. Note No. 79 (1966) particularly with reference to their applicability for climatological analysis. The frequency response curves for low pass filters (b) and (c), moving average filter and band pass filter are given in Fig. 1.

We have not utilized the Maximum Entropy Method of power spectrum for rainfall analysis because this method generally gives a large number of signal peaks which appear at very close frequency intervals. This makes it difficult to decide as to which of the peaks is a real peak. Further, till date, there is no proper method of testing the significance of signals.

3. 5-year moving averages

We have examined rainfall series for the period 1901-1967 of 10 stations within 100 km of Bombay. Of these Bombay (Colaba) and Alibagh are India Meteorological Department stations and the rest are maintained by the State Government. The rainfall curves of Colaba, Mahim, Kalyan and Karjat are given in Fig. 2, as an example. Of these, Colaba has the lowest annual rainfall while Karjat has the highest. It is interesting to note peaks occurring at all these stations in the year 1915, 1945 and 1955 and lows in 1920 and 1947. The progressive increase in average rainfall from the beginning of the century at all these stations is unmistakable. This filter can repress periodicities of one or two years. After the peak of 1957 (sunspot maximum also) there has been a downward trend at Bombay where data upto 1980 has been examined.

4. Low pass filter with 9 effective weights

This filter eliminates periodicities of less than 3 years and suppresses those between 3 and 10 years as can be seen from the response curve (a) in Fig. 1. Annual as well as the monsoon rainfall curves of 23 representative stations although for a few stations—notably Vengurla, Belgaum only data upto 1973 could be utilised due to breakage in the records. These curves may be categorized into a number of similar groups mentioned below.

4.1. *West coast of India-north*

Veraval, Colaba (Bombay), Ratnagiri and Vengurla (all to the north of Lat. 15 deg. N) have almost similar characteristics with maxima occurring in 1885, 1915, 1930 and 1955 although so far as Veraval is concerned the 1955 maximum was delayed and occurred at 1960. A few subsidiary maxima, notably at 1948, may also be seen from the curves. A notable feature is that Vengurla is showing a maximum in 1900, a feature not shown by the other stations. The sharp peak (55-60) shown at Bombay and Veraval becomes a broad hump between 1950-1952 as we proceed south to Ratnagiri and Vengurla-Vengurla showing 3 small humps before showing the falling tendency. All the 3 stations Veraval, Bombay and Ratnagiri, are showing a minimum at 1967-68 although Bombay is the only station showing a marked increasing tendency after 1968.

The most pronounced minimum shown by Veraval, Bombay and Ratnagiri is in 1905 while what shown by Vengurla is in 1920. Other minima are in 1920, 1940, 1950 and 1968. The fall from the unprecendented peak at 1955-60 to the minimum at 1967 is remarkable at all stations. However, the minimum in 1967 is still appreciably above the worst minima of 1905 and 1920, showing that the rainfall situation during the second half of 1960s in this part of the century was not as bad as during the earlier part of the century. 10-15 year periodicity is indicated at all these stations.

Since the southwest monsoon curves closely follow the annual pattern, the above periodicity can be attributed to the southwest monsoon rainfall along the west coast north of 15 deg. N. The amplitude of fluctuation is also quite considerable. At Colaba the annual rainfall decreased from a maximum of 210 cm in 1885 to 150 cm in 1905 and rose to 250 cm in 1955. It again fell to 178 cm in 1967 before appreciably rising again.

At Ratnagiri there was a similar drop from 260 cm in 1890 to 210 cm in 1905 and a rise to 330 cm in 1955. After 1955 the rainfall has shown in downward trend and in 1967 it was only 257 cm before reversing the trend.

4.2. *West coast-south*

Mangalore, Cochin and Trivandrum are typical of the region. Data of Trivandrum before 1900 were not available. Since the region, specially Cochin and Trivandrum is affected both by the southwest monsoon and northeast monsoon, the annual and southwest monsoon curves differ appreciably during certain periods. There is a tendency for the Mangalore curve to follow the Vengurla pattern to the north.

Mangalore has peaks in 1875, 1897, 1903, 1923, 1932, 1947, 1961, 1974, while the troughs are shown in 1880,1900, 1918, 1940, 1952 and 1966. Most of the peaks and troughs are reflected at Cochin and Trivandrum also although there are significant differences. Cochin shows two peaks in 1959 and 1967 respectively against one in 1961 shown by Mangalore. In fact the 1967 Cochin peak is not shown even by Trivandrum. Trivandrum has got a maximum at 1960 followed by a fall till 1969 with slight rise near the end period. The Mangalore monsoon rainfall series follows the annual rainfall series more closely than those of Cochin and Trivandrum. This is because Mangalore receives most of its rainfall in the southwest monsoon season while the contribution of the premonsoon and post-monsoon rainfall to Cochin and Trivandrum rainfall is considerable. The 1966 minimum of the annual rainfall series of Mangalore was only 310 cm as against the maximum 405 cm in 1961 while the 1969 minimum of Trivandrum was 174 cm as against the maximum of 1961 of 215 cm. Cochin has also shown a decreasing trend after the last maximum of 1967. The amplitude of variation is, however, small compared to the annual mean.

4.3. *Peninsular India*

The annual and monsoon rainfall curves of Nagpur in Fig. 3(c), Pune, Belgaum and Bangalore in Fig. 3 (b) and Hyderabad in Fig. 3 (e) show the following peaks and troughs which are almost common :

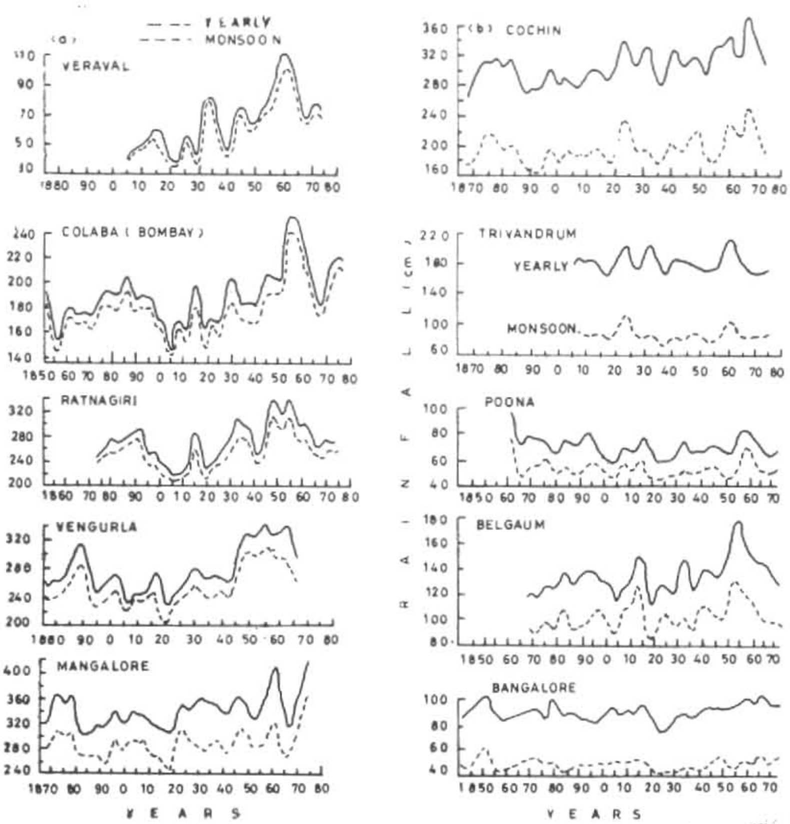
Name of the station	Maximum year	Minimum year
Nagpur	1883, 1894, 1915, 1936, 1960	1900, 1921, 1952, 1968,
Pune	1883, 1895, 1915, 1933, 1957	1904, 1923 1951, 1970
Belgaum	1882, 1893, 1913, 1932, 1954	1899, 1919, 1948, 1969
Hyderabad	1880, 1894, 1916, 1934, 1956, 1963	1899, 1922, 1952, 1967
Bangalore	1880, — 1917, 1933, 1963	1900, 1924, — 1966

In addition, there are a few other minor peaks and troughs shown by these stations which are individualistic.

From the above table it is seen that the common peaks and troughs roughly show a periodicity of 20 to 25 years except at Bangalore, the rainfall of which does not conform to the pattern of other Peninsular stations. This is understandable as Bangalore gets a considerable amount of rainfall from the northeast as well as pre-monsoon thundershowers. All the stations show an increasing trend near the end of the series except Belgaum. Since, Belgaum data were available only upto 1973 the last phase of the curve is not available. It might have shown an increasing trend. Bangalore has maintained a somewhat increasing trend since 1925.

4.4. *East coast*

Visakhapatnam and Madras rainfall along the east coast show different characteristics since the former gets most of its rainfall from the southwest monsoon and the latter from the northeast monsoon.



Figs. 3 (a & b). Rainfall series annual & monsoon treated with low pass filter (9 wts)

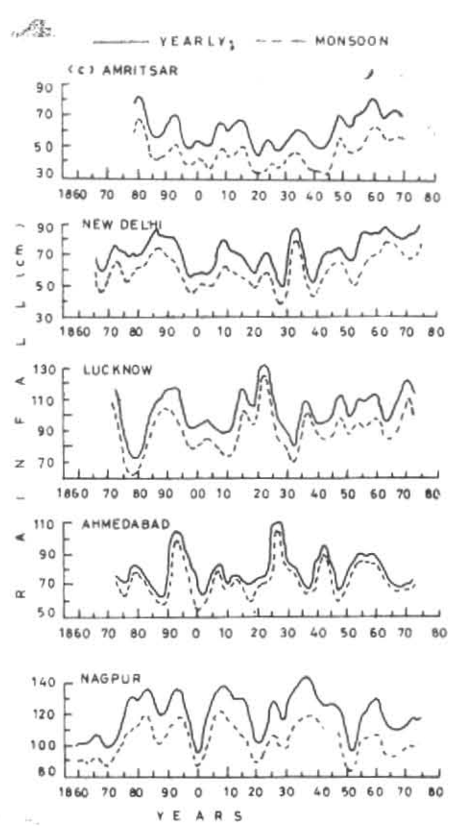


Fig. 3 (c). Rainfall series treated with low pass filter (9 wts)

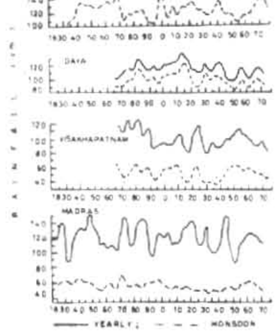


Fig. 3(d). Rainfall series treated with low pass filter (9 wts)

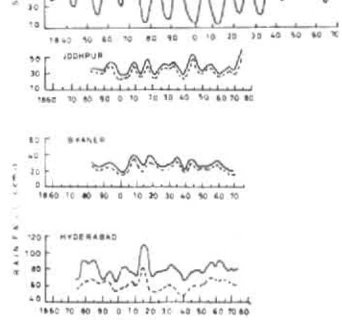


Fig. 3 (e). Rainfall series annual & monsoon treated with low pass filter (9 wts)

The maxima and minima in the annual rainfall series of these two stations are as shown below :

Station	Maxima	Minima
Visakhapatnam	1880, 1893, 1915, 1929, 1940, 1956, 1970	1891, 1900, 1922, 1935, 1945, 1967
Madras	1872, 1885, 1897, 1919, 1930, 1944, 1962	1877, 1891, 1906, 1924, 1935, 1950

The southwest monsoon rainfall curves of Visakhapatnam show more or less the same pattern as the annual rainfall curve while those for Madras are often out of phase. At times the monsoon rainfall curve does not show a maximum where the annual curve shows one.

Detailed investigations are necessary for more stations in the southwest and northeast monsoon zones along the east coast.

4.5. *Northeast India stations*

Gaya, Calcutta (Alipore) and Tezpur [Fig. 3 (d)] reveal that the annual and monsoon rainfall curves have peaks round about 1918, 1935, 1948 and 1969 and troughs in 1873, 1895, 1925, 1954 and 1963. Since the data of Tezpur was only upto 1973 the last maximum could not be shown by the station's curve. However, some notable differences are also there, *viz.,* the prominent maximum of 1880 at Tezpur is not reflected either at Gaya or Alipore. Another remarkable difference in northeast Indian rainfall is that the stations there are showing a peak round about 1918-1920, a period when the monsoon rains generally were poor in most parts of India. Further, these stations are showing a minimum round about 1955 when most of the Indian stations have been showing a maximum. Both Alipore and Gaya are showing a downward tendency near the end of the period after reaching a maximum at about 1969.

4.6. *Northwest India*

The annual rainfall curves of Amritsar, New Delhi, Lucknow, Ahmedabad [Fig. 3 (c)] and Bikaner and Jodhpur [Fig. 3 (e)] reveal the following common features :

Stations	Maxima years
Amritsar	1880, 1893, 1910, 1915, 1925, 1935, 1950, 1960, 1966
New Delhi	—, 1893, 1910, 1915, 1924, 1934, 1948, 1960, 1963
Lucknow	—, 1893, —, 1915, 1923, 1937, 1947, 1960, 1971
Bikaner	—, 1893, 1908, 1917, —, 1934, 1943, 1959
Jodhpur	—, 1893, 1908, 1916, 1925, 1933, 1943, 1956, 1966
Ahmedabad	1880, 1893, 1906, 1914, 1925, — 1043, 1958, —

Stations	Minima years
Amritsar	—, 1885, 1897, 1905, 1920, 1944, 1952, 1964
New Delhi	1880, —, 1897, 1905, 1920, 1940, 1952, 1969
Lucknow	1880, —, 1910, 1919, 1941, 1952, 1965
Bikaner	—, 1887, — 1902, 1913, 1939, 1947, 1969
Jodhpur	—, 1886, 1897, 1904, 1920, 1937, 1948, 1969
Ahmedabad	—, 1888, —, 1902, 1918, 1937, 1948, 1969

It can be seen that roughly a frequency of 10 to 15 years in shown by the above stations although the peaks and troughs of the stations often coincide with each other.

During the recent years Jodhpur and Delhi have shown an increasing trend while Lucknow, after attaining a prominent maximum in 1971 has shown a slight decrease. Amritsar and Ahmedabad have remained indifferent lately.

4.7. *Sun-spot cycle*

Fig. 3 (c) also shows the sun-spot cycle treated with the low pass filter of 9 binomial weights. It can be seen that the series shows a very regular fluctuation of 10 to 12 years the lowest minima occurring between 1877 and 1912 at 1877, 1888, 1900 and 1912 while 1958 has recorded the highest maximum.

It is seen from the above analysis that the common maxima and minima shown by rainfall stations of various regions when treated with low pass filter with 9 effective binomial weights show a periodicity of 10 to 15 years, which is close to the sun-spot cycle. Further the nature of the filter itself rules out any frequency less than 4 years to be shown by the curve. As against this the power spectrum analysis of rainfall should show all the significant frequencies (short period as well as long period). Hence a comparison has been made regarding the periodicities shown by the curves of different low pass filters and power spectrum analysis and the results are given in Table 1.

5. Low pass filter for long period trend

In order to find out long period trend which can suppress frequencies of 10 years or less, a low pass binomial filter with 100 weights had been used. It may be seen from the response curve for $n = 100$* (Fig. 1) that the response is zero for periods upto 10 years. Hence any series treated with this filter would clearly bring out any long period trends if they are present in the series.

In order to show the various types of smoothening given by the various filters, the rainall series of Colaba (Bombay) 1901-1977 was treated with (a) 10 years ordinary moving average, (b) Low pass filters $n=12$,

*Although the use of low-pass filter ($n=100$) requires 101 weights (fifty on each side of the central weight) in effect the use of 31 effective weights (15 on each side of the central weight) is sufficient because the weights beyond this area are less than one per cent of the central weight and hence their contribution is insignificant. This economizing in weights also results in a sufficiently long series after treatment with the filter without any apparent loss in the smoothening of the series.

TABLE 1

Periodicities shown by the curves of different low pass filters

Station	Low pass filter of 9 e.w.	Low pass filter of 31 e.w.	Power spectrum
West coast (North)			
Veraval	10-15 yr	50 yr	40 yr
Bombay	10-15 yr	50 yr	2.0 2.9 yr 5 yr, 40 yr
Ratnagiri	Do.	Do.	2.5-2.9 yr, 40 yr
Vengurla	Do.	Do.	2.5-2.9 yr, 6-7 yr, 40 yr
West coast (South)			
Mangalore	7-10 yr	About 25 yr	Nil
Cochin	Do.	40-45 yr	3-3.5 yr, 4-5 yr
Trivandrum	Do.	Short series	Nil
Peninsular India			
Nagpur	15-25 yr	28-32 yr	2-2.4 yr, 36 yr
Poona	8-12 yr	Not significant	—
Belgaum	7-10 yr	About 20 yr	—
Hyderabad	7-10 yr	35-40 yr	4 yr
Bangalore	6.8 yr	30-35 yr	5.6 yr
East coast			
V. Pattinam	8-12 yr	25-35 yr	2.5-2.9 yr, 4 yr
Madras	12-15 yr	25-35 yr	2 2.4 yr, 12-13 yr
Northeast India			
Calcutta	8-12 yr	30-40 yr	4 yr
Tezpur	Do.	25-30 yr	4 yr, 6-7 yr
Gaya	Do.	30-35 yr	2-2.4 yr, 3-4 yr
Northwest India			
Amritsar	10-15 yr	20-25 yr	Nil
Delhi	8-12 yr	20-25 yr	3-3.5 yr, 12-13 yr
Lucknow	10-15 yr	25-30 yr	2 2.4 yr
Bikaner	8-10 yr	Not significant	—
Jodhpur	8-10 yr	Do.	—
Ahmedabad	10-15 yr	30-35 yr	5 yr
Sun-spot	10-12 yr	30-35 yr	11 yr

and (c) Low pass filter n = 100* and the results are shown in Fig. 4. The remarkable smoothening of the rainfall curves when created with (c) as also the long period trend in the Bombay rainfall series is clearly brought out.

Figs. 5. (a & b) show the annual rainfall series of the 23 representative stations of India treated with the low pass filter with 31 effective binomial weights. The sunspot numbers series treated with the same filter is shown in the diagram 5 (a) in order to compare the trends.

5.1. *West coast of India*

Of the 7 stations on the west coast of India, 4 stations situated north of Lat. 14 deg. N show marked increase in the annual rainfall during the present century as pointed out in an earlier communication by the authors (Koteswaram and Alvi 1969). The chief features are as follows :

(*i*) *Veraval* (1901-1976) — The series is rather short as the data are available from 1901. The treated series which shows a minimum weighted average of about 45 cm round about 1923 shows considerable increase thereafter in two stages and the total increase shown is over 30 cm, *i.e.*, about 60% of the normal. The curve shows a flattening near the end indicating that it has reached its maximum.

(*ii*) *Bombay* (*Colaba*) (1847-1977) — Shows a minimum round about 1905 but later there is a continuous increase of varying degrees which becomes marked after 1940, till 1958 when it reaches a maximum before reversing the trend. The increase from 1905 till 1957 is almost 60 cm which is about 33% of the normal annual rainfall.

(*iii*) *Ratnagiri* (1869-1975) — Also shows a minimum round about 1905 and later more or less a continuous increase with 3 marked stages till 1953 after which it shows a downward trend. It is worth noting that the maximum of the curve is reached 5 years earlier than Bombay. The increase between 1923 and 1935 and 1946 onwards is remarkable and there has been an increase of over 70 cm from the lowest point in the series which also works out to almost 30% of the annual normal.

(*iv*) *Vengurla* (1871-1970) — The difference between Vengurla and Bombay-Ratnagiri is that Vengurla does not show a minimum in 1905 but shows a downward trend from the beginning of the series to about 1919 when it reaches a minimum and thereafter a much more marked increasing trend. The increase between 1919 and end of the series is nearly 70 cm, which is over 25% of the normal. As the data of Vengurla is only upto 1970 the downward trend has not been shown by the curve near its end.

(*v*) *Mangalore* (1864-1978)—Shows a wavy pattern with a minimum in the present century at about 1916. The difference between the minimum and the end of the series is only about 30 cm which is only about 10% of the normal. Mangalore also shows a downward trend near the end of the series.

(*vi*) *Cochin* (1884-1977) — Shows a minimum in the last century and although there is slight increase upto 1925 there is appreciable fall later. However, there is appreciable increasing trend near the end of

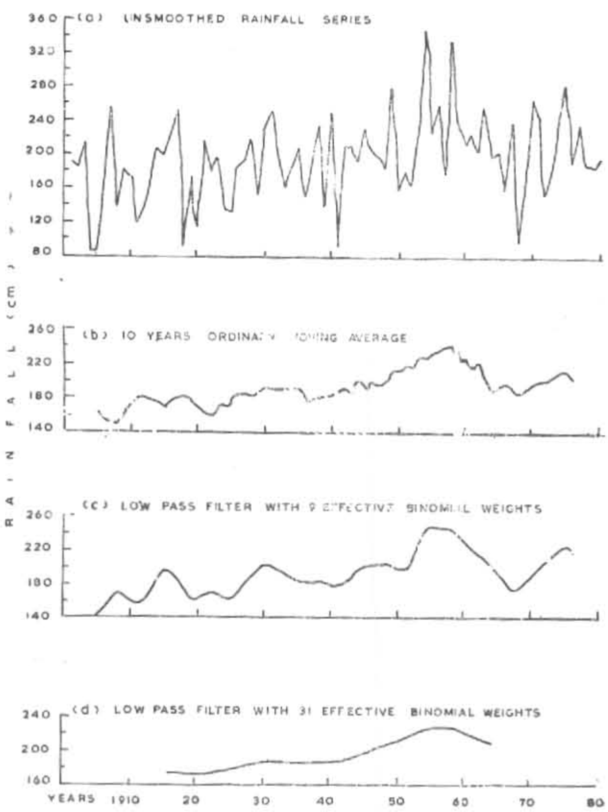


Fig. 4 Annual rainfall series of Bombay (1901-80) treated with different filters

the series the last point recording 332 cm. The increase between minimum and maximum is about 45 cm which is less than 20% of the normal.

(*vii*) *Trivandrum* (1901-1977) — The series is short, shows a decreasing trend at first then an increasing trend from 1952 onwards. There is no appreciable trend, the difference between maximum and minimum is less than 20 cm.

5.2. *Peninsular stations east of the Western Ghats*

Of the 4 stations Pune, Bangalore. Nagpur and Hyderabad [Fig. 5 (a)], Pune and Bangalore show a maximum about 1910 and a minimum about 1927. No appreciable trends are shown by these stations. Nagpur shows a marked periodicity of about 25 years but no trends. Hyderabad has a maximum about 1915 and then slightly falling trend upto 1940 and then a light rising trend.

5.3. *Western and northern India*

Of the 6 stations Ahmedabad, Jodhpur, Bikaner, Delhi, Lucknow and Amritsar [Fig. 5 (b)] — Amritsar and Delhi in northwest India show a slight rising trend after reaching a minimum at 1923. The trend near the end of the series is appreciable. Ahmedabad shows a maximum at about 1925 and then a falling trend although there is again rising trend and then a falling near the end of the series. Jodhpur shows a minimum at about 1900 and shows little variation between 1910 and the end of the series although there is a falling trend. Bikaner has a maximum at about 1915 and practically no trend later. Lucknow shows a periodicity of 25-30 years — a feature shown by Nagpur and to some extent by Ahmedabad. However, Lucknow shows a rising trend after 1940 while Nagpur shows a falling trend during the same period.

5.4. *East coast of India*

The two stations Madras and Visakhapatnam show the following features :

(*i*) In the present century Visakhapatnam shows a slight peak about 1928 while Madras shows two marked peaks in 1918 and 1943.

(*ii*) The two stations often show opposing trends, *e.g.*, Visakhapatnam has a rising trend between 1910 and 1930 and after 1942 while Madras indicates a falling trend during these periods. The two stations belong to different rainfall regimes, the former being dominated by the southwest monsoon (53 per cent of annual normal) and the latter by the northeast monsoon (60 per cent of anual normal). Near the end of the series Madras is showing increasing trend while Visakhapatnam a falling trend.

5.5. *Northeast India*

The three stations Gaya, Calcutta (Alipore) and Tezpur represented here show the following features :

(*i*) All the three stations show a maximum round about 1915 although the peak is marked only in the case of Gaya.

(*ii*) Tezpur shows a marked minimum at about 1925 there is slight rising trend with a slight fall at the end of the series.

(*iii*) Calcutta and Gaya both show an appreciable falling trend after 1940 till about 1960 when the trend is reversed. In fact Gaya shows a decrease of about 20 cm in rainfall (17% of normal) between 1917 and 1960 before reversing the trend.

6. Power spectrum analyses

The power spectrum analyses of ten representative stations are shown diagrametrically in Fig. 6. The null continuum as well as the significance levels of 90 and 95% have been shown for each diagram. The main features are given below :

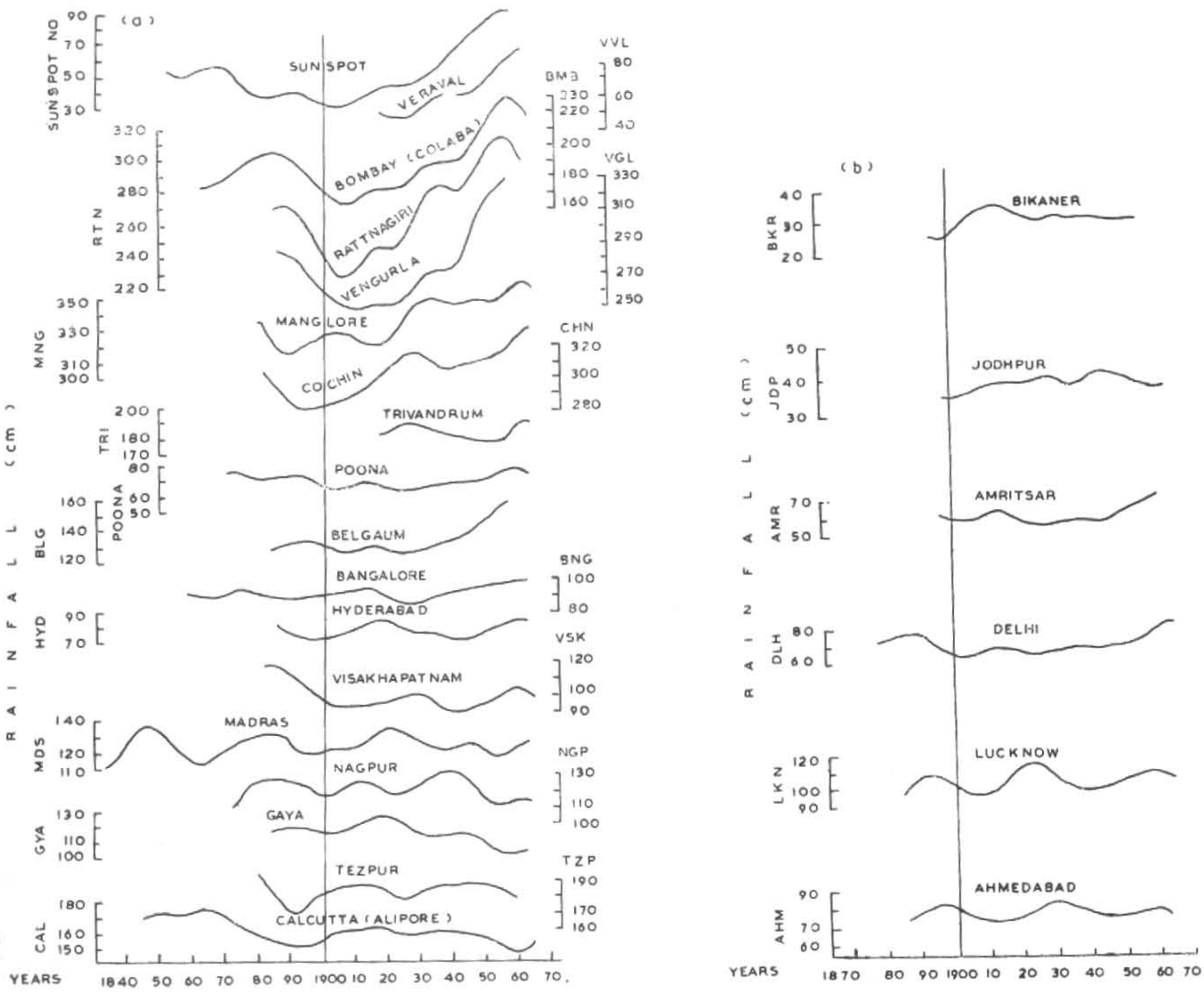
6.1. *Bombay (Colaba)*

The spectrum is that of a while noise.

(*i*) The first harmonic is significant even at 95% level and hence there is no doubt that there is a long period trend in the series ($>$ 40 years) a fact which has also been shown by low pass filter analysis.

(*ii*) The 34th and 35th spectral values representing a frequency of 2.4 and 2.3 years respectively are significant at 95% level and the 2.3 years frequency is significant even at 99% level.

(*iii*) Another frequency 4.7 years cycle is significant at 90% level. This is also a harmonic of 2.3 years frequency.



Figs. 5(a&b). Annual rainfall series treated with low pass filter with 31 binomial weights

6.2. *Vengurla*

(*i*) The spectrum is partly that of red noise. The first peak representing a frequency of > 40 years is significant at 95% level, a trend also shown by low pass filter.

(*ii*) Frequencies 4.7 and 5 years are significant at 95% level while two spectral values representing 2.8 and 2.9 years frequencies are significant at 90% level.

6.3. *Cochin*

(*i*) The spectrum is that of white noise and does not show any long period trend.

(*ii*) The most prominent frequencies significant at 95% level are 3.3 and 3.5 years respectively.

(*iii*) Two other frequencies representing 4.5 and 4.7 years are significant at 90% although they are not significant at 95% level.

6.4. *Bangalore*

Shows a spectrum which is part that of red noise.

(*i*) Does not show any long period trend.

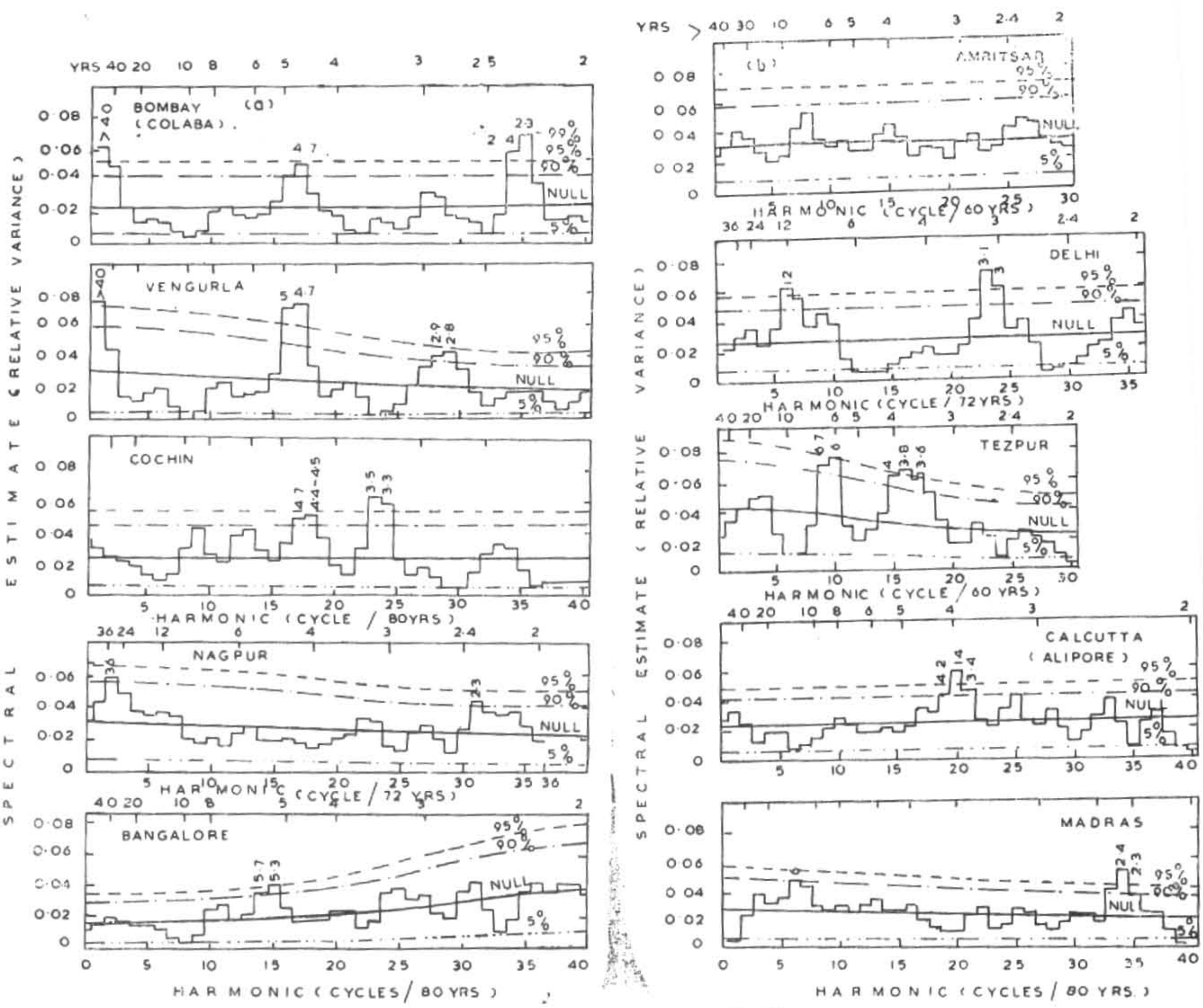
(*ii*) The only frequencies significant are 5.3 years which is significant at 95% level and 5.7 years which is not significant at 95% level but is significant at 90% level.

6.5. *Madras*

The spectrum is partly that of red noise.

(*i*) The frequencies of 2.4 years is significant at 95% level while the adjacent frequency 2.3 is significant at 90% level.

(*ii*) A frequency of 13.3 years is just significant at 90% level.



Figs. 6 (a & b)

6.6. *Nagpur*

The spectrum is slightly that of red noise.

(*i*) No frequency is significant at 95% level. However, two frequencies equivalent to 2.3 years and about 36 years are just significant at 90% level.

6.7. *Calcutta*

The spectrum is that of white noise. The only prominent frequency is that corresponding to 4 years period which is quite significant at 95% level. Its adjacent frequencies corresponding to 4.8 years and 5.3 years are also just significant at 90% level. No long period frequencies are revealed by the spectrum.

6.8. *Tezpur*

The spectrum is in part that of red noise.

(*i*) The most significant frequency are equivalent to 3.8 and 6 years which are significant at 95% level.

(*ii*) The adjacent frequencies of 3.6 and 4 years and 6.7 years are also significant at 90% level.

6.9. *Delhi*

The spectrum is that of pure white noise.

(*i*) The most prominent frequency is equivalent to 3.1 years significant at 95% level while the adjacent frequency of 3.0 years is also just significant at 95% level.

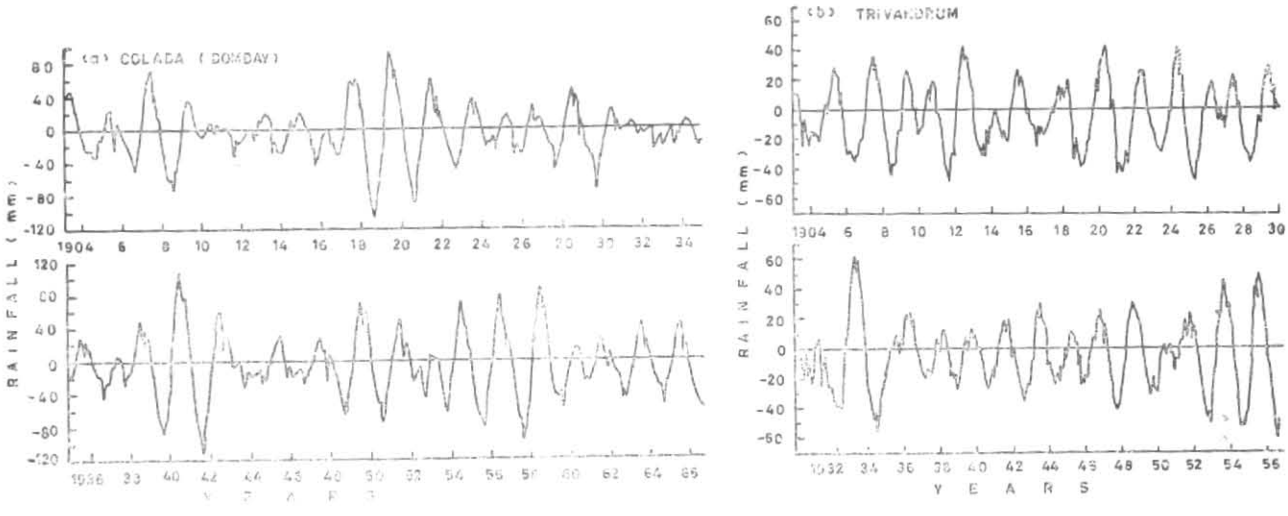
(*ii*) Another prominent frequency is equivalent to 12 years, significant at 95% level while adjacent frequency of 10.3 years is significant only at 90% level.

6.10. *Amritsar*

The spectrum is that of pure white noise. No frequency is significant even at 90% level.

7. Test of significance of trends

As can be seen that although some trends in rainfall is shown by a number of stations, the only trend which is significant according to Mann-Kendal test are those shown by west coast stations north of



Figs. 7 (a&b). Band pass filtered monthly rainfall series tuned to 24 months for period (a) 1901-1967 Colaba (Bombay) and (b) 1903-1957 Trivandrum

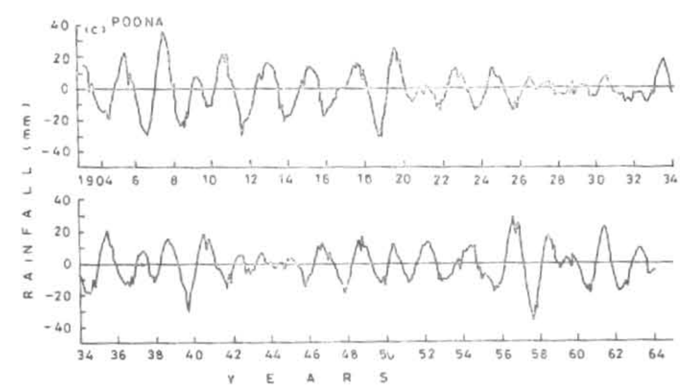


Fig. 7(c). Band pass filtered monthly rainfall series tuned to 24 months for period 1903-1964, Poona

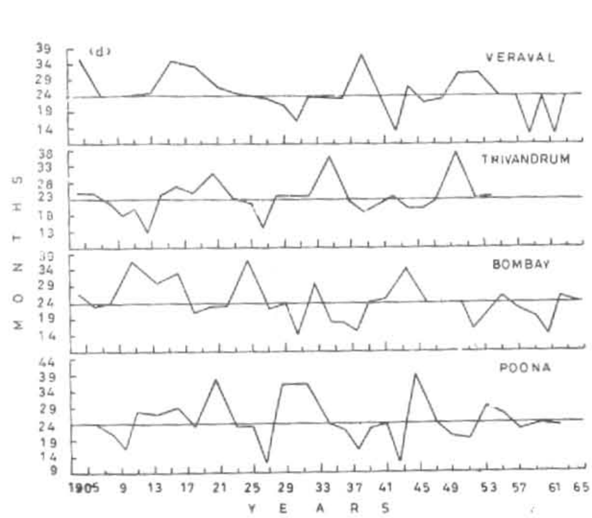


Fig. 7 (d). Period variation of biennial oscillation

TABLE 2

Period average of increase or decrease in rainfall per year and test of randomness against trend

Station	Period From	Period To	Period average (mm)	% increase or decrease per year	Rank statistics r	Rank statistics $(r)t$	Remarks regarding trend
Veraval	1901	1978	607	+1.24	+.253	+.156	Significant
Colaba	1851	1900	1821	+.17	+.030	+.183	Insignificant
(Bombay)	1901	1978	1935	+.49	+.230	+.166	Significant
Ratnagiri	1869	1900	2531	—.30	—.093	—.197	Insignificant
	1901	1975	2729	+.46	+.283	+.160	Signifiacnt
Vengurla	1871	1920	2643	—.30	—.023	—.191	Insignificant
	1921	1970	2959	+.82	+.323	+.197	Significant
Mangalote	1866	1915	3286	—.11	—.031	—.187	Insignificant
	1916	1978	3490	+.15	+.157	+.172	Do.
Cochin	1866	1905	2882	—.04	—.039	—.207	Do.
	1906	1977	3118	+.23	+.156	+.159	Do.
Trivandrum	1901	1977	1820	+.11	+.065	+.156	Do.
Poona	1901	1977	660	+.22	+.050	+.156	Do.
Belgaum	1871	1900	1287	+.47	+.234	+.225	Significant
	1901	1973	1359	+.51	+.160	+.159	Do.
Bangalore	1901	1978	914	+.21	+.104	+.156	Insignificant
Nagpur	1901	1978	1196	—.16	—.122	—.156	Do.
New Delhi	1901	1978	712	+.46	+.206	+.156	Significant

Lat. 14 deg. N except for Delhi which has also shown a significant increasing trend (Table 2). As regards Delhi, it is interesting to note that it did not show an increasing significant trend when the rainfall data for the period 1901-1967 was tested. However, when the data 1901-1978 was tested its increasing trend became significant due to the significantly more than normal rainfall which the station received during the period 1968-1978. This can be seen from the fact that the station's period average for 1901-1967 comes to 846 mm while the average for the whole period 1901-1978 amounted to only 712 mm.

7.1. *Band pass filter tuned to* 24 *months*

In the tropics quasi-biennial oscillations (QBO) have been found in stratospheric winds and temperatures and a few other parameters. In order to see whether the rainfall series of any station has got QBO the best way is to treat the monthly rainfall series with a band pass filter of suitable weights tuned to a 24 months cycle. Landsberg *et al.* (1963) first studied amplitude and phase relationships of the biennial pulse in the atmosphere by means of filtering technique suggested by Brier (1961) using a 55-term moving average with weights distributed like a Gaussain distribution which preserves around a period of 24 months amplitude, phase and period [*see* Fig. 1 (d)]. The Figure indicates the periods below 14 and above 60 months have practically zero response periods between 17.5 and 37 months are preserved with at least 50 per cent and periods between about 20-28 months are transmitted with an error of about ± 10 per cent of their amplitude. It can also be seen that this filter nearly completely eliminates the annual cycle which is the predominent cycle in the Indian rainfall series. The band pass filters of 24 months as applied to the monthly rainfall series for the period from 1901 onwards for selected stations. Colaba (Bombay) representing west coast stations north of Lat. 14 deg. N, Trivandrum representing stations south of Lat. 14 deg. N, and Pune representing in land stations east of Ghats and the resultant series are shown in Figs. 7 (a), (b) and (c). On examination of these treated series, it is seen that all the stations under consideration are having an oscillation of period about 2 years. The analysis induces a two years cycle in a random series and therefore, caution is necessary in this case also while deriving conclusions. About 1/3 of the amplitude shown in the filtered series may be due to noise. Thus the annual amplitude of the biennial pulse may be taken after reducing it by the above factor for the stations.

The main properties of the filtered series are as follows :

(a) Though the annual cycle is nearly eliminated from the series the maximum still occur mainly in the monsoon months.

(b) The amplitude of the pulse varies rather irregularly and these variations do not in every case appear simultaneously at all stations.

(c) (*i*) Periods 1910-1916, 1930-1938, 1944 1948 are the period of decreased amplitude for Bombay.

(*ii*) Periods 1930-1932 and 1936-1942 are are periods of decreased amplitude for Trivandrum.

(*iii*) Periods 1926-1932 and 1942-1946 are the periods of decreased amplitude for Pune.

It can be seen that apart from the amplitude of the biennial pulse, its period also differs often considerably from the 24 months. Fig. 7 (d) shows the period variations of the biennial oscillation at the four stations, Veraval, Trivandrum, Bombay and Pune during the present century. It can be seen that the period varies between 14 months to as long as 36 months. The following features can be seen from the figures :

(*i*) *Veraval*

During the periods 1914-1921, 1937-1940 and 1949-1955, the period of the pulse was more than 24 months. During the periods 1929-1931, 1934-1936 and 1957-1962 it was less than 24 months.

(*ii*) *Bombay*

During the periods 1909-1918, 1923-1926 and 1941-1945 the period of the pulse was more than 24 months while during the periods 1929-1932, 1934-38, 1951-1954 and 1957-1961, it was less than 24 months.

(*iii*) *Trivandrum*

During the periods 1917-1922, 1933-1936, 1948-1952 the period of the pulse was more than 24 months. During the periods 1908-1913 and 1925-28 it was less than 24 months.

(*iv*) *Pune*

During the periods 1918-1922, 1928-1932 and 1944-1947, the period of the pulse was more than 24 months, while during the periods 1907-1910, 1925-1927, 1936-1939, 1941-1943 and 1948-1952 it was less than 24 months.

8. Conclusions

(*i*) The above analyses indicate that there have been an increasing trend in rainfall of west coast stations north of Trivandrum from the beginning of the present century. The increase at Veraval, Bombay, Ratnagiri and Vengurla after 1920 onwards has been considerable (30-35%). These trends are statistically significant. The power spectrum analysis also shows that Bombay, Ratnagiri and Vengurla all have a frequency greater than 40 years quite significant at 95%. The long period trend follows the sun-spot cycle.

(*ii*) Delhi also has shown the increasing significant trend mainly due to the excess rainfall which it received during 1968-1978 period. A few other stations, Belgaum, Bangalore, Delhi, Lucknow and Amritsar show increasing trends after 1920. Although these are not statistically significant, the trend is unmistakable.

(*iii*) A frequency of 2.3 to 2.5 years is significant at many stations. For Bombay and Madras this period is quite significant at 95% level while for Nagpur it is significant only at 90% level. Many of the remaining stations which do not show this frequency (Cochin, Vengurla, Bangalore) show a significant frequency of 4.7 to 5.3 years which is a harmonic of the basic frequency 2.3 to 2.5 years. Cochin and Delhi also show a predominent frequency of 3.1 to 3.3 years. Eastern India stations of Calcutta and Tezpur show a predominent frequency round about 4 years. The quasi biennial oscillation (QBO) seems to be prevalent in the rainfall at these stations.

(*iv*) Frequencies close to the sun-spot cycle of 10-12 years are found in the rainfall series of all the stations with low pass filter analysis. These are however masked by noise and do not show up significantly in power spectra.

(*v*) There is no downward trend at stations over and near the Rajasthan desert as claimed by Winstanlay (1971). On the other hand there has been an upward trend at Jodhpur after 1970.

(*vi*) A downward trend commenced along the Konan coast after sunspot maximum of 1957 and has been continuing. A slight downward trend is noticeable at Ahmedabad, Nagpur and Gaya also.

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