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HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL OF INDIAN STATIONS

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By

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ABSTRACT

The paper presents a study of the space-time variations of Indian rainfall based on the harmonic analysis of the normal pentad rainfall data of 160 stations distributed over the country, including island stations in the Arabian Sea and the Bay of Bengal. Diagrams showing (i) amplitude, (ii) time of occurrence of maximum (phase) and (iii) percentage of variance contributed, are presented in respect of the first five harmonics and the salient features discussed. Pentad rainfall diagrams of 18 selected stations and the numerical values of their harmonic components are also included.

The annual wave has its largest amplitude at stations along the west coast of the peninsula, the amplitude rapidly decreasing to the east of the Western Ghats. The amplitude decreases from east to west across north India. At most of the stations the amplitude of the annual wave exceeds the mean annual pentad rainfall. The epoch of the minimum coincides with the driest part of the year. The annual wave reaches its maximum amplitude at Assam stations in the first week of July (pentad 38) and at the west coast stations in the last week of July (pentad 41, 42). Along the east coast the maximum of the first harmonic shifts progressively in time from pentad 41 at Calcutta to pentad 66 (last week of November) at Pamban. The second maximum of the second harmonic is generally in phase with the maximum of the first harmonic at north Indian stations. The annual wave alone is able to account for over 90% of the variance at Assam stations. The annual and semi-annual wave together account for over 80% of the variance over most parts of the country excepting parts of West Rajasthan, Saurashtra and Kutch and Madhya Maharashtra. The first five harmonics together account for over 90% of the variance at 93% of the stations.

Several stations over north and central India show a distinct rainfall minimum towards mid-August (pentad 46).

1. Introduction

1.1 The topographical features of the Indian sub-continent and its latitudinal extent from about $8^{o}N$ to $37^{o}N$ give rise to a wide range of rainfall regimes over the different parts of the country. The main rainfall season for most parts of India is the summer or southwest monsoon season from June to September which accounts for over 75% of the annual rainfall for most parts of the country. The conspicuous exception is the southeastern part of peninsular India for which the northeast monsoon months from October to December constitute the principal rainy season. The northeastern parts of India and the southern parts of the peninsula also receive rain from thunderstorms during the months March to May which is known as the hot weather season. The northern parts of India are affected by extra-tropical weather systems during the months November to May. During these months, eastward moving depressions and low pressure systems known as western disturbances give precipitation in the form of rain over the plains and sub-montane regions and as snow over the elevated terrain of the Himalayas and adjoining mountain ranges. The southern parts of the peninsula receive occasional rain during the winter months from westward moving disturbances of the low latitudes. Thus, there is no part of the year when the entire country is free from rain.

1.2 The spatial distribution of the annual rainfall of India and the rainfall of the four seasons of the year expressed as percentage of the annual are shown in Fig 1 and 2 respectively. Orography plays a large part in the spatial distribution of the rainfall. The orographic lifting of the southwest monsoon current by the Western Ghats and the hills of Assam are responsible for the heavy rainfall along the West Coast of India and over northeast India respectively. The monsoon trough that normally extends from the head of the Bay of Bengal towards northwest India and the monsoon depressions that originate in the north Bay of Bengal and traverse the country in a westnorthwesterly direction along the monsoon trough are important synoptic features that control the rainfall over the central parts of the country and over northwest India. The rainfall tends to concentrate over the southern parts of these low pressure systems with a distinct decrease towards the north. Interaction between the monsoon circulation and east-ward moving troughs in the mid-latitude westerlies also gives rise to rainfall over the northwestern parts. The southwest monsoon has 'active', 'weak' and 'break' monsoon phases with distinctive rainfall features. The northeast monsoon period from October to December is associated with tropical storms and depressions in the south Bay of Bengal which generally move in a westerly to northwesterly direction towards the Tamil Nadu - Andhra coasts causing heavy rainfall along the coastal belt and adjoining areas to the interior.

2. Advance and Retreat of the Southwest Monsoon

2.1 The mean date of onset of the southwest monsoon rains over the south Kerala coast is June 1. However, there are appreciable year to year variations in the date. During the 80-year period 1901-1980 the date of onset has fluctuated between May 11 and June 18 as can be seen from Fig. 3. This diagram shows that the frequency of dates of onset has a skew distribution with a maximum at the beginning of June.

2.2 The onset of the monsoon occurs at about the same time over the south Kerala coast and over northeast India. Because of the pre-monsoon thunderstorm activity over these areas it is often difficult to locate a sharp increase in rainfall accompanying the onset of the monsoon. The widespread and persistent nature of the rainfall and changes in the upper air circulation features are some of the characteristics associated with the monsoon onset. The monsoon rains advance towards the north along the west coast and in a northwesterly direction across central India towards the northwest. By about the second week of July the monsoon is fully established over the entire country. July and August are the months of maximum rainfall activity over the country. The retreat of the monsoon from northwest India sets in by the beginning of September. The retreat proceeds in a southeasterly direction, but it is not a reverse replica of the advance. The northeast monsoon which gives rainfall to the southeastern parts of peninsular India is, as a matter of fact, the retreating phase of the southwest monsoon. Over the extreme south of the peninsula the northeast monsoon rainfall continues till the end of December or the beginning of January.

2.3 The spatial and temporal variations of monsoon rainfall differ from year to year. Averaged over several years these features are largely smoothed out but some semi-permanent features stand out.

3. Pentad Rainfall Data

A very large volume of rainfall data is available in the climatological archieves of the India Meteorological Department on the basis of which various rainfall statistics such as normals of monthly and annual rainfall and number of rainy days have been worked out and published from time to time. Normals of daily accumulated rainfall for about 300 observatory stations have also been published (IMD, 1965). These are based on the rainfall data for the 50-year period 1901-1950. From this publication the normal pentad rainfall data for 160 selected stations shown in Fig 4 were worked out for each of the 73 pentads of the year. The present study is based on this data. For ready reference in later discussions the periods and middle dates of the 73 pentads are given in Table 1.

Table 1 : Middle dates of Pentads

Pentad	Period	Middle Date	Pentad	Period	Middle Date
1	Jan 1 - 5	Jan 3	41	Jul 20 - 24	Jul 22
2	6 - 10	8	42	25 - 29	27
3	11 - 15	13	43	Jul 30 - Aug 3	Aug 1
4	16 - 20	18	44	Aug 4 - 8	6
5	21 - 25	23	45	9 - 13	11
6	26 - 30	28	46	14 - 18	16
7	Jan 31 - Feb 4	Feb 2	47	19 - 23	21
8	Feb 5 - 9	7	48	24 - 28	26
9	10 - 14	12	49	Aug 29 - Sep 2	31
10	15 - 19	17	50	Sep 3 - 7	Sep 5
11	20 - 24	22	51	8 - 12	10
12	Feb 25 - Mar 1	27	52	13 - 17	15
13	Mar 2 - 6	Mar 4	53	18 - 22	20
14	7 - 11	9	54	23 - 27	25
15	12 - 16	14	55	Sep 28 - Oct 2	30
16	17 - 21	19	56	Oct 3 - 7	Oct 5
17	22 - 26	24	57	8 - 12	10
18	27 - 31	29	58	13 - 17	15
19	Apr 1 - 5	Apr 3	59	18 - 22	20
20	6 - 10	8	60	23 - 27	25
21	11 - 15	13	61	Oct 28 - Nov 1	30
22	16 - 20	18	62	Nov 2 - 6	Nov 4
23	21 - 25	23	63	7 - 11	9
24	26 - 30	28	64	12 - 16	14
25	May 1 - 5	May 3	65	17 - 21	19
26	6 - 10	8	66	22 - 26	24
27	11 - 15	13	67	Nov 27 - Dec 1	29
28	16 - 20	18	68	Dec 2 - 6	Dec 4
29	21 - 25	23	69	7 - 11	9
30	26 - 30	28	70	12 - 16	14
31	May 31 - Jun 4	June 2	71	17 - 21	19
32	Jun 5 - 9	7	72	22 - 26	24
33	10 - 14	12	73	27 - 31	29
34	15 - 19	17			
35	20 - 24	22			
36	25 - 29	27			
37	Jun 30 - Jul 4	Jul 2			
38	Jul 5 - 9	7			
39	10 - 14	12			
40	15 - 19	17			

4. Pentad Rainfall Patterns

4.1 The pentad and monthly rainfall patterns for the 160 stations have been briefly discussed in an earlier publication (Ananthakrishnan and Pathan, 1971). Pentad rainfall diagrams for 18 selected stations listed in Table 2 are shown in Fig 5 (a) to (f). These diagrams illustrate the large diversity of rainfall patterns across the country.

Table 2 : Coordinates and annual rainfall of selected stations.

	Station	Latitude		Longitude		Elevation	Annual Rainfall
		o	'N	o	'E	(m)	(mm)
1.	Allahabad	25	27	81	44	98	1431
2.	Bombay	18	54	72	49	11	1805
3.	Car Nicobar	09	10	92	50	10	2841
4.	Coimbatore	11	00	76	58	409	614
5.	Coonoor	11	21	76	48	1745	1540
6.	Dalhousie	32	32	75	58	1959	2291
7.	Gauhati	26	11	97	45	54	1634
8.	Gorakhpur	26	45	83	22	77	1259
9.	Indore	22	43	75	48	567	929
10.	Jabalpur	23	01	79	57	393	980
11.	Jammu	32	44	74	55	367	1116
12.	Madras	13	04	80	15	6	1286
13.	Mangalore	12	52	74	51	22	3398
14.	Nagpur	21	09	78	09	311	1242
15.	New Delhi	28	35	77	12	216	660
16.	Port Blair	11	40	92	43	79	2995
17.	Srinagar	34	05	74	50	1587	659
18.	Trivandrum	08	29	76	59	64	1812

4.2 The rainfall of Trivandrum shows two maxima associated with the southwest and northeast monsoon seasons. The contrasting features shown by the rainfall patterns of Mangalore on the west coast and Madras on the east coast, both at nearly the same latitude illustrates the effect of the orography along the west coast during the southwest monsoon season and of cyclonic storms and depressions during the north-east monsoon season along the east coast. The hill station of Dalhousie in north India has a principal rainfall maximum during the southwest monsoon and a secondary maximum in the winter season. The characteristic minimum in the rainfall curves of Allahabad, Indore, Jabalpur and Nagpur near pentad 46 (mid-August) is a noteworthy feature which is also shown by several other stations in north and central India. This feature can also be seen in the rainfall curve for Bombay. This climatological discontinuity appears to be linked with the tendency for 'break monsoon' conditions to occur with greater frequency around this epoch (Ramamurthy, 1969). The curve for Gauhati shows a gradual increase in rainfall from mid-March to the beginning of July and a gradual decrease thereafter till the end of October. Comparison of the rainfall curves of Jammu and Srinagar on the same longitude shows that the monsoon current does not penetrate into the Kashmir Valley.

5. Harmonic Analysis of Pentad Rainfall

5.1 The theory of harmonic analysis (Chapman and Bartels, 1940) shows that if y_o , y_1, y_2 .... y_σ .... y_r (where $y_o = y_r$) are equi-spaced values of any parameter $y = f(t)$ at the time epochs t_o , t_1, t_2 .... t_σ .... t_r, the data series can be exactly represented by a finite Fourier series of n harmonics

$$f(t_\sigma) = \frac{a_o}{2} + [(a_1 \cos t_1 + b_1 \sin t_1) + \ldots$$

$$\ldots + (a_n \cos nt_\sigma + b_n \sin nt_\sigma)]$$

$$= \frac{a_o}{2} + [\, C_1 \sin (t_\sigma + \varphi_1) + \ldots + C_n \sin (nt_\sigma + \varphi_n)] \qquad \ldots\ldots\ldots (1)$$

where

$$t_\sigma = \frac{2\pi}{r}\,\sigma \qquad (\sigma = 1, 2, 3, \ldots.\, r)$$

and

$n = 1/2(r-1)$ or $r/2$ depending upon whether r is odd or even.

The expressions for the Fourier coefficients are

$$a_k = \frac{2}{r} \sum_{\sigma=1}^{r} y_\sigma \cos kt_\sigma \qquad (k = 1, 2, 3, \ldots.. n)$$

$$b_k = \frac{2}{r} \sum_{\sigma=1}^{r} y_\sigma \sin kt_\sigma$$

When r is even $b_n = o$ and

$$a_n = \frac{1}{r} (- y_1 + y_2 - y_3 + \ldots.. + y_n)$$

$$C_k = (a_k{}^2 + b_k{}^2)^{1/2} = \text{amplitude of the } k^{th} \text{ harmonic}$$

$$\varphi_k = \tan^{-1} (a_k/b_k) = \text{phase of the } k^{th} \text{ harmonic}$$

$$\frac{a_o}{2} = \frac{1}{r} \sum_{\sigma=1}^{n} y_\sigma = \overline{y} = \text{arithmetic mean of the data series}$$

5.3 If m^2 is the variance of the data series $y_1, y_2 \ldots. y_r$ it follows from theory that

$$m^2 = \tfrac{1}{2} (C_1^2 + C_2^2 + \ldots. + C_n^2) \qquad \ldots\ldots. \qquad (2)$$

The harmonic components are independent of one another and the percentage of the variance accounted for by the k^{th} harmonic is

$$V_k = (\tfrac{1}{2} C_k^2 / m^2)\, 100 \qquad \ldots\ldots\ldots\ldots \quad (3)$$

5.4 In the present study, our data series for each station consists of 73 equi-spaced pentad rainfall values. The maximum number of harmonics for the exact representation of the data series is 36. However, the first few harmonics are found sufficient to account for more than 90% of the variance of the rainfall series so that they give a good representation of the annual variation of rainfall.

5.5 The harmonic analysis of the pentad rainfall data of the 160 stations was carried out on a CDC-3600 computer at the TIFR, Bombay. The programme printed out for each harmonic, the values of a, b, C and φ, the pentad of first maximum (P) evaluated from the phase angle, the percentage variance (V) accounted for by the harmonic and the cumulative percentage variance ΣV with increasing number of harmonics. The number of harmonics required to account for 90% or more of the variance for the stations are as follows :

Harmonics	No. of stations
I	6
I and II	61
I to III	108
I to IV	137
I to V	149

The six stations for which the first harmonic alone is able to account for over 90% of the variance are : Dibrugarh, Gauhati, Krishnagar, Sibsagar, Silchar and Tezpur. These are all stations in northeast India. The eleven stations which require more than 5 harmonics to account for 90% of the variance are : Anantapur, Barmer, Bhuj, Bijapur, Car Nicobar, Dwarka, Ganganagar, Jaisalmer, Kondul, Phalodi and Srinagar. Car Nicobar and Kondul are low latitude island stations in the Bay of Bengal which experience rainfall almost throughout the year with minimum in February-March. Many of the other stations belong to the arid or semi-arid areas where the monsoon rainfall is small and highly variable. Srinagar receives more rain during the non-monsoon months as can be seen from Fig 5.

6. Harmonic components

Isopleths of the amplitude (C), the phase angle (φ) and the percentage variance (V) in respect of the first five harmonics are shown in Fig. 6 to 10 (a), (b), (c). The phase angle is depicted as the pentad (P) in which the first maximum of the respective harmonics occur. If T is the period of the first harmonic ($T = 73$ pentads), then the k^{th} harmonic whose period is T/k has k maxima in the interval T. The pentads of successive maxima of the first five harmonics are :

Harmonic No.	First Maximum	Subsequent Maxima
I	P_1	-
II	P_2	$(P_2 +)$ 36.50
III	P_3	$(P_3 +)$ 24.33, 48.67
IV	P_4	$(P_4 +)$ 18.25, 36.50, 54.75
V	P_5	$(P_5 +)$ 14.60, 29.20, 43.80, 58.40

The constant term $a_o/2$ in equation (1) represents the annual rainfall averaged over the 73 pentads. The spatial distribution of this quantity is, therefore, the same as that of the annual rainfall shown in Fig. 1.

6.1 First Harmonic (annual wave) : Fig. 6 (a), (b), (c).

(a) Amplitude : The annual wave has its largest amplitude along the west coast between 10° and 18°N where the amplitudes generally exceed 50 mm and locally exceed 70 mm. There is a rapid decrease in amplitude to the east of the Western Ghats with values reaching 10 mm or less over the region stretching from Madurai-Palayamkottai in the south to Bijapur-Sholapur in the north. Further east there is a gradual increase, the amplitude reaching 20 mm towards coastal Madras.

Another area of large amplitudes is north Assam and the adjoining parts of north Bengal. The heavy rainfall stations of Cherrapunji and Mahabaleshwar are conspicuous with very large amplitudes of slightly over 200 mm at the former station and a little less than 150 mm at the latter. From coastal Orissa towards West Rajasthan and Punjab the amplitudes progressively decrease from 25 to 30 mm to 5 mm. The larger amplitudes over east Madhya Pradesh are associated with the heavy rainfall caused by monsoon lows and depressions moving west-northwestwards after crossing the Orissa coast. Over the Bay islands the amplitude is 20 to 30 mm.

(b) Phase : The annual wave attains maximum amplitude near pentad 38 over the whole of Assam. On the west coast the maximum is reached around pentad 41, that is a fortnight later. South of Trivandrum there is a rapid change due to the decreasing effect of the southwest monsoon and increasing influence of the northeast monsoon on the rainfall regime. On the east coast from Calcutta to Kanyakumari the time of maximum shifts progressively from pentad

42 to pentad 66. The change in date is gradual upto Gopalpur and rapid thereafter. Some typical dates are : Gopalpur - pentad 48, Visakhapatnam - pentad 51, Nellore and Madras - pentad 59, Nagapattinam - pentad 64, and Pamban - pentad 66. Over the Bay Islands the maximum occurs around pentad 45.

To the east of the Western Ghats over most of the Deccan Plateau south of 20°N, the annual wave has its maximum around pentad 46. South of Bangalore the influence of the northeast monsoon becomes increasingly dominant. Over most of central and northwest India, the first harmonic reaches maximum around pentad 44. The annual wave has its maximum around pentad 18 over the Kashmir valley where the monsoon current does not penetrate and the rainfall is mostly caused by western disturbances.

(c) Variance : It is interesting to note that more than 90 % of the variance of rainfall over Assam is accounted for by the first harmonic, showing that the annual wave alone is able to give a fairly good representation of the rainfall regime. Moving westwards, the percentage variance contributed by the annual wave gradually decreases and reaches 30 to 40 % over the extreme northwestern parts of the country. This is due to the increasing variability of monsoon rainfall, the shorter duration of the monsoon season and the contribution from winter precipitation. On account of these, the higher harmonics assume greater importance to account for the observed rainfall distribution.

Unlike Assam, only 60 to 70 % of the variance is accounted for by the first harmonic over most parts of peninsular India including the coastal regions. This is also the case over Bay Islands. In the extreme south, the first harmonic accounts for only about 50 % of the variance. Examination of the data for the individual stations shows that for 14 stations out of 160, the first harmonic accounts only for less than 50 % of the variance.

6.2 Second Harmonic (Semi-annual wave) : Fig 7 (a), (b), (c).

(a) Amplitude : The second harmonic has its largest amplitude of about 30 mm along the west coast between 12° and 18°N. The amplitude again decreases towards the interior of the peninsula reaching a minimum value of 3 mm around Raichur. The amplitude of 15 mm along the east coast to the south of Madras is associated with the northeast monsoon rainfall. There is a steady increase in amplitude from Raichur towards east Madhya Pradesh where it reaches 20 mm. The amplitude is small over Assam with a gradual increase followed by a decrease towards the west. A larger amplitude can be seen over the hilly tracts of west Uttar Pradesh and Himachal Pradesh. The amplitude is about 10 mm over the region of the Bay Islands.

(b) Phase : Almost over the whole of north India outside Assam, the second maximum of the second harmonic occurs near pentad 44 and thus re-inforces the maximum of the first harmonic. Such re-inforcement occurs partially over part of peninsular India including the coastal regions. Over the Bay Islands the maxima of the second harmonic are not in phase with the first harmonic.

(c) Variance : The variance contributed by the second harmonic increases from about 2 % over Assam to about 30 % over Uttar Pradesh and 40 to 50 % over Punjab, Haryana and Himachal Pradesh. There is a decrease towards the Kashmir valley. The second harmonic contributes only 5 to 10 % of the total variance over the Bay Islands. Over the south-eastern parts of the peninsula coming under the influence of the north-east monsoon the second harmonic accounts for 20 to 30 % of the variance. Along the west coast north of 10°N, it accounts for 20 to 25 % of the variance and about 5 to 10 % in the interior of the peninsula.

6.3 Third, Fourth and Fifth Harmonics :
Fig 8, 9, 10 (a), (b), (c).

(a) Amplitude : The third harmonic has an amplitude of 10 to 20 mm along the west coast and about 5 mm along the south Andhra and Madras coasts, over the central parts of the country and over the hills of west Uttar Pradesh and Himachal Pradesh. Elsewhere the amplitude is generally 2 mm or less. The fourth harmonic has an amplitude of 5 to 10 mm over the west coast, 5 mm along coastal Madras and 2 mm or less over the rest of the country. The fifth harmonic has an amplitude of 5 to 10 mm along the west coast and 1 to 2 mm elsewhere over the country.

(b) Phase : The third and fourth harmonics are not generally in phase with the maximum of the annual wave along the west coast, but they partially re-inforce the first and second harmonics along the southeast coast of the peninsula. Over north India the second maximum of the third harmonic reinforces the annual wave while the fourth and fifth harmonics partially do so.

(c) Variance : The third harmonic contributes about 7 to 10 % of the variance over the east and west coasts of peninsular India, about 5 % over the Bay Islands and 2 to 5 % over the central parts of the country. The fourth harmonic accounts for about 2 to 5 % of the variance over the coastal parts of peninsular India, and over Bay Islands. Elsewhere its contribution is generally less than 2 %. The contribution of the fifth harmonic to the variance is only about half that of the fourth harmonic.

Fig 11 shows the percentage variance of the rainfall accounted for by the first and second harmonics together. It can be seen that except over the extreme northwestern parts and Madhya Maharashtra more than 80 % of the variance is accounted for by these two harmonics.

7. Some Special Features

7.1 For most of the stations it is found that the amplitude of the first harmonic (C_1) exceeds the mean annual pentad rainfall ($a_o/2$). Hence the mean added to the minimum of the first harmonic becomes negative. The epoch of this minimum generally falls during the dry period. For 21 stations out of the total of 160, the annual mean pentad rainfall exceeds the amplitude of the first-harmonic. These are : Alleppey, Bangalore, Car Nicobar, Chitaldurga, Coimbatore, Coonoor, Dalhousie, Hassan, Jammu, Kodaikanal, Kondul, Madurai, Minicoy, Mysore, Ootacamund, Palayamkottai, Salem, Srinagar, Tiruchirapalli, Trivandrum and Vellore. For these stations the annual mean added to the minimum of the first harmonic remains positive. It may be noted that these stations lie either in the south of the peninsula or in the extreme north of the country. Apart from the monsoon rains, the southern stations come under the influence of low latitude disturbances moving from east to west and also experience premonsoon thunderstorm activity; the northern stations experience both winter and summer rains.

7.2 The second harmonic contributes more towards the variance than the first harmonic for the following four stations :

Station	V_2 / V_1
1. Coimbatore	1.56
2. Coonoor	1.30
3. Dalhousie	1.96
4. Jammu	1.26

The rainfall curves of these stations can be seen in Fig 5.

8. Harmonic Components of Selected Stations

Table 3 gives the first five harmonic components for the 18 stations whose rainfall curves are shown in Fig 5. For all stations excepting Car Nicobar and Srinagar, about 95% of the variance is accounted for by the first five harmonics. Notice that for Gauhati the first harmonic alone accounts for nearly 95% of the variance.

Table 3 : Harmonic components of selected stations

Station	H	C	P	V	ΣV	Station	H	C	P	V	ΣV
1. ALLA-	I	20.4	44.2	59.8	59.8	6. DAL-	I	24.4	42.9	27.6	27.
HABAD	II	14.3	7.7	29.4	89.2	HOUSIE	II	34.2	7.3	54.2	81.
(13.9)	III	4.9	19.3	3.5	92.7	(31.4)	III	14.6	19.5	9.9	91.7
	IV	1.3	3.4	0.3	93.0		IV	9.0	6.7	3.7	95.4
	V	3.1	9.2	1.4	94.4		V	3.3	13.6	0.5	95.9
2. BOMBAY	I	40.2	41.9	64.3	64.3	7. GAU-	I	26.5	37.2	94.5	94.5
(24.9)	II	22.0	4.1	19.2	83.5	HATI	II	3.7	0.7	1.9	96.4
	III	11.0	13.1	4.8	88.3	(22.4)	III	2.6	3.3	0.9	97.3
	IV	12.1	18.0	5.8	94.1		IV	0.8	13.4	0.1	97.4
	V	9.9	7.7	3.9	98.0		V	1.1	7.1	0.2	97.6
3. CAR	I	28.1	44.7	61.6	61.6	8. GORA-	I	25.8	43.4	70.7	70.7
NICOBAR	II	9.7	29.8	7.4	69.0	KHPUR	II	15.2	7.2	24.6	95.3
(38.9)	III	9.1	6.4	6.5	75.5	(17.2)	III	4.1	18.7	1.8	97.1
	IV	6.1	12.3	2.9	78.4		IV	1.5	1.8	0.2	97.3
	V	2.0	11.8	0.3	78.7		V	2.6	8.6	0.7	98.0
4. COIMBA-	I	5.6	56.2	27.9	27.9	9. INDORE	I	20.2	43.7	67.8	67.8
TORE	II	7.0	25.2	43.6	71.5	(12.9)	II	11.7	6.4	22.6	90.4
(8.4)	III	3.1	11.8	8.7	80.2		III	4.2	17.6	3.0	93.4
	IV	3.8	5.8	13.0	93.2		IV	1.8	0.6	0.5	93.9
	V	1.6	0.5	2.2	95.4		V	3.3	8.0	1.8	95.7
5. COONOOR	I	11.4	63.2	32.8	32.8	10. JABAL-	I	29.7	43.5	60.4	60.4
(21.1)	II	13.0	25.1	42.8	75.6	PUR	II	21.0	6.8	30.2	90.6
	III	4.9	14.8	6.1	81.7	(19.6)	III	9.2	18.1	5.8	96.4
	IV	6.3	6.5	10.1	91.8		IV	3.3	4.5	0.7	97.1
	V	2.8	3.9	2.0	93.8		V	3.2	8.7	0.7	97.8

Station	H	C	P	V	ΣV	Station	H	C	P	V	ΣV
11. JAMMU	I	15.3	42.7	34.5	34.5	15. NEW DELHI	I	11.9	44.0	56.5	56.5
(15.3)	II	17.1	7.3	43.3	77.8	(9.0)	II	9.0	7.6	32.4	88.9
	III	8.4	18.9	10.5	88.3		III	2.6	19.5	2.7	91.6
	IV	5.1	6.5	3.9	92.2		IV	1.0	2.6	0.4	92.0
	V	3.1	12.9	1.4	93.6		V	2.4	9.5	2.2	94.2
12. MADRAS	I	20.8	59.1	58.6	58.6	16. PORT BLAIR	I	37.6	44.5	77.9	77.9
(17.6)	II	11.7	26.0	18.5	77.1	(42.9)	II	10.9	32.5	6.6	84.5
	III	8.6	14.4	10.1	87.2		III	9.3	6.8	4.8	89.3
	IV	6.4	7.5	5.6	92.8		IV	11.8	13.8	7.7	97.0
	V	4.1	3.3	2.3	95.1		V	2.2	3.4	0.3	97.3
13. MANGA-LORE	I	70.1	40.5	68.7	68.7	17. SRI-NAGAR	I	4.5	18.5	49.7	49.7
	II	37.0	2.0	19.2	87.9		II	3.3	11.4	27.7	77.4
(46.6)	III	23.2	12.7	7.6	95.5	(9.2)	III	1.4	22.4	4.8	82.2
	IV	12.1	0.1	2.1	97.6		IV	1.2	4.2	3.4	85.6
	V	6.6	5.6	0.6	98.2		V	0.8	1.4	1.4	87.0
14. NAGPUR	I	24.1	42.7	66.5	66.5	18. TRIVAN-DRUM	I	17.5	42.6	43.8	43.8
(16.8)	II	14.1	5.9	22.7	89.2	(25.2)	II	14.2	29.2	29.0	72.8
	III	5.4	15.6	3.4	92.6		III	11.0	10.5	17.4	90.2
	IV	3.8	0.3	1.7	94.3		IV	1.2	17.0	0.2	90.4
	V	4.7	7.6	2.5	96.8		V	4.9	3.4	3.4	93.8

Note : The figure in brackets below the station name is the annual normal pentad rainfall in mm.

H = Harmonic   C = amplitude in mm

P = Time of first maximum in pentads

V = % variance   ΣV = cumulative % variance.

9. Discussion

Harmonic analysis enables the separation of the periodic components from the non-periodic variations in time series of geophysical data. Bryson (1957) employed the technique of harmonic analysis for the study of Australian rainfall. Horn and Bryson (1960) made a similar study of the annual march of precipitation over the United States. Lettau and White (1964) made a harmonic analysis of the space-time variations of the rainfall over India, Bangla Desh, Burma and Pakistan making use of the monthly rainfall normals of 250 stations published by the India Met. Department. These normals had been worked out on the basis of all available rainfall data upto 1940. For the present study we have made use of a more homogeneous set of rainfall normals for the fifty-year period 1901-1950. The 160 stations chosen for the study are fairly evenly distributed over the country (Fig. 4) and includes also five island stations, three in the Bay of Bengal and two in the Arabian sea. Instead of 12 monthly mean values to represent the annual rainfall, we have made use of 73 equi-spaced pentad rainfall normals which give a better representation of the temporal rainfall variation. Because of the seasonal nature of Indian rainfall, harmonic analysis can be advantageously utilised for the study of its variations in space and time.

10. Conclusions

The more important conclusions brought out by the present study are :

(i) The geographical location and orographical features of the Indian sub-continent give rise to a wide range of rainfall regimes across the country which are high-lighted by the normal pentad rainfall diagrams of individual stations.

(ii) Harmonic analysis brings out in an objective manner the salient features of the space-time variations of the annual march of rainfall.

(iii) The annual wave alone is able to account for 90% or more of the variance of the pentad rainfall for stations in Assam. The annual and semi-annual wave together account for 80 % or more of the variance over most parts of the country except over the extreme northwest and over Madhya Maharashtra.

(iv) In consonance with the high rainfall on the west coast of India, the annual wave has its largest amplitude over this region. The amplitude decreases rapidly to the east of the Western Ghats and increases again towards the east coast of the peninsula. The amplitude also decreases from east to west across north India.

(v) Barring a few stations in the extreme north and south of the country the amplitude of the annual wave exceeds the mean annual pentad rainfall at the remaining stations. The epoch of the minimum generally coincides with the driest part of the year.

(vi) The annual wave reaches its maximum amplitude over Assam about a fortnight earlier than on the West Coast of peninsular India.

(vii) While the maximum of the first harmonic falls during pentad 41 or 42 all along the west coast from Trivandrum to Veraval, the corresponding maximum along the east coast has a wide range of time variation from around pentad 41 near Calcutta in the north to pentad 65 near Pamban in the south. This highlights the distinctly different nature of the rainfall regimes along the west and east coast of India.

(viii) The second maximum of the second harmonic is generally in phase with the maximum of the first harmonic over north India and so reinforces the latter.

(ix) Several stations over north and central India show a distinct rainfall minimum around mid-August which is perhaps related to the tendency for the more frequent occurrence of 'break' monsoon conditions around this period.

(x) The first three harmonics together account for more than 90% of the variance of pentad rainfall at 70% of the stations; the first five harmonics together account for over 90% of the variance at 93% of the stations.

(xi) For four stations, two over south India (Coimbatore and Coonoor) and two in the north (Jammu and Dalhousie), the second harmonic is more dominant than the first.

(xii) Harmonic analysis of the pentad rainfall of Jammu and Srinagar on the same longitude shows that the southwest monsoon current does not penetrate into the Kashmir Valley.

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REFERENCES

Ananthakrishnan, R. and Pathan, J. M.	1971	Rainfall Patterns over India and adjacent seas : Ind. Met. Deptt. Sci. Rep. No. 144.
Bryson, R. A.	1957	Fourier Analysis of the annual march of precipitation in Australia. Tech. Rep., 5, Inst. Atmos. Phys. Univ. Arizona.
Horn L. H. and Bryson, R. A.	1960	Harmonic Analysis of the annual march of precipitation over the United States, Ann. Ass. Amer. Geogr. L, 2, pp. 157 - 171.
Chapman, S. and Bartels, J.	1940	Geomagnetism. Vol. II, pp. 545-605, Clarendon Press, Oxford.
India Met. Dept. (IMD)	1965	Normals of daily accumulated rainfall.
Lettau, K. and White, F.	1964	Fourier Analysis of India Rainfall. Ind. Jour.-Met. and Geophys., 15, pp. 27 - 38.
Ramamurthy, K.	1969	Some aspects of the 'break' in the southwest monsoon during July and August : Ind. Met. Dept. F.M.U. Rep. No. IV - 18.3.

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BHEGADE / 29.5.1981.

Legend of Diagrams

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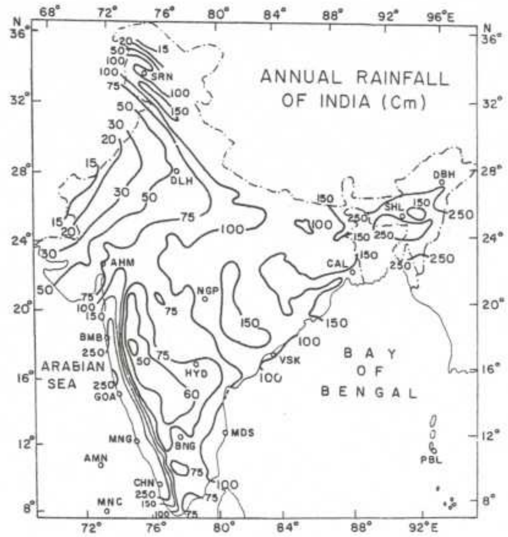

ANNUAL RAINFALL
OF INDIA (Cm)
ARABIAN
SEA
B A Y
O F
B E N G A L

FIG I

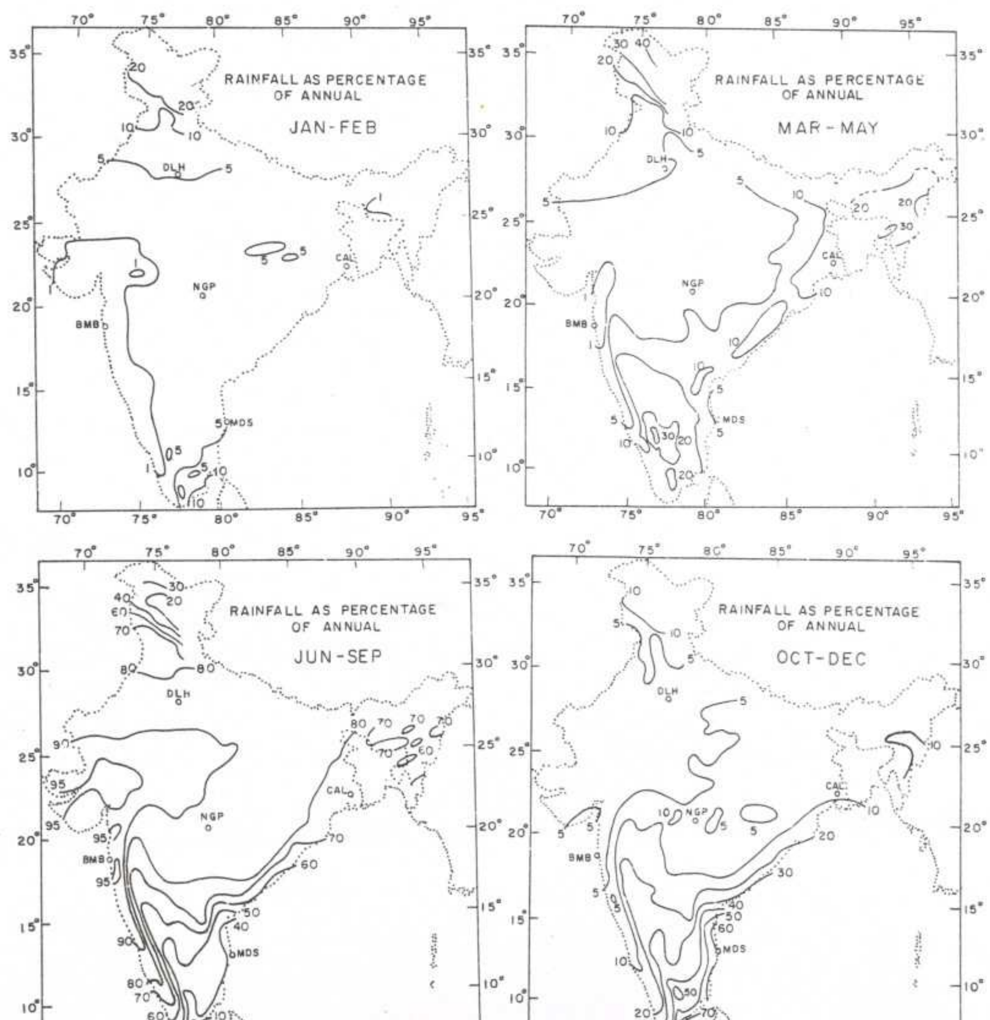

RAINFALL AS PERCENTAGE
OF ANNUAL
JAN-FEB
RAINFALL AS PERCENTAGE
OF ANNUAL
MAR-MAY
RAINFALL AS PERCENTAGE
OF ANNUAL
JUN-SEP
RAINFALL AS PERCENTAGE
OF ANNUAL
OCT-DEC

FIG 2

ONSET OF THE SW MONSOON
OVER SOUTH KERALA COAST
(1901-1980)

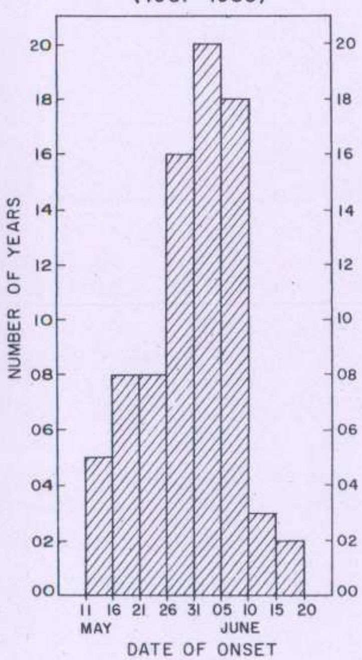


FIG 3

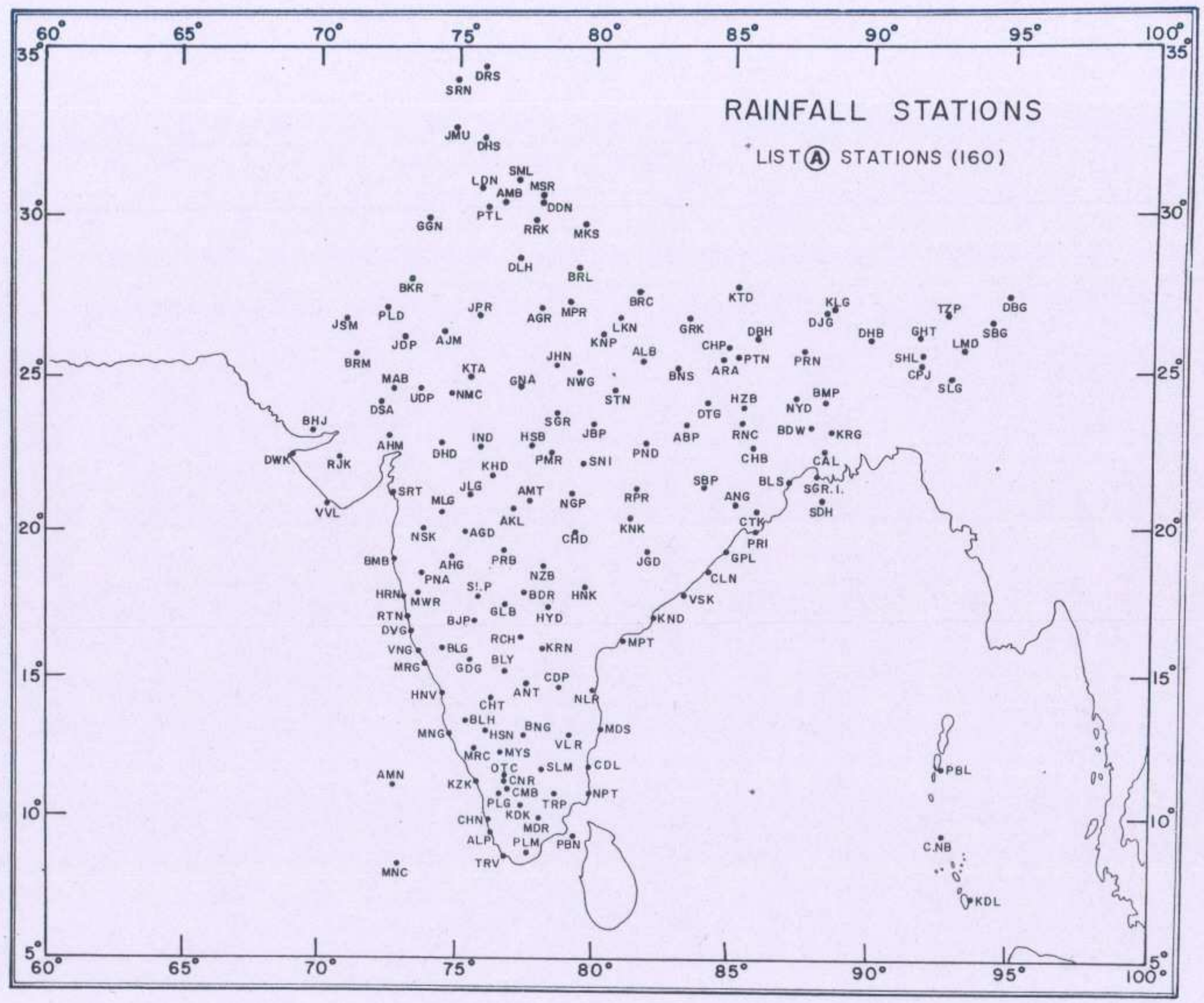


FIG 4

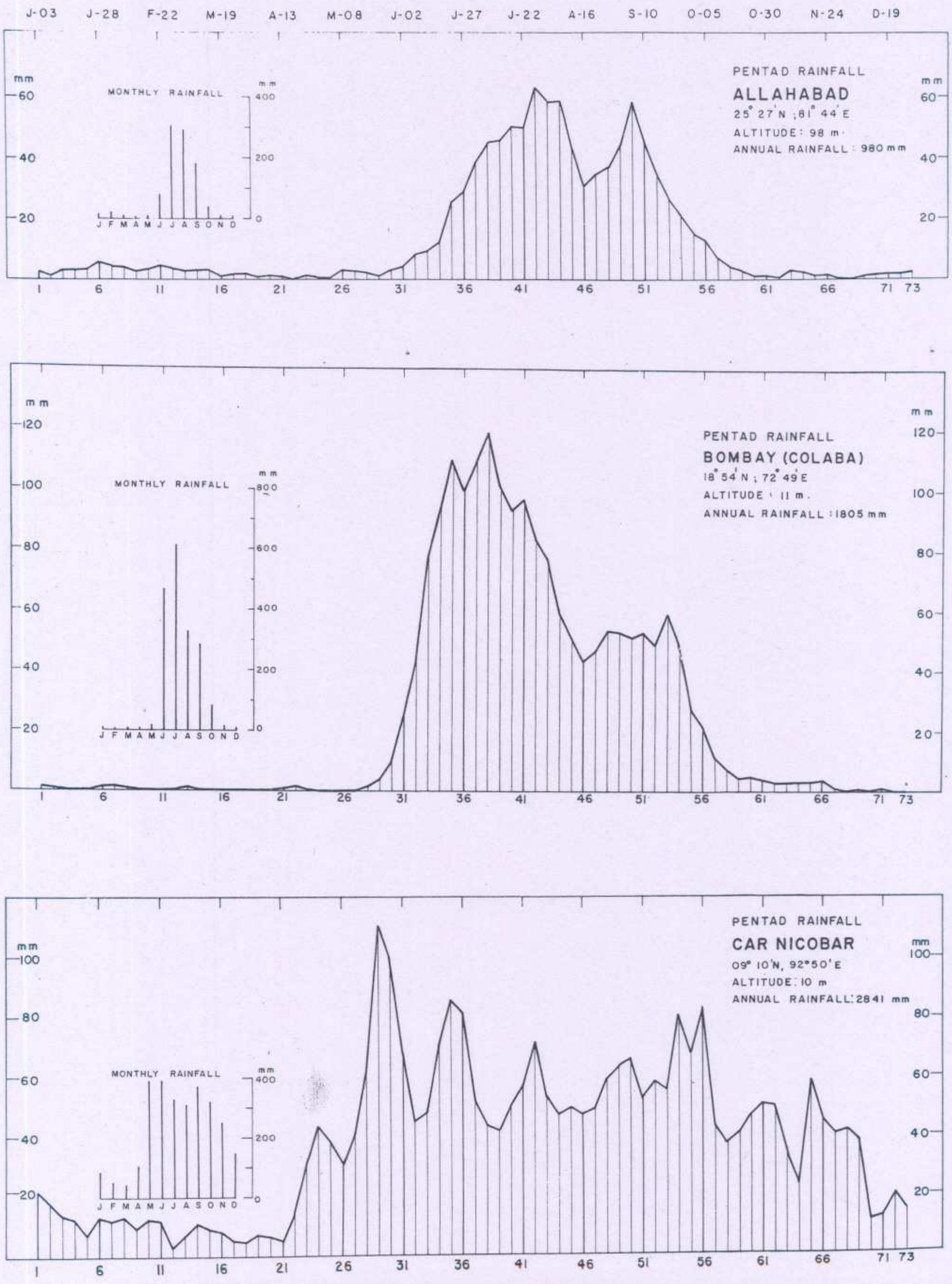

J-03 J-28 F-22 M-19 A-13 M-08 J-02 J-27 J-22 A-16 S-10 O-05 O-30 N-24 D-19
PENTAD RAINFALL
ALLAHABAD
25° 27' N ; 81° 44' E
ALTITUDE : 98 m
ANNUAL RAINFALL : 980 mm
MONTHLY RAINFALL
mm
PENTAD RAINFALL
BOMBAY (COLABA)
18° 54' N ; 72° 49' E
ALTITUDE : 11 m.
ANNUAL RAINFALL : 1805 mm
MONTHLY RAINFALL
mm
PENTAD RAINFALL
CAR NICOBAR
09° 10'N, 92°50' E
ALTITUDE: 10 m
ANNUAL RAINFALL: 2841 mm
MONTHLY RAINFALL
mm
J F M A M J J A S O N D

Fig 5a

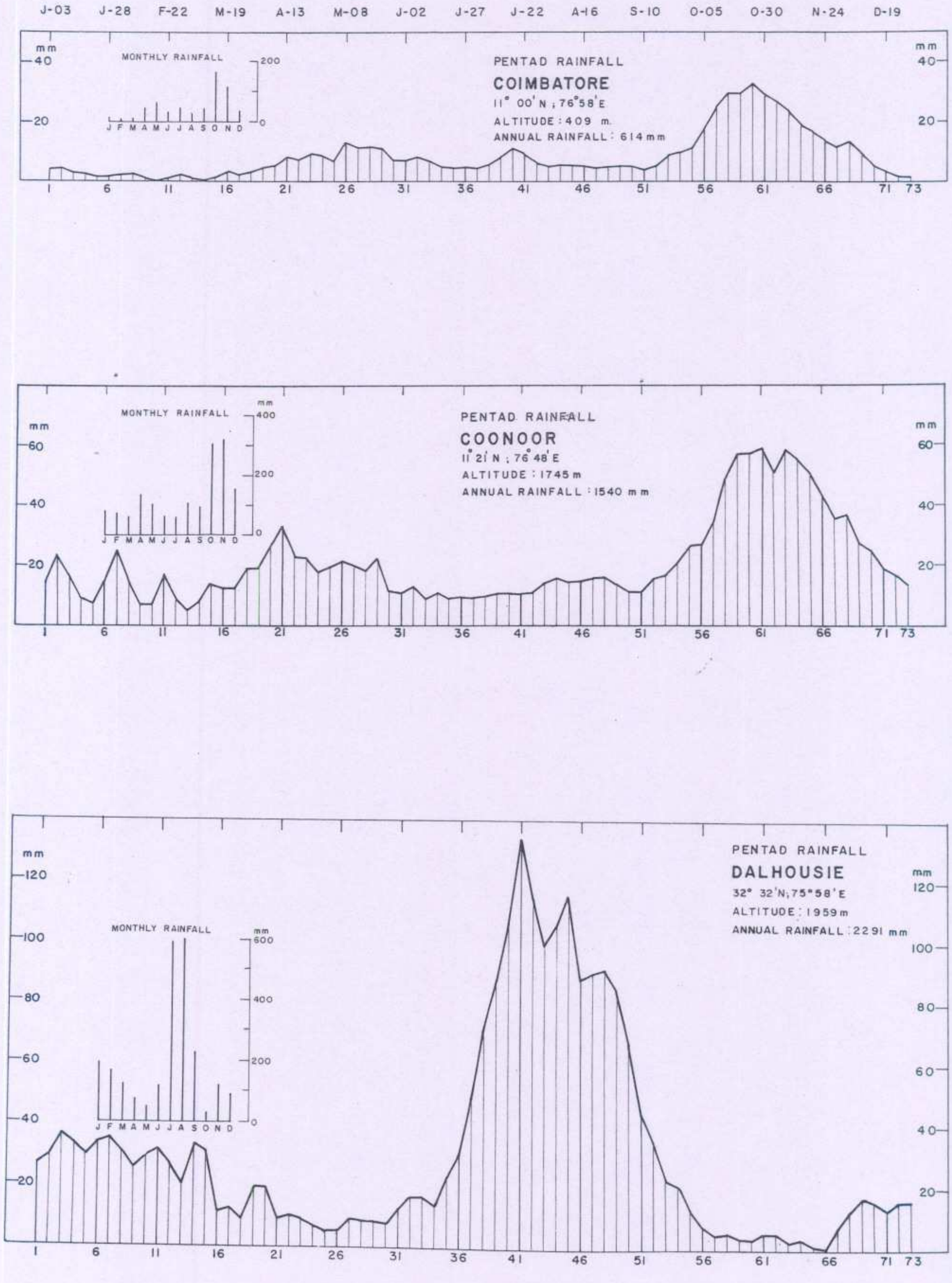
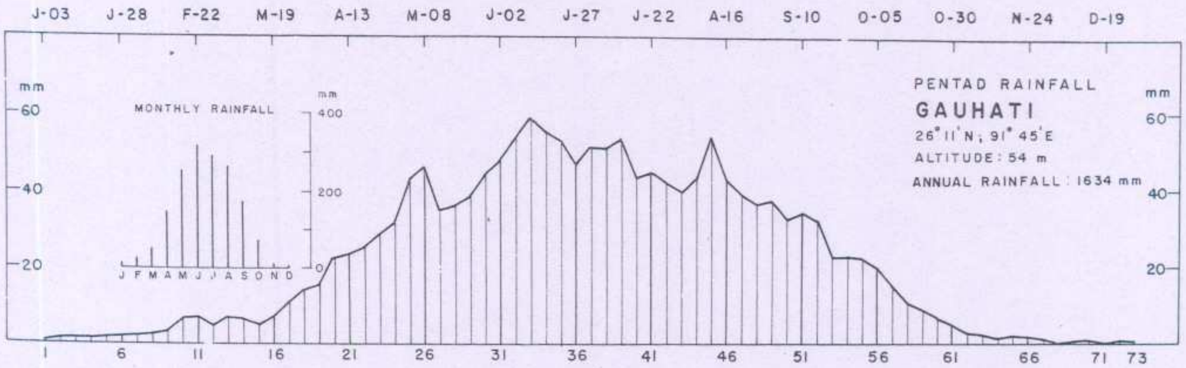
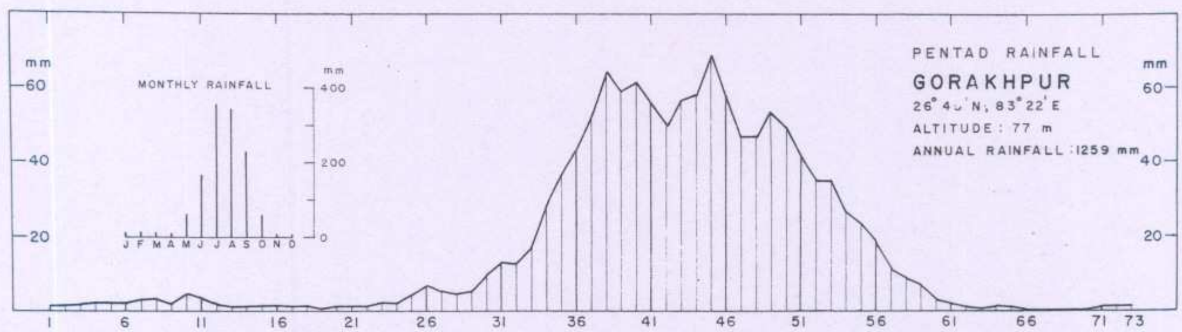

J-03 J-28 F-22 M-19 A-13 M-08 J-02 J-27 J-22 A-16 S-10 0-05 0-30 N-24 D-19
mm
MONTHLY RAINFALL
J F M A M J J A S O N D
PENTAD RAINFALL
COIMBATORE
11° 00' N ; 76°58' E
ALTITUDE : 409 m.
ANNUAL RAINFALL : 614 mm
PENTAD RAINFALL
COONOOR
11° 21' N ; 76° 48' E
ALTITUDE : 1745 m
ANNUAL RAINFALL : 1540 mm
PENTAD RAINFALL
DALHOUSIE
32° 32' N; 75° 58' E
ALTITUDE : 1959 m
ANNUAL RAINFALL : 2291 mm
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 73

FIG 5b


J-03 J-28 F-22 M-19 A-13 M-08 J-02 J-27 J-22 A-16 S-10 O-05 O-30 N-24 D-19
PENTAD RAINFALL
GAUHATI
26° 11' N; 91° 45' E
ALTITUDE: 54 m
ANNUAL RAINFALL : 1634 mm
MONTHLY RAINFALL
mm
J F M A M J J A S O N D
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 73


PENTAD RAINFALL
GORAKHPUR
ALTITUDE : 77 m
ANNUAL RAINFALL : 1259 mm
MONTHLY RAINFALL
mm
J F M A M J J A S O N D
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 73

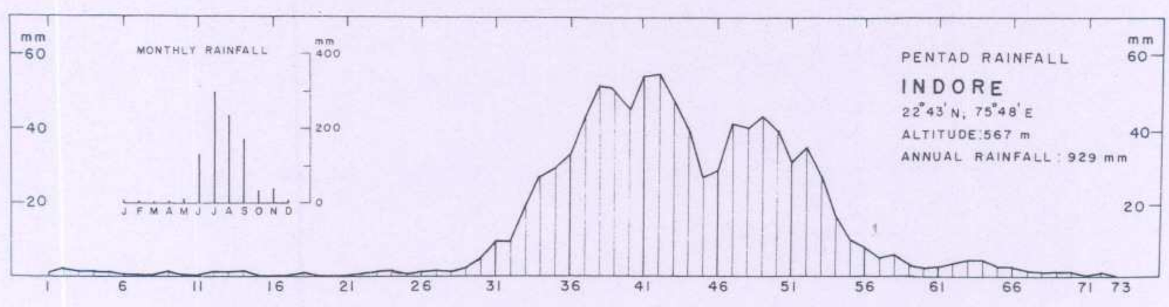

PENTAD RAINFALL
INDORE
22° 43' N; 75° 48' E
ALTITUDE: 567 m
ANNUAL RAINFALL : 929 mm
MONTHLY RAINFALL
mm
J F M A M J J A S O N D
1 6 11 16 21 26 31 36 41 46 51 56 61 66 71 73

FIG 5c

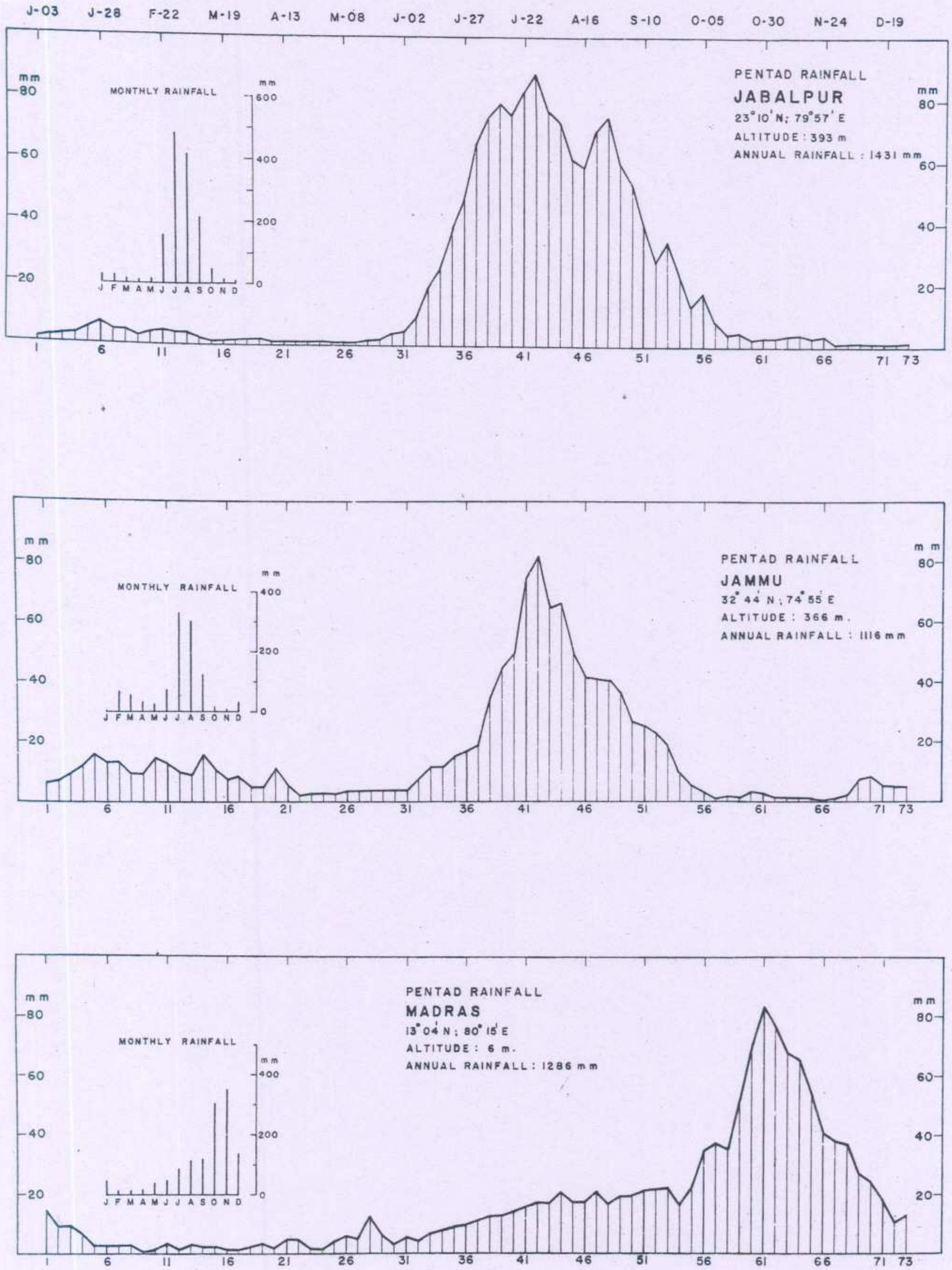

J-03 J-28 F-22 M-19 A-13 M-08 J-02 J-27 J-22 A-16 S-10 O-05 O-30 N-24 D-19
PENTAD RAINFALL
JABALPUR
23°10'N; 79°57'E
ALTITUDE: 393 m
ANNUAL RAINFALL: 1431 mm
MONTHLY RAINFALL
PENTAD RAINFALL
JAMMU
32°44'N; 74°55'E
ALTITUDE: 366 m.
ANNUAL RAINFALL: 1116 mm
MONTHLY RAINFALL
PENTAD RAINFALL
MADRAS
13°04'N; 80°15'E
ALTITUDE: 6 m.
ANNUAL RAINFALL: 1286 mm
MONTHLY RAINFALL

FIG 5d

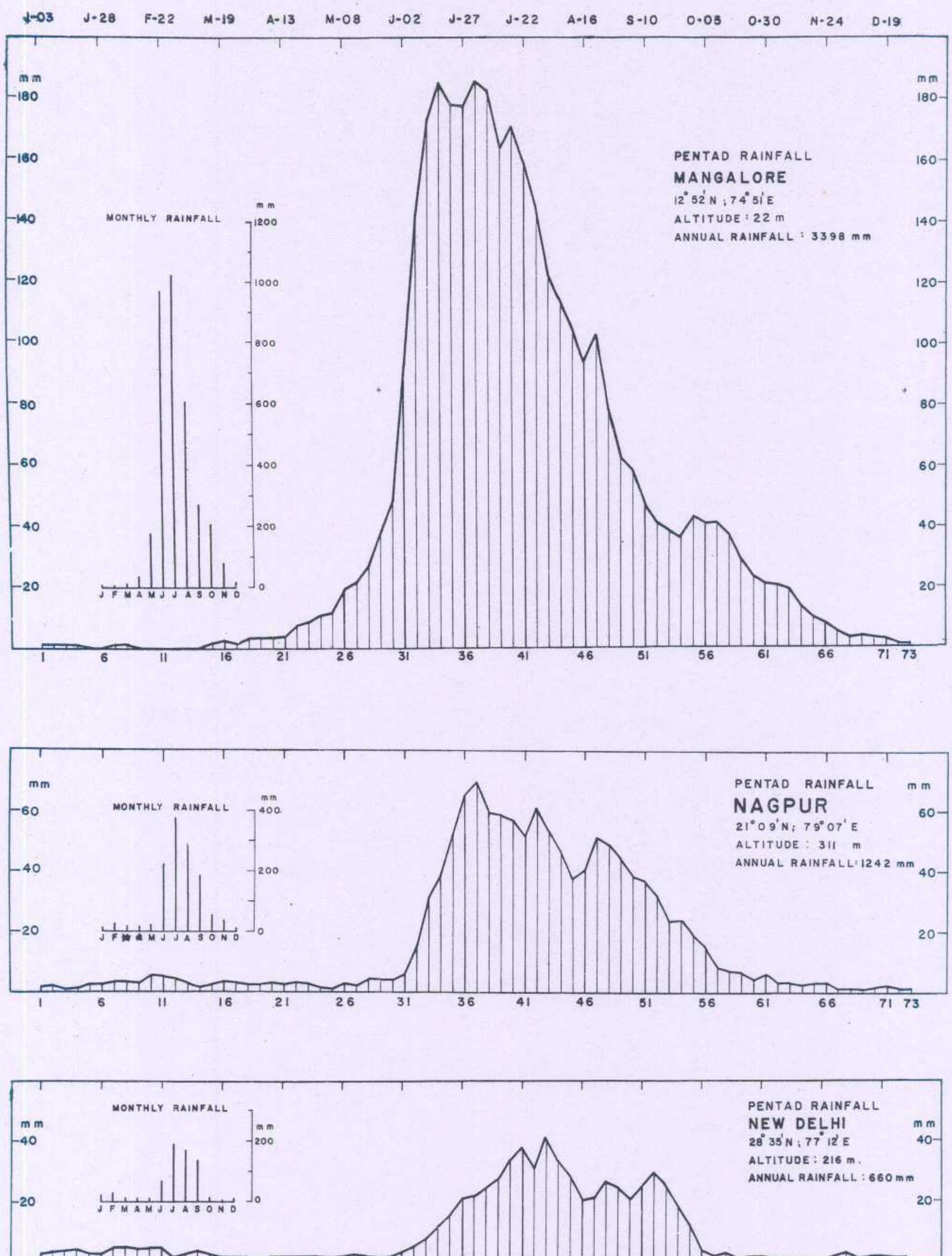

J-03 J-28 F-22 M-19 A-13 M-08 J-02 J-27 J-22 A-16 S-10 O-05 O-30 N-24 D-19
PENTAD RAINFALL
MANGALORE
12° 52' N ; 74° 51' E
ALTITUDE : 22 m
ANNUAL RAINFALL : 3398 mm
MONTHLY RAINFALL
J F M A M J J A S O N D
PENTAD RAINFALL
NAGPUR
21° 09' N ; 79° 07' E
ALTITUDE : 311 m
ANNUAL RAINFALL : 1242 mm
MONTHLY RAINFALL
PENTAD RAINFALL
NEW DELHI
28° 35' N ; 77° 12' E
ALTITUDE : 216 m.
ANNUAL RAINFALL : 660 mm
MONTHLY RAINFALL
mm

FIG 5 e

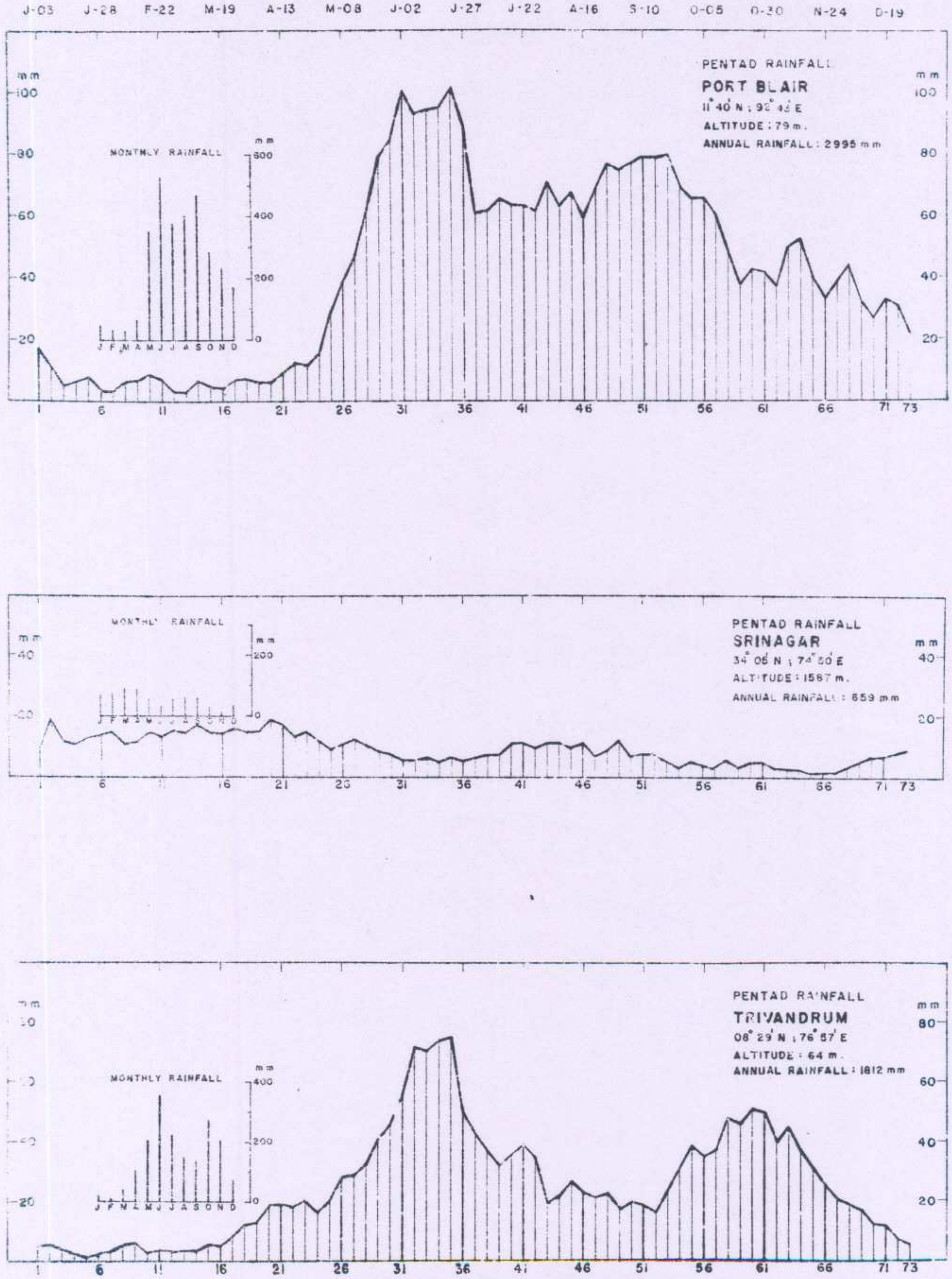

PENTAD RAINFALL
PORT BLAIR
11° 40' N ; 92° 43' E
ALTITUDE : 79 m.
ANNUAL RAINFALL : 2995 mm
MONTHLY RAINFALL
PENTAD RAINFALL
SRINAGAR
34° 05' N ; 74° 50' E
ALTITUDE : 1587 m.
ANNUAL RAINFALL : 659 mm
MONTHLY RAINFALL
PENTAD RAINFALL
TRIVANDRUM
08° 29' N ; 76° 57' E
ALTITUDE : 64 m.
ANNUAL RAINFALL : 1812 mm
MONTHLY RAINFALL

FIG 5f

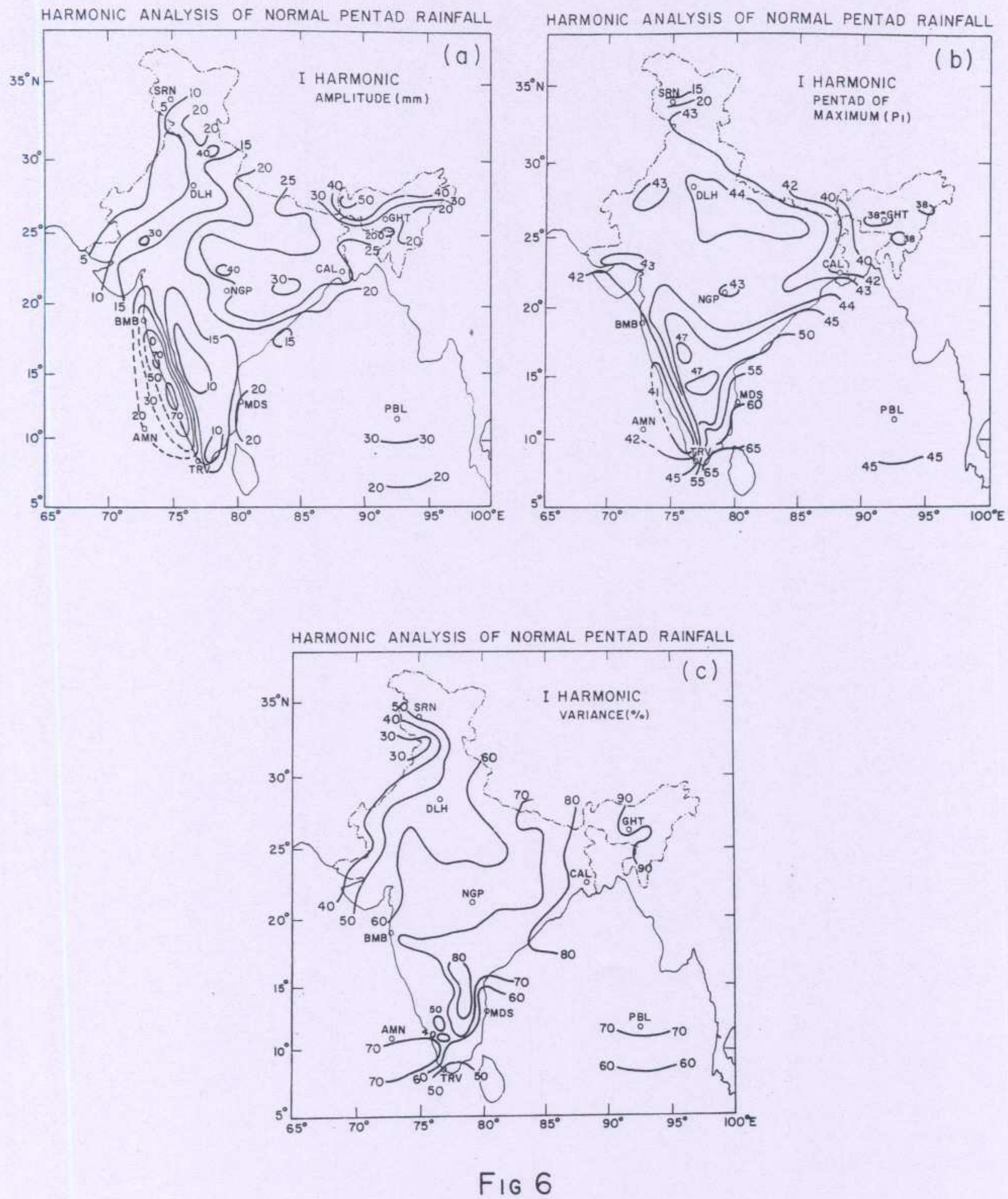

HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(a)
I HARMONIC
AMPLITUDE (mm)
SRN
DLH
NGP
CAL
GHT
BMB
MDS
AMN
TRV
PBL
HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(b)
I HARMONIC
PENTAD OF
MAXIMUM (P1)
SRN
DLH
NGP
CAL
GHT
BMB
MDS
AMN
TRV
PBL
HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(c)
I HARMONIC
VARIANCE (%)
SRN
DLH
NGP
CAL
GHT
BMB
MDS
AMN
TRV
PBL
35°N
30°
25°
20°
15°
10°
5°
65°
70°
75°
80°
85°
90°
95°
100°E

FIG 6

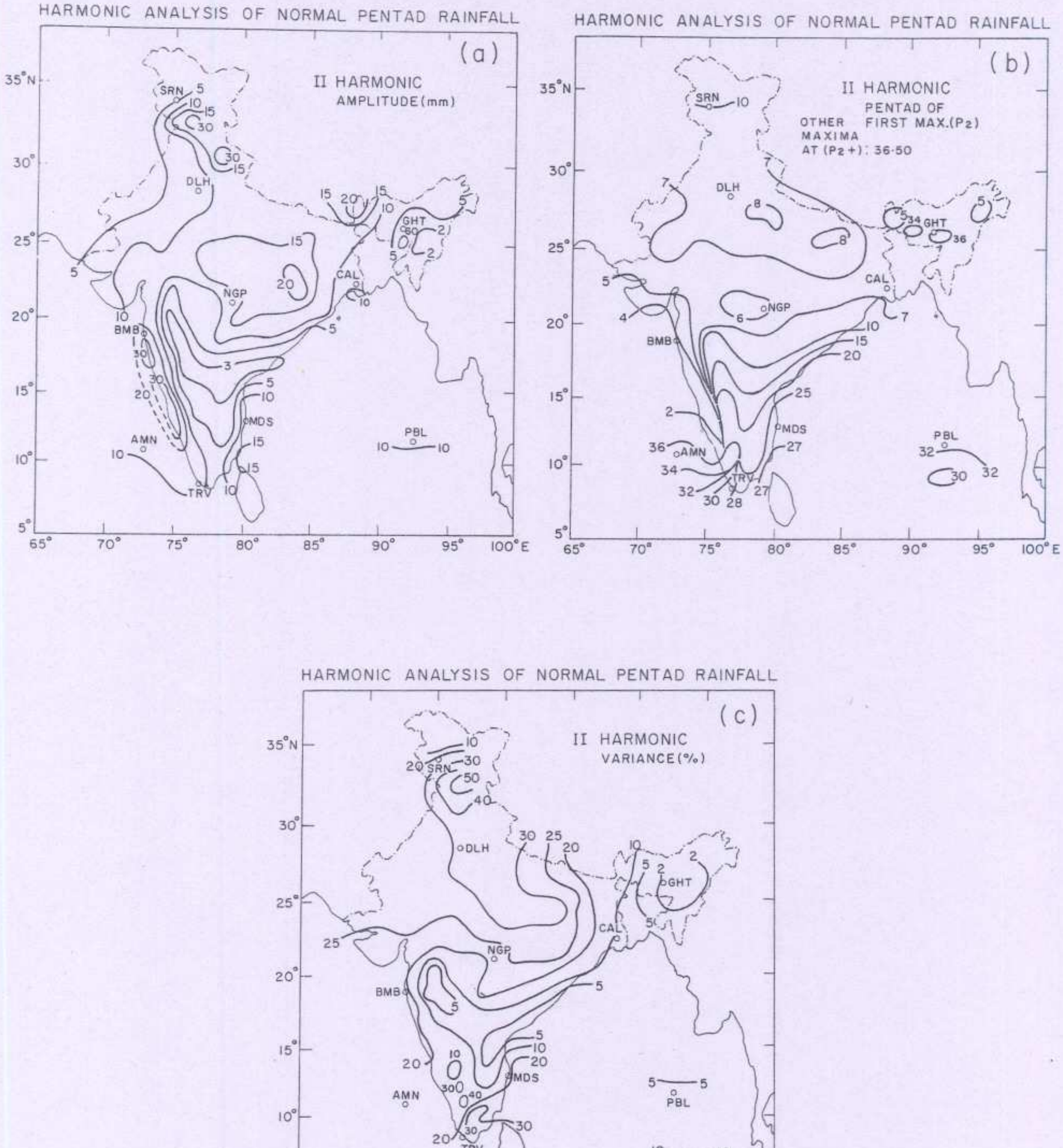

HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(a)
II HARMONIC
AMPLITUDE (mm)
SRN
DLH
GHT
CAL
NGP
BMB
MDS
AMN
TRV
PBL
HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(b)
II HARMONIC
PENTAD OF FIRST MAX.(P2)
OTHER MAXIMA AT (P2+): 36-50
SRN
DLH
GHT
CAL
NGP
BMB
MDS
AMN
TRV
PBL
HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(c)
II HARMONIC
VARIANCE (%)
SRN
DLH
GHT
CAL
NGP
BMB
MDS
AMN
TRV
PBL

FIG 7

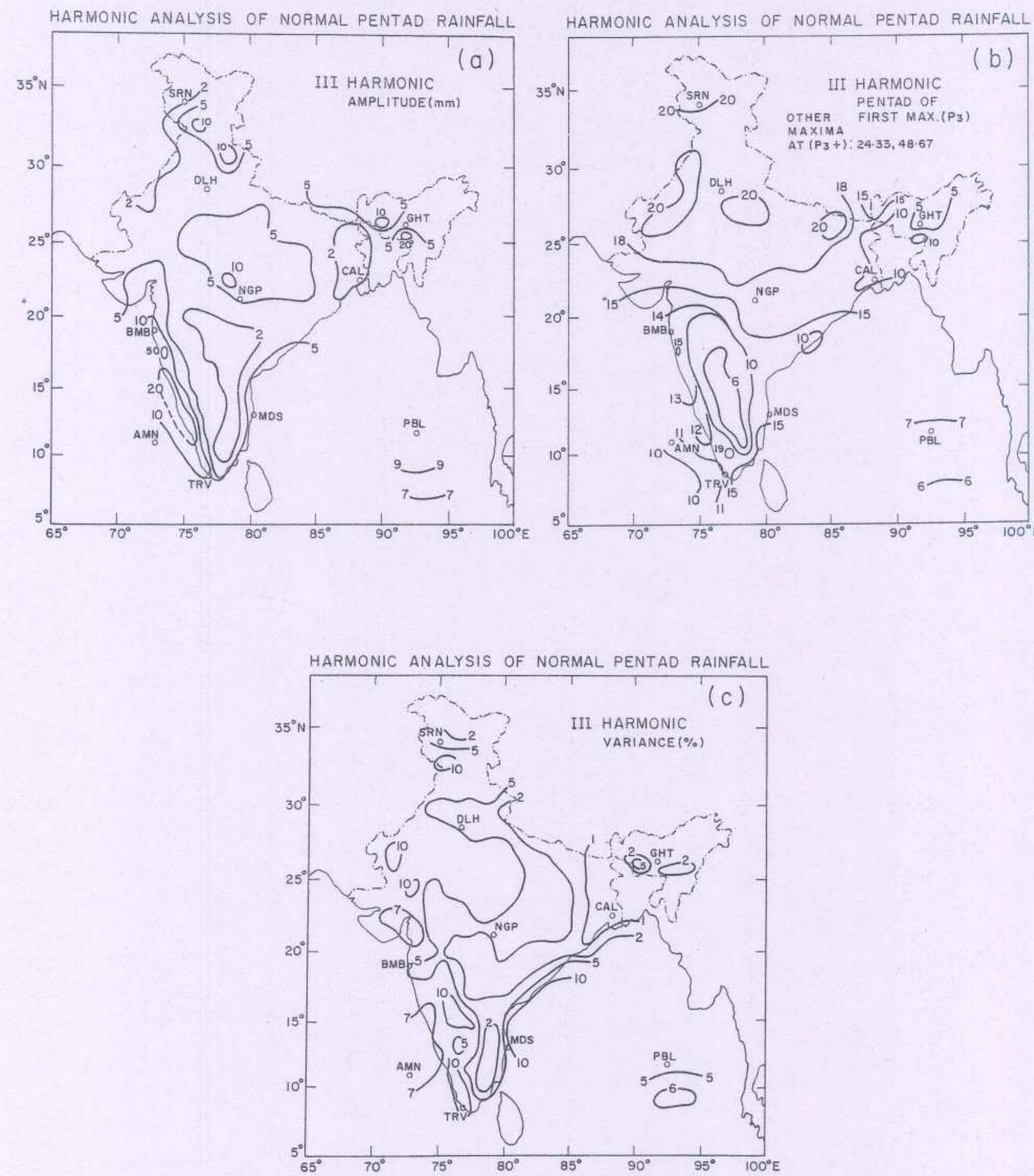

HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(a)
III HARMONIC
AMPLITUDE (mm)
HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(b)
III HARMONIC
PENTAD OF FIRST MAX. (P3)
OTHER MAXIMA AT (P3+): 24·33, 48·67
HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(c)
III HARMONIC
VARIANCE (%)
SRN
DLH
GHT
CAL
NGP
BMB
MDS
AMN
TRV
PBL
35°N
30°
25°
20°
15°
10°
5°
65°
70°
75°
80°
85°
90°
95°
100°E

FIG 8

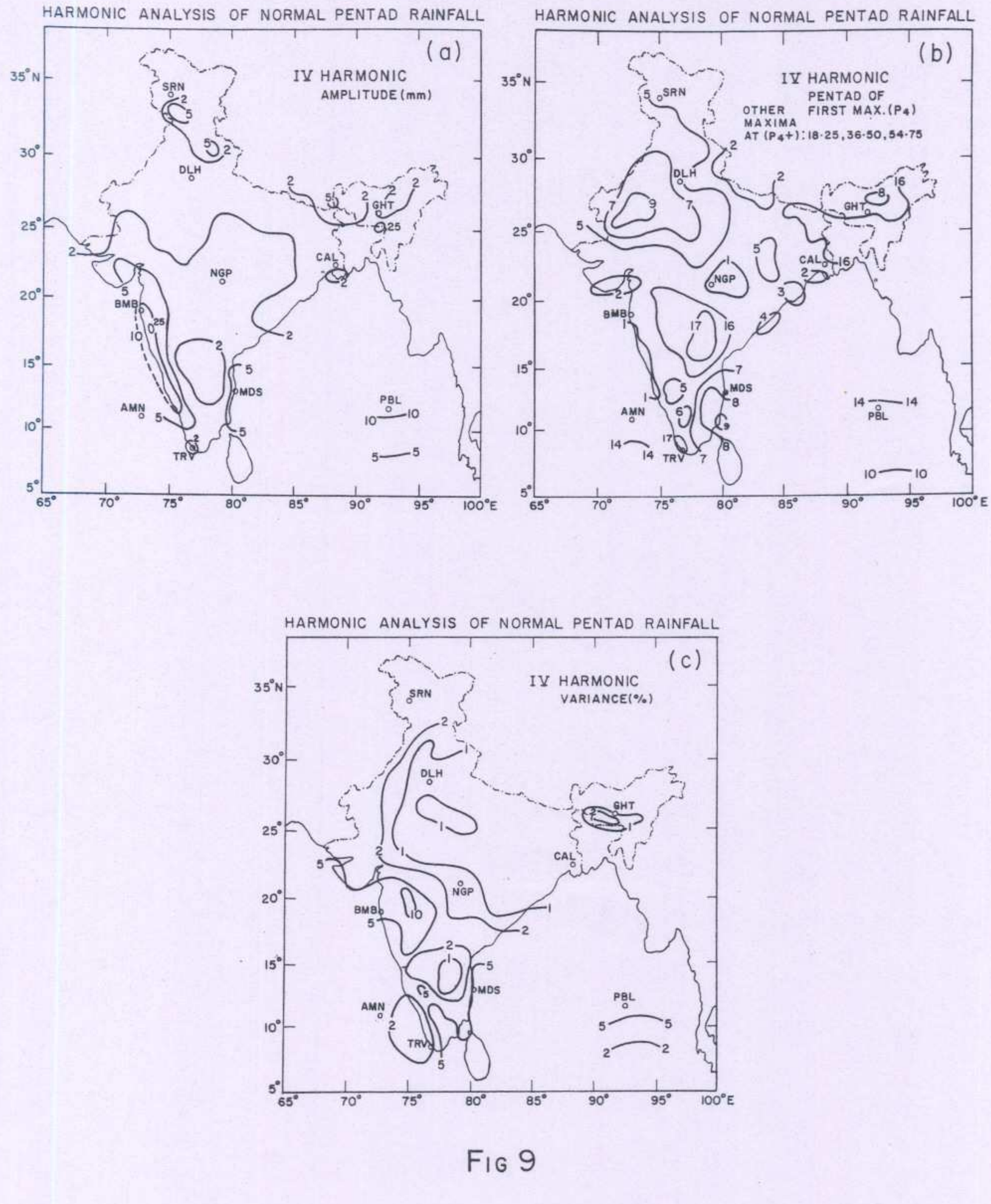
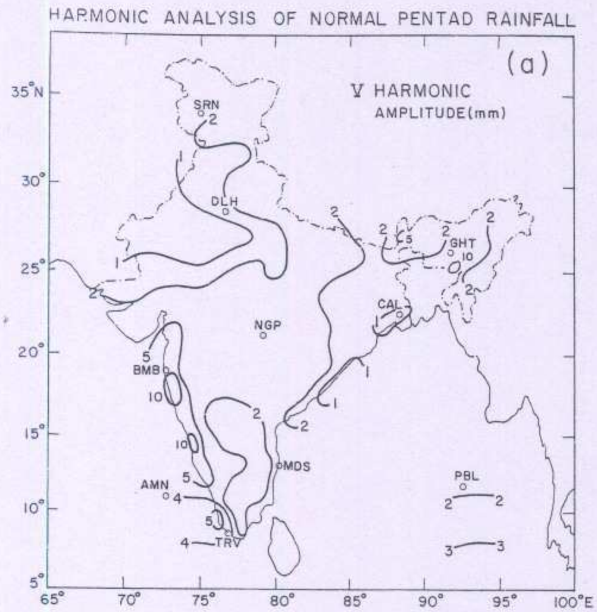
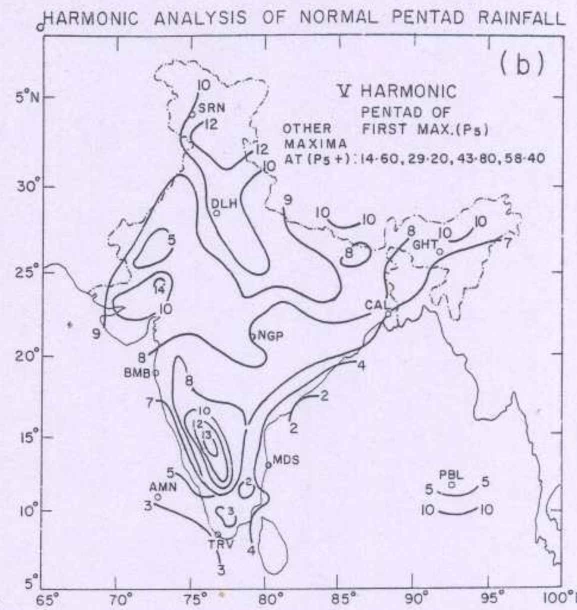

HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(a)
IV HARMONIC
AMPLITUDE (mm)
HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(b)
IV HARMONIC
PENTAD OF FIRST MAX. (P4)
OTHER MAXIMA AT (P4+): 18-25, 36-50, 54-75
HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(c)
IV HARMONIC
VARIANCE (%)
SRN
DLH
GHT
CAL
NGP
BMB
MDS
AMN
TRV
PBL
35°N
30°
25°
20°
15°
10°
5°
65°
70°
75°
80°
85°
90°
95°
100°E

FIG 9


HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(a)
V HARMONIC
AMPLITUDE(mm)
SRN
DLH
GHT
CAL
NGP
BMB
MDS
AMN
TRV
PBL
35°N
30°
25°
20°
15°
10°
5°
65°
70°
75°
80°
85°
90°
95°
100°E


HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(b)
V HARMONIC
PENTAD OF
FIRST MAX.(P5)
OTHER
MAXIMA
AT (P5 +) : 14·60, 29·20, 43·80, 58·40
SRN
DLH
GHT
CAL
NGP
BMB
MDS
AMN
TRV
PBL
35°N
30°
25°
20°
15°
10°
5°
65°
70°
75°
80°
85°
90°
95°
100°E

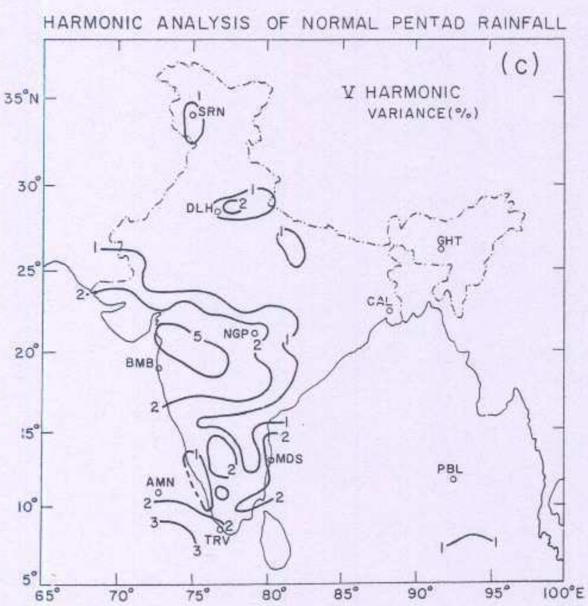

HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(c)
V HARMONIC
VARIANCE(%)
SRN
DLH
GHT
CAL
NGP
BMB
MDS
AMN
TRV
PBL
35°N
30°
25°
20°
15°
10°
5°
65°
70°
75°
80°
85°
90°
95°
100°E

Fig 10

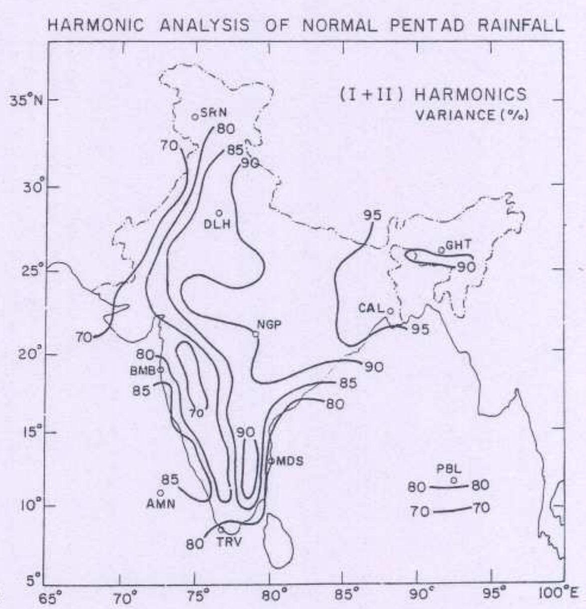

HARMONIC ANALYSIS OF NORMAL PENTAD RAINFALL
(I + II) HARMONICS
VARIANCE (%)
SRN
DLH
GHT
CAL
NGP
BMB
MDS
AMN
TRV
PBL
35°N
30°
25°
20°
15°
10°
5°
65°
70°
75°
80°
85°
90°
95°
100°E

Fig 11