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INDIA METEOROLOGICAL DEPARTMENT

FORECASTING MANUAL

PART IV

COMPREHENSIVE ARTICLES ON SELECTED TOPICS

13 : RAINFALL OF INDIA

ISSUED BY

THE DEPUTY DIRECTOR GENERAL OF OBSERVATORIES (FORECASTING)

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Part IV. Comprehensive Articles on Selected Topics

13. Rainfall of India

by

P. Jagannathan

1. Introduction.

1.1 For a country like India, which is essentially agricultural, rainfall is by far the most important of the weather elements. Even though abundant rain falls over the entire Indian territory as a whole, the disparity in its distribution over the different parts of the country is so great that some parts suffer from perennial dryness, while in some others the rainfall is so much that only a small fraction could be utilised. Further, the year to year variations in the total amount and the pattern of distribution over the different parts of the season are large in most parts of the country; even in the areas where on the average fairly good amount of rain falls, in many years the rainfall is precariously low and large portions of this region are drought-ridden affecting the economy very adversely. On the character of the rainfall depends not only agriculture but also several water power undertakings, transport by land, water and air, industrial, constructional and a wide variety of other public utility interests. Above all, water, which has no substitute for our sustenance has rendered the phenomenon of rainfall a matter of utmost interest to one and all.

1.2 On the different aspects of rainfall, mainly from the climatological point of view, Blanford made detailed studies and his publication entitled "Rainfall of India" (1886) is still considered as a monumental work, considerable work on the rainfall climatology of India has been done by many authors subsequently. To a forecaster, all the climatological aspects of rainfall are not of practical importance. Some of them are purely informative and some instructive in as much as they can act as a guide for prognostic purpose. Climatological knowledge is, however, fundamental for providing guidelines and even when we have attained the stage when Numerical Weather Prediction based on completely physical and dynamical considerations could be made, in view of the several errors and approximations involved in the observations, transmissions etc. and above all the truncation errors and approximations of the computational processes, the climatological knowledge has necessarily to be built in, to control the outputs. Dynamical and physical considerations dictated by synoptic observations do help us in some cases to successfully forecast, for example the development of thunderclouds. Beyond this it is now impossible to predict whether these clouds will give showers and if so at what time, over what area and with what intensity etc. A Garrison Engineer, engaged in an important cementing or concreting operation outdoor, may require such information and to meet his needs at least partially, a forecaster at present has no other alternative but to depend almost entirely on a judicious interpretation of the relevant climatological data.

1.3 In this article an attempt is made to discuss such of the climatological aspects of Indian rainfall as are considered useful for a short range weather forecaster to meet the needs of the multifarious interests. A bibliography comprising of some of the papers which are considered helpful to the forecaster in this connection alone is given at the end.

1.4 Raingauges are supposed to have been used in India even in fourth century B.C. However, systematic observations are available at a sufficient number of stations only from the middle of the 19th century; the oldest records relate to Madras dating back to 1792. Observations at most of the stations are taken only once a day in the mornings. Continuous records of rainfall are available for a few stations only from latter half of the forties of this century. Considerable volume of the rainfall data have already been analysed and studied and our knowledge of the rainfall climatology is essentially based on such studies. However, the available knowledge falls very much short of the several sophisticated requirements of the modern activities. The potentialities of the data accumulated have not

been fully utilized so far. There is urgent need for adequate processing and studies to fill these lacunae.

1.5 A brief description of the rainfall distribution during the different seasons is given in the next section. The different aspects of variation of rainfall, the average intensity, maximum intensity over periods of a day, an hour and five minutes and the diurnal variation are discussed in the third section. The synoptic climatology of the different rain producing systems like the thunderstorms, tropical disturbances, extra-tropical disturbances as also the monsoons, is discussed in the fourth section. As the dynamics of such phenomena are being discussed elsewhere in this manual, these aspects will not be dealt with. It is presumed also that the reader should have equipped himself with the necessary knowledge of physiographic features of India, which is necessary for a proper appreciation of the rainfall distribution.

2. Distribution of Rainfall

2.1 The mean annual rainfall of India is about 105 cm. The distribution of the total annual rainfall over the country is shown in Fig. 1. The heavy orographic rainfall on the windward side of hill ranges of the Western Ghats, and the rapid decrease of rainfall on the lee-side of the hills are immediately brought out. The striking feature is the very heavy rainfall over the whole of Assam and the west coast of the Peninsula amounting to over 200 cm. The southern slopes of the Khasi Hills, the Brahmaputra valley and the narrow slopes of the west coast strip extending from about 11°N to 13°N receive more than 400 cm . On the other side of the spectrum, Western Rajasthan receives less than 40 cm with the extreme west of it receiving less than 20 cm. East of Western Ghats, there is a big patch extending north to south, which receives less than 60 cm. In general the southern slopes of the Himalayas and the western slopes of the Western Ghats receive more than 100 cm and 200 cm respectively. Besides, the coastal strip on the east extending from the Madras coast to the head of the Bay of Bengal and practically the whole of Bihar, Orissa and Madhya Pradesh receive more than 100 cm.

2.2 The march of rainfall through the year in the different parts of the country, besides indicating that the rainfall is not uniform over the year, brings out* the seasonal character of the rainfall over the country. The period December to May is generally drier, while June to November is largely wet over the country as a whole. Broadly the year can be divided into four seasons:

i.	January and February	:	(Winter Season).
ii.	March to May	:	(Hot Weather Season).
iii.	June to September	:	(Southwest Monsoon Season).
iv.	October to December	:	(Post Monsoon Season).

The mean annual rainfall over the different sub-divisions of the country together with the seasonal totals expressed as percentage of the annual are shown in Table 1. Practically over the entire country, excepting Assam, Jammu and Kashmir and the south Peninsula, more than 75% of the annual rainfall is received during the southwest monsoon season. In Madras State about 47% of the annual rainfall is received during the post monsoon season. In Jammu and Kashmir about 20% of the annual rainfall is received during January-February and another 25% during the period, March to May. There is a wide variation in the distribution even of the seasonal rainfall in the different parts of the country. For example, during the southwest monsoon season, the west coast of the Peninsula receives more than 250 cm, while West Rajasthan receives less than a tenth of this quantity. The seasonal rainfall distribution is discussed below.

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* Refer to the author's paper "Seasonal Forecasting in India - A Review" (Meteorological Office, Poona, 1960)

Table 1 : Rainfall of India

Name of the Sub - Division	Annual		Rainfall (R) and number of rainy days (D) as percentage of annual							
	Rainfall (in mm)	Number of Rainy Days	January to February		March to May		June to September		October to December	
			R	D	R	D	R	D	R	D
1. Bay Islands	2994.5	140.5	2.7	2.8	15.0	15.4	59.3	57.1	23.0	24.8
2. Assam (including Manipur and Tripura)	2516.4	113.6	2.3	4.3	25.1	27.5	65.3	59.7	7.3	8.5
3. Sub-Himalayan West Bengal	3126.2	99.5	1.0	2.5	15.4	21.7	78.0	68.9	5.6	6.9
4. Gangetic West Bengal	1485.3	71.8	2.7	3.9	12.4	14.2	73.6	73.4	9.3	8.5
5. Orissa	1482.2	72.3	2.7	3.5	8.6	11.6	76.7	73.7	12.0	11.2
6. Bihar Plateau	1372.0	71.2	3.9	5.6	6.5	9.7	82.0	76.8	7.6	7.9
7. Bihar Plains	1202.9	54.0	2.9	5.3	6.1	8.9	85.0	79.8	6.0	6.1
8. Uttar Pradesh, East	1007.7	47.8	3.4	6.5	3.0	5.4	88.2	82.4	5.6	5.6
9. Uttar Pradesh, West	964.2	43.8	5.1	8.4	3.9	7.5	87.0	79.2	4.0	4.8
10. Punjab (including Delhi)	624.7	31.7	4.6	12.6	7.2	12.4	80.0	69.1	4.2	6.0
11. Jammu and Kashmir	994.6	54.4	19.2	19.7	24.0	27.5	47.5	41.7	9.3	11.0
12. Rajasthan, East	704.1	34.3	2.1	4.1	2.3	4.9	92.5	86.8	3.0	4.1
13. Rajasthan, West	311.1	16.8	3.6	6.5	4.9	8.3	89.1	81.5	2.4	3.6
14. Madhya Pradesh, West	1044.9	48.8	2.2	4.3	2.0	3.8	90.7	85.5	5.1	6.3
15. Madhya Pradesh, East	1401.7	66.7	3.1	5.1	3.5	6.4	87.7	81.5	5.7	6.8
16. Gujarat Region	976.5	42.5	1.4	1.1	1.0	1.6	95.2	93.2	3.2	4.2
17. Saurashtra and Kutch	482.6	23.1	0.9	1.7	2.1	2.6	93.1	91.3	3.8	4.4
18. Konkan	2872.0	93.2	0.1	0.3	1.2	2.1	93.9	90.5	4.8	7.4
19. Madhya Maharashtra	920.7	48.5	0.8	1.2	4.1	6.0	83.6	80.0	11.5	12.8
20. Marathwada	773.6	45.5	1.5	2.2	4.0	6.1	83.3	80.4	11.0	11.2
21. Vidarbha	1099.6	55.5	2.0	3.9	3.1	5.6	87.0	82.3	7.0	8.1
22. Coastal Andhra Pradesh	1008.3	53.0	2.3	2.6	8.8	9.6	56.6	63.6	32.3	24.1
23. Telangana	926.5	54.2	2.1	2.6	6.1	7.7	81.7	79.1	10.0	10.3
24 Rayalaseema	877.8	41.3	2.2	2.4	11.3	11.8	54.4	57.1	32.0	28.6
25. Madras State	1008.1	53.3	3.3	3.4	14.6	15.3	33.0	36.6	47.1	42.7
26. Coastal Mysore	3264.8	112.0	0.1	0.3	4.4	6.6	87.7	81.1	7.8	12.1
27. Interior Mysore, North	675.0	47.5	0.9	0.8	12.7	13.5	55.2	67.3	91.1	18.3
28. Interior Mysore, South	1244.9	66.8	0.8	1.2	13.0	15.3	67.6	62.7	18.5	20.5
29. Kerala	2996.1	126.0	1.3	1.7	13.5	15.4	66.9	62.2	18.3	20.5
30. Andaman Sea Islands	1572.4	87.0	2.8	3.1	13.0	11.4	62.3	63.1	21.4	22.4

2.3 Winter season (January to February)

This is the driest season for the country as a whole. The salient exceptions are Northwest India, in particular Jammu and Kashmir and the Punjab hills and the southeast Peninsula. The distribution of precipitation is shown in Fig 2. In the Himalayas, at heights above 2 km, precipitation is generally in the form of snow. The precipitation amounts to over 20 cm in the mountain regions of the Western Himalayas and decreases rapidly southwards across the sub-montane tracts and eastwards to Bihar from where it increases over West Bengal and Assam to about 10 cm in the extreme northeast. The precipitation of this season occurs in association with the passage of low pressure systems, called "Western Disturbances" across North India.

2.4 The Hot Weather Season (March to May)

2.4.1 The pattern of distribution of rainfall during the Hot Weather Season is shown in Fig 3. Over a wide area, comprising roughly of Maharashtra, Madhya Pradesh, Uttar Pradesh, Rajasthan and Gujarat, rainfall is 5 cm or less. There is a remarkable increase of rainfall to 30-40 cm towards Kerala in south, to 60-80 cm over Assam in the east and to 20-40 cm over Jammu and Kashmir and the adjoining parts of Punjab in the north. Compared to the winter season, the first two regions show an increase of rainfall, whereas the last region particularly the Punjab portion shows a decrease. Western parts of Rajasthan and the adjoining parts of Saurashtra-Kutch remain practically dry with about 0.5 cm.

2.4.2 The rainfall of this season is essentially in the form of thunderstorms. The thunderstorms particularly in Punjab, West Uttar Pradesh and Assam and to some extent the central parts of Deccan are sometimes accompanied by hail; however as the season advances hailstorms decrease in frequency. The hailstorms of North India are occasionally very destructive; hail stones 5-8 cm in diameter have been reported. In Mysore Plateau hailstorms occur chiefly in April-May.

2.4.3 An important synoptic system, which causes rainfall during this season is the tropical storm, which occasionally develops between 10^{o}N and 15^{o}N over the ocean areas. The Bay of Bengal storms move northward and cross Coastal Andhra Pradesh or Bengal coast and cause considerable damage in those areas. On rare occasions storms may cross the Peninsula in lower latitudes and dissipate over the Peninsula or develop once again in the Arabian Sea. Storms which form in the Arabian Sea as also those of the Bay of Bengal, which cross the Peninsula and emerge into the Arabian Sea generally move westwards. Occasionally a storm may recurve and cross Kathiawar Coast causing extensive rain and flood in Gujarat and adjacent areas.

2.5 The Southwest monsoon season (June to September)

2.5.1 This is the main rainfall season, when over 75% of the annual rainfall is received practically over the entire country, excepting over the South Peninsula, Jammu and Kashmir and Assam. In general, July is the rainiest month. The most conspicuous regions of heavy rainfall in this season are Assam with 200 to 400 cm, West Coast and the adjoining Ghats with 200 to 300 cm, Bihar Plateau with 120 to 140 cm and the sub-montane regions of Uttar Pradesh and Punjab with 100 to 120 cm. Elsewhere, the rainfall is of the order of 30 to 50 cm, with the exception of Ladakh valley in the extreme north, western parts of Rajasthan and a small area over the southern-most part of Madras State where the rainfall is very low, between 5 and 10 cm. The distribution of rainfall during this season is shown in Fig 4.

2.5.2 The southwest monsoon and the associated depressions which usually form near the head of the Bay of Bengal and move westward along the trough of low pressure towards Northwest India, are the important synoptic features for the production of rainfall during this season.

2.6 Post monsoon season (October to December)

2.6.1 In this season, not only the amount of rainfall but its distribution also differs significantly from those of the monsoon season. The heavy rainfall belt of more than 20 cm is seen almost as a continuous one extending from Assam to Mysore through the coast of Andhra Pradesh, Madras State and Kerala. Madras State experiences its wettest season now with an average rainfall of 40 to 80 cm. Western India including Jammu and Kashmir is the driest with less than 5 cm of rainfall. Elsewhere, the average rainfall is of the order of 5 to 10 cm. The seasonal rainfall distribution is shown in Fig 5.

2.6.2 The retreating monsoon current, which is directed towards the Peninsula from the northeast is sometimes referred to as the 'Northeast Monsoon current'. The cyclonic storms which form in the Bay of Bengal and move

towards land and the low pressure waves which move westwards across the Peninsula are the important rain producing synoptic systems of this season. In the earlier part of October the storms travel north or northeastwards and cause widespread and heavy rainfall in Bengal and Assam. Later in the season, they mostly strike the Madras and Andhra coasts and produce very heavy rainfall along their track.

3. Rainfall Variations

3.1 Rainfall, as is well known, is very much variable both in space and time. When we consider periods less than a season, say, any single day, the rainfall distribution over the country bears no semblance to the normal seasonal distribution. Similarly if we consider the day-to-day rainfall amounts over two locations a few kilometers apart, one may find on certain days that one station goes dry, while the other experiences a deluge of rainfall.

3.2 The rainfall at any location over a specified time interval may vary from a nil value to a maximum quantity. This maximum quantity depends mainly upon the amount of moisture available over the station during the period under consideration and the efficacy of the weather producing mechanisms responsible for the precipitation. The rain droplets travel towards the ground at speeds determined by their mass, and during the course of the travel evaporate at rates determined by their diameter, the time of travel as well as the moisture condition of their environment. The time of travel of the droplets depends on the height, as well as the lateral and vertical drifts experienced by them before they actually reach the raingauge. As such the rainfall yield depends upon several factors. The precipitating mechanisms as well as the moisture status of the atmosphere have their own characteristic variations associated with the planetary features viz. the time of day and the seasons. Obviously the variations of rain at the station will exhibit in appropriate measure the component variations. The various component features will interact with the environmental orography (including the existance of water bodies) and exhibit distinctive features in the different parts of the country. The variations of the average rainfall and its seasonal distribution over the different parts of the country have been described in the previous section. The further types of variation will be discussed here. In view of the highly variable nature, the mean daily rainfall is of little use to a forecaster. He is interested in knowing what is the order of rainfall on a rainy day, in a particular season, over a certain region. This information together with the maximum daily rainfall may give him a fair idea of the limits within which he may reasonably risk his forecast. If we split up a day into broad periods of hours, then we see that the rainfall amounts in certain parts of the country undergo remarkable diurnal variation in each season. For periods less than an hour, say 5 or 10 minutes, the variations are extremely large. Considering these aspects, frequencies of rain spells of different durations and the average and maximum intensity in such spells associated with the synoptic systems would be necessary. Analysis on these lines on the basis of whatever autographic data of rainfall are available are still to be done. In the following subsections the variations in the rainfall in the different scales are discussed.

3.3 Year-to-year variability

3.3.1 No two years have exactly the same amount of rainfall, and this is still more so as regards the pattern of distribution of rainfall in the year. The year-to-year sequence of monthly rainfalls, and even the total annual rainfall show considerable fluctuations. This is a characteristic feature of all time-series; in some, the variation is small and in others quite large. Some years stand out as phenomenal years when the rainfall was very much in excess and some others, when the rainfall was much in defect. The average annual rainfall in the plains of India has been estimated as about 105 cm while in the worst famine year on record viz. 1899, it was 26% below normal and in 1917, the year of very heavy rainfall, it was 29% above normal.

3.3.2 Taking the coefficient of variation (CV = Standard deviation x 100/Mean) as a measure of variation, the variability of rainfall in the different parts of the country is shown in Fig 6. The variability exceeds 30% over large areas of the country and is over 40 to 50% in parts of Saurashtra, Kutch and Rajasthan. In some of the interior districts* in these areas as also Deccan Plateau, the variability is as high as 100% or more and these are particularly liable to very heavy rainfalls in some of the years and very scanty rainfall in others. The variability is least over the northeastern parts of

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* These areas are too small to be shown in Fig 6.

India and the southwestern coast of the Peninsula, being of the order of 15 - 20% indicating very high reliability of rainfall in these areas.

3.3.3 It is also seen, that as a rule, areas which have the lowest rainfalls are also those in which rainfall is most irregular.

3.3.4 The variability of the monthly rainfalls as also the variability of rainfall of the monsoon season in the arid and semi-arid sub-divisions, where the total annual rainfall is small and the year-to-year variability is large, are given below :

Table 2 : Variability of rainfall (percentage)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jun to Sep
West Rajasthan	223	152	157	170	182	96	59	76	146	253	333	180	49
East Rajasthan	107	152	162	231	138	62	38	50	78	150	145	171	28
Rayalaseema	207	241	221	81	61	41	52	63	45	56	83	172	30
Madhya Maharashtra	215	175	144	71	76	33	30	37	39	61	101	200	18

The variabilities are high during the non-monsoon months indicating the highly erratic nature of the rainfall during these months. Even during the monsoon months, the variabilities are high, the lowest being in the month of July, when the monsoon is at its height.

3.3.5 As we have seen, the southwest monsoon is the main rainfall season for most parts of India. Inspite of the systematic nature of the monsoon rainfall occurring during the season, its behaviour during the different years shows considerable variation. The important aspects in which they differ are:

i. the timing of the onset or the commencement of the rainy season in the different parts of the country,

ii. the pattern of distribution of rainfall including the timing and duration of breaks in the monsoon,

iii. the timing of withdrawal of the monsoon from the different parts of the country and

iv. the total amount of rainfall of the season.

Obviously late commencement of the monsoon rains, long breaks in the rains and early withdrawal are harmful to the crops. Similarly excessive rainfall over short periods lead to flooding and waterlogging. For success in crop production, both the total rainfall and its distribution are very important.

3.4 The average rainfall on a 'wet day'

3.4.1 For the purpose of the study here, we consider daily rainfalls less than 0.25 mm (1 cent) as negligible and a day with more than this amount as a 'wet day'. Figure 7 shows the average rainfall intensity on a wet day during the different seasons in the different parts of the country.

3.4.2 During the winter season, a wet day normally receives about 1 cm of rainfall in Punjab, Southeast Madras State and coastal Mysore. As the season advances, over Assam, Gujarat, Telangana, Rayalaseema and adjoining parts it is less than 0.5 cm. Over the rest of the country it is between 0.5 and 1.0 cm; the intensity increases to nearly 1 cm over Andhra - Orissa coasts and the plains of Punjab.

3.4.3 In the hot weather season, the intensity over the country is 0.5 to 1 cm except in the southern half of the Peninsula and Bengal-Assam region where it is over 1 cm. By May this region extends upto West Uttar Pradesh and Saurashtra including the adjacent Konkan coast, while in the coastal area south of Konkan and in the coastal belt of Madras State, Andhra Pradesh and Orissa upto Bengal-Assam region, the intensity increases to over 1.5 cm.

3.4.4 The intensity of rainfall over the country in general is a maximum during the southwest monsoon season. In the plains, it is about 1.5 to 2 cm. To the east of the Western Ghats it is less than 0.5 cm. Maximum intensity of 2 to 3 cm is over Western Ghats and the adjoining coastal plains during the months June and July; by the end of August, the intensity decreases to less than 1.5 cm. It is interesting to note that during this season the intensity over Assam in general is not more than 2 cm.

3.4.5 In the post-monsoon season, maximum intensity is experienced in the east coast with about 1 to 2 cm. Elsewhere, the intensity is less than 1 cm with a minimum of the order of 0.5 cm or less in West Rajasthan.

3.5 Heaviest rainfall in a day

3.5.1 Large tracts of India are liable to receive excessive rainfall in heavy downpours caused by cyclonic storms and depressions. Locally heavy falls caused by depressions vary from 7 to 20 cm extending over several districts. Falls to the extent of 25 to 35 cm in a day have been recorded

especially in the neighbourhood of hills and on the coast near the central regions of storms. Heavy falls exceeding 25 cm in a day are not uncommon even in Gujarat and Rajasthan. Dwarka in Saurashtra with an annual average rainfall of 32 cm has received about this amount in a day in November 1951. Dharampur in Surat district had recorded 100 cm on 2 July 1941. This is the heaviest 24 hour rainfall in any of the plain stations in India. Generally rainfall of 75 cm and over in a day is confined to a very small area in the Khasi and Jaintia Hills in Assam, the head of the Gulf of Cambay around Surat district and Bhagamandla area in Coorg. The record 24 hour rainfall for India is maintained by Cherrapunji in Khasi Hills with 103.3 cm.

3.5.2 As in the case of average rainfall, the heavy spells of rain have also certain preferences for certain regions. This is clearly brought out from Fig 8. For the purpose of drawing the isopleths,* which is mainly intended for bringing out the regional disposition, the isolated rainfalls which are not considered as representative of the region have been omitted. This is based on data for the years upto 1960.

3.5.3 During the winter season, Kerala and Madras States in the south and the hill ranges of Jammu-Kashmir and Punjab and Bengal in the north have experienced heavy falls of about 10 cm a day. The rest of the country exhibits two distinct regimes of rainfall. To the west of about 80°E rainfall is within the ranges of 5 to 10 cm in the plains of Punjab and adjoining Uttar Pradesh, West Madhya Pradesh and North Hyderabad. Further west, the falls are less than 5 cm. To the east of 80°E there is a narrow belt of less than 5 cm running north-south from East Uttar Pradesh to Rayalaseema. The adjoining regions upto Bengal have received heavier falls of 5 to 10 cm. Like the western parts of India, Assam, in the east also is not liable to experience more than 5 cm of rainfall a day during this season.

3.5.4 During the hot weather season, there is a general tendency for heavier falls to occur in most parts of the country except in northwest India and Uttar Pradesh where the heaviest falls continue to be limited below 5 cm. Practically the entire central parts of the country and eastern Assam receive in a day upto a maximum of about 5 to 10 cm. The heaviest falls of more than 20 cm a day are restricted in this season to Sub-Himalayan West Bengal and adjoining parts of Assam, the coastal strip from Nellore to Nagapattinam and southern half of the west coast.

3.5.5 For the country in general, the monsoon season is the period of very heavy downpours. Two coastal belts-one adjoining the northwest Bay and the other adjoining the northeast Arabian Sea-have experienced very heavy falls of more than 30 cm in a day. Between these two regions, in the central parts of Madhya Pradesh and adjoining areas of Maharashtra also, heaviest rainfalls of the order of 30 cm have occurred. The sub-montane regions of West Uttar Pradesh and West Bengal have recorded rainfalls exceeding 30 cm. Southeast Madras State remains conspicuous in this season for its moderate falls of less than 10 cm a day. In general one may expect heaviest rainfalls of the order of 10 to 20 cm in North Assam and the Peninsula, and 20 to 30 cm elsewhere in the country in this season.

3.5.6 With the withdrawal of the monsoon, there is a phenomenal decrease in the heaviest intensities practically all over the country. East coast of Madras State, however, receives its heaviest falls of over 30 cm during this season. In general a narrow belt extending from NE India to South Kerala along the east coast may be considered liable to have the heaviest falls of over 20 cm in a day. Westwards of this belt, the intensity is found to decrease to about 10 cm towards Rajasthan and to less than 5 cm over West Rajasthan.

3.5.7 The probability of rainfall of 25 cm or over occurring in 24 hours at a station is, however, very small over most parts of the country. Only in regions of pronounced orographic features or in those subjected to maximum effect of cyclonic storms like the South Gujarat area and the east coastal regions of the Peninsula such rainfalls have occurred on an appreciable number of occasions.

3.6 Diurnal variation of rainfall

3.6.1 The shorter the period to which a rainfall forecast relates, the greater is the uncertainty in the rainfall forecast. This is mainly for want of satisfactory objective methods to estimate the time required for the cloud

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* As rainfalls are recorded at 0830 hrs I.S.T., the maximum rainfalls relate to 24 hour ending 0830 hrs I.S.T. If we are interested in the maximum 24 hour rainfalls, the values given have to be multiplied by a factor of 1.13

droplets under different atmospheric conditions to grow sufficiently large to get discharged as rain. However, the knowledge of the normal climatic features of the diurnal variation will be helpful for indicating the rainfall periods. The diurnal variation of rainfall will have naturally to depend upon the diurnal variation of cloudiness and the intensity of the precipitating mechanisms during the course of the day. Even though continuous observations of rainfall are available for over 50 stations for over 15 years, regular studies of the diurnal variation of rainfall are very few.* The characteristic diurnal and seasonal variation of rainfall at some representative stations are shown in Fig 9 (i) to (vi). In Fig 10 the six-hourly periods during which the maximum and minimum rainfall during the day occur in the different parts of the country are shown. Due to the sparse network of stations, the demarcation should be considered purely tentative. It may be seen that by and large there is a seasonal tendency for rainfall to increase and decrease during certain periods of the day in the different parts of India.

3.6.2 During the winter season, South Rajasthan, Gujarat, Konkan, Madhya Pradesh and the plains of Uttar Pradesh have their most rainy period between 9 to 15 hrs I.S.T. and the lean period between 3 and 9 hrs. For Madras State and adjoining parts of Mysore and Andhra, the most favourable period for rainfall is between 3 and 9 I.S.T. while the rainfall is least between 15 and 21 hours. The rest of the country receives maximum rainfall during the hours 15 to 21 and minimum during 3 to 9 hrs.

3.6.3 During the hot weather season, the coastal belt from Gujarat to Kerala experiences its maximum rainfall between the hours 9 and 15 and minimum between 3 and 9. In coastal Madras State the maximum is between 9 and 15 I.S.T. and the minimum between 15 and 21 I.S.T. The northern parts of East Uttar Pradesh, Bihar, Bengal and Assam have their rainiest period from 21 to 3 hrs with low amounts between 9 and 15 hrs. In the rest of the country the rainiest hours are 15 to 21. But the period of minimum is not the same everywhere. In Rajasthan and West Madhya Pradesh, it is during 3 to 9 and over Jammu-Kashmir, Punjab, Uttar Pradesh (W) and interior Madras State the minimum occurs between 9 and 15 hrs.

3.6.4 During the monsoon season, mainly Rajasthan has its maximum rainfall in the noon hours, 9 to 15. The west coast and practically the entire North India excluding the Bengal plains receive their maximum between 3 and 9 hrs. The above regions with the exception of Assam and Bihar experience their minimum during the period 15 to 21 hrs. Assam, Bihar, Bengal, Orissa Andhra Pradesh and Madras State have least rainfall between 9 and 15 hrs. Madras State receives its intense falls between 21 and 3 hrs while the adjoining regions of Andhra Coast upto Bengal plains experience their maximum during 15 to 21 hrs.

3.6.5 During the post-monsoon season Northeast India receives its maximum rainfall between 3 and 9 hrs and minimum between 9 and 15 hrs. Gujarat coast to Kerala including Mysore Pleateau is another region where maximum rainfall occurs between 3 and 9 hrs and the minimum between 15 and 21 hrs. In the rest of the country, excluding Madras State, maximum is between 15 and 21 hrs and minimum between 3 and 9. In Madras State the most rainy period is the midnight hours (21 to 3) and the lean hours between 15 and 21 hrs.

3.7 Heaviest rainfall in an hour

3.7.1 Very heavy falls over short periods are often called 'flash rainfall' as they are capable of causing 'flash floods'. The present network of autographic raingauges is not sufficient to give us finer aspects of such phenomenal fall. Moreover, the available records of heavy rainfalls for one hour refer to a clock-hour and not for any sixty minute interval.* In Fig 11 is shown the general characteristics of the heaviest rainfall recorded during a clock-hour in each season. This is based on data for the years 1948 to 1961.

3.7.2 In the winter season, Jammu-Kashmir and the adjoining parts of Punjab have experienced heaviest rains of the order of 2 cm in an hour.

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* Rao and Raman (1956) partitioned the rainfall between the daylight hours 0830 to 1730 I.S.T. which are the times of the daily routine observations and during the night time comprising the period 1730 to 0830 I.S.T. of next morning and described the patterns.

* The heaviest rainfall over a period of 60 mts, may be obtained by multiplying the clock hour values by a factor of 1.13.

Similar heavy falls have also occurred over the eastern parts of the Peninsula and over West Bengal. The region extending as a tongue from south Konkan to East Gujarat is conspicuous where even heaviest falls have not exceeded 0.5 cm in an hour.

3.7.3 During the hot weather season, the distribution and intensity substantially differ from the previous season. The intense falls of 6 cm and more have occurred in the west coast, mainly over Kerala. Over the whole of Assam and Bengal, coastal Orissa and the Madras coast, the record had been 5 cm or more. The maximum hourly intensity decreases from these areas towards north and northwest to values of the order of 1-2 cm.

3.7.4 During the monsoon season, the maximum intensity is highest in all parts of the country. In the coastal regions of northeast Arabian Sea and northwest Bay the maximum intensity is more than 8 cm/hr; the general order of the heaviest falls elsewhere is between 5 and 6 cm.

3.7.5 As the monsoon recedes, the intensity of the falls decreases considerably. In Madras State and the adjoining parts of Kerala, Mysore and Andhra the maximum intensities are between 5-6 cm and decrease northward to 2 cm in the sub Himalayan region.

3.8 Heaviest rainfall in 5 minutes interval

3.8.1 The true nature of tropical rainfall cannot be fully understood from the distribution of intensities we have so far considered. This is mainly because the time interval of rainfall considered is more than the time usually taken for convective cells to discharge their water content. The average amount of rainfall in a day or in an hour over a certain region does not indicate whether the rainfall is generally of a showery type lasting for a few minutes or of continuous type lasting for a few hours. Showers lasting for a few minutes seem to contribute to a great extent to the daily or the hourly rainfall of India almost in all seasons. The maximum 5 minutes intensities are shown in Fig 12.

3.8.2 In the winter season, rainfalls of a little over 1 cm in 5 minutes have been recorded in the hills of western Himalayas and adjoining plains. The intensity is less than 0.5 cm over most of the west coast and Bengal and their neighbouring areas. Over the rest of the country, the intensity of the falls varies between 0.5 and 1 cm.

3.8.3 In the hot weather season there is a general increase of maximum intensity from NW India where it is of the order of 0.5 cm to values of just over 1 cm over the Peninsula and to over 2 cm over South Bengal and Assam.

3.8.4 The short lived nature of these heavy falls can be seen by a comparison of the figures 11 and 12. eg. if Bengal were to receive during the hot weather season rainfall for an hour at its maximum rate of 2 cm/5 mts., the total catch in the hour should have been 24 cm while the maximum hourly intensity had been only of the order of 5 cm., indicating thereby that very heavy showers last only for a few minutes. This feature is observed in the country in all the seasons.

3.8.5 With the arrival of the monsoon, very heavy showers of about 1 to 2 cm in 5 minutes may be expected practically in all parts of the country. It is interesting to find that Rajasthan which normally receives relatively poor rainfall has recorded intense rainfall of 2 cm/5 minutes which is more than that recorded in some parts of the west coast.

3.8.6 After the monsoon recedes, the areas with heaviest falls exceeding 1 cm in 5 minutes are confined to the South Peninsula and the coastal regions adjoining Head Bay. Elsewhere in the country the intensity is less than 1 cm and it is less than 0.5 cm over North-West India.

4. Synoptic Climatology of Rainfall

4.1 To what extent is the rainfall organized? A knowledge of this will be helpful to the forecaster to indicate the temporal and spatial variations of rainfall in his forecasts. It is known that for the production of rainfall, the atmosphere should contain sufficient moisture and should be cooled below the saturation point to form clouds, and the cloud droplets should grow to sufficient size and be released in the form of rain. This cooling is achieved by upward motion which is determined by the synoptic features and by local factors such as coastal or orographic effects. As a consequence, the configuration of the rain areas in relation to the synoptic systems will exhibit variations to that extent. The rainfall patterns associated with the following phenomena are discussed :

i. Thunderstorms,

ii. The tropical storms/depressions and western disturbances,

iii. The monsoon.

4.2 Thunderstorm rains

4.2.1 The intense local rainfall, which was mentioned earlier is invariably associated with thunderstorms. These arise as a result of large scale convection due to building up of marked latent instability in the atmosphere over the locality and release of the same by appropriate triggering mechanism. They are associated with the formation of towering cumulus or cumulonimbus clouds and usually accompanied by violent upcurrents, thunder and lightning, even though at times thunder may not be heard.

4.2.2 The rainfall pattern follows closely the arrangement of the thunderstorm cells and reflects to a considerable extent the stages of the development of the different cells. The rain from a newly developed cell may fall over a very small area at first and then spread gradually; the rain area contracts gradually in the dissipating stage. Showers from a single cell usually cover a small area of about 15 to 20 km. in extent; but many such cells may occur over a wide area and give widespread showers.

4.2.3 At fixed locations on the ground, the duration of rain depends upon such features as the number, size and rate of movement of the cells and also the location relative to the individual cell. The average life of thunder-shower is about 5 to 6 hours but owing to the progressive movement of the cells, the duration of the shower at any one place is generally less than 2-hours. The rate of movement depends upon the dynamics and the wind field in which it is embedded. In level country the rate of movement is about 50-60 km. per hour, but in mountainous regions, they often remain practically stationary till they have rained out.

4.2.4 The most intense rain occurs under the core of the cell within 2 or 3 minutes of the first measurable rain from that cell reaching the ground and the rain usually lasts for about 5 to 15 minutes; the commencement is usually sharp but the decrease after the peak rainfall rather gradual.

4.2.5 In the winter season, thunderstorm rainfall is the least. It is restricted mainly over regions with seasonal rainfall $\geq$ 5 cm shown in Fig 2. In the hot weather season thundery activity increases generally over the whole country, and except for the heavy rainfalls associated with tropical storms the rainfall of this season is essentially an index of thunderstorm activity. During the southwest monsoon season, the thunderstorm activity reaches its maximum in the country in general. But it is not possible to say, for want of observational data, what proportion of thunderstorm rainfall is to non-thunderstorm rainfall in this season in the different parts of the country. However, it is generally observed that at and near the monsoon trough the rainfall is mainly of showery type associated with thunder clouds. As the monsoon trough shifts southwards by October, the thunderstorm activity also shifts similarly. In the post-monsoon season, the heavy rainfall region of $\geq$ 40 cm (Fig 5) roughly represents the region of thunderstorm rainfall.

4.3 Rainfall of the western disturbances

4.3.1 Western disturbances are cyclonic disturbances of the extratropical type. They contribute to the rainfall over the country in all the seasons. In the monsoon season they are normally restricted to Jammu-Kashmir. With the withdrawal of the monsoon, they start affecting the plains of India. On the average during each of the months January to April about five such disturbances enter India from the west and move eastwards. The average number of disturbances in December is four and in May and November two each. All these are not equally active. During February and March they are observed as far south as 20°N, and the precipitation north of this latitude particularly along the northern border is mainly due to western disturbances. Thereafter they gradually shift to higher latitudes.

4.3.2 Continuous light rain or drizzle falls over an area sometimes extending to 500 to 800 kms, ahead of these disturbances. In the rear usually no precipitation occurs but when they occur they are in the form of heavy showers of short duration sometimes accompanied by thunderstorms. Occasionally these disturbances give rainfall in the central parts of the country as well as in the northern fringes of the Peninsula.

4.4 Rainfall of the tropical storms/depressions

4.4.1 The tropical storms and depressions are low pressure systems easily recognizable on the synoptic charts. When formed they maintain their identity

for a number of days and can be tracked with considerable accuracy. Though some of the storms have been found to form over land area also, a majority of them form over the Bay of Bengal or the Arabian Sea generally beyond 5° of the equator. The frequency of tropical storms and depressions which affected the Indian mainland and the adjoining seas along with their life duration is given below :

Table 3 : Statistics of storms/depressions - 1891-1960.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
I. Bay of Bengal												
i. Number of storms/deprns.	9	3	5	27	45	67	102	112	107	106	85	42
ii. Number which moved over to land	0	1	0	9	27	56	88	98	98	65	34	4
iii. Average life in days	3.8	4.7	3.4	3.5	3.9	4.2	4.1	4.5	5.3	4.4	4.3	3.2
iv. Average life over land	0	0.4	0	0.4	1.0	2.3	2.6	2.0	3.2	1.5	1.1	0.3
II. Arabian Sea												
i. Number of storms/deprns.	1	0	0	7	16	22	5	0	4	22	20	2
ii. Number which moved inland	0	0	0	3	2	8	4	0	2	8	6	0
iii. Number which formed in Bay of Bengal and moved into Arabian Sea (not included in i)	0	0	-	0	3	2	2	1	3	6	13	7
iv. Average life in days of (i)	1.0	-	-	5.6	4.8	3.8	2.4	0	4.2	5.2	5.9	5.0
v. Average life of (i) over land in days.	0	-	-	0.6	0.6	0.5	0.9	0	1.4	0.2	0.2	0

4.4.2 These disturbances have a controlling influence on the distribution of rainfall over the different parts of the country. Some of the heaviest rains (during 24 hrs) on record have been experienced with slowly moving tropical cyclones. If these systems move fast the duration of the system over the area is considerably reduced and consequently the total accumulation of rain is very much less. Their contribution to the seasonal rainfall seems to be a maximum in the coastal regions, where they strike from the seas. They cause rainfall along their track over a radius of about 500 km. Within this distance there are at times dry and wet zones of about 30 to 50 km wide. From radar observations it is evident that the rain is distributed in bands and between the bands the rain is either missing or of light intensity. In mature storms, the radar pattern shows that the eye of the storm is free from precipitation echoes. As the disturbances move, these zones cause variation in the intensity of rainfall. However, depending upon the seasons and tracks of disturbances, rainfall is restricted mainly to certain sectors. The actual rainfall caught will depend upon the motion of the storm exposing different parts of the storm field over the recording station.

4.4.3 No systematic estimates of rainfall contributions by cyclonic disturbances have been made so far.* However, the distribution of heavy rainfall in 24 hours (Fig 8) gives us an idea of the maximum rainfall so far caused by any phenomenon including cyclonic disturbances. Thus we might reasonably consider the values given in Fig 8 as the upper limit of rainfall in association with cyclonic disturbances in the different seasons.

4.4.4 It is seen that in the winter season, the rainfall intensities associated with these cyclonic disturbances are the lowest for the year as a whole, being not more than 5-10 cm in a day. The maximum rainfall intensities associated with these storms have not exceeded 20 cm per day during the hot weather season and 30 cm per day during the post monsoon season. However, during the monsoon season the upper limits in the different parts of the country are higher and in certain areas it is even over 40 cm per day.

4.4.5 Occasionally two cyclonic disturbances simultaneously occur over the Indian region. The distribution of rainfall under such circumstances undergoes radical changes. Usually the disturbances are located along a line mainly oriented east-west and the belt between the disturbances situated normal to the line connecting the centres of the two disturbances remains practically dry. A typical distribution is shown in Fig 13.

4.5 Monsoon rainfall

4.5.1 The Indian summer monsoon is the most widely known and most spectacular of the continental circulations. Late in May or early in June monsoon sets in over Kerala Coast. By the second week of June the rainfall extends

* The only studies in this connection are the various storm studies for hydrometeorological purposes where the rainfall intensities over the river catchment or over the storm have been estimated for several maximum storms. In another, Jagannathan (1964) computed rainfall contributed by the several synoptic causes over Rajasthan and Sind. He found that in the heaviest rainfall year 1917, the rainfall contributed by 'depressions' was of the order of 0.73" ($\approx$ 1.8 cm) while the monsoon as such (the Bay current and Arabian Sea current) contributed only about a third of this amount.

into Gujarat and the central parts and the monsoon is more or less established over the country by the first week of July.

4.5.2 During the monsoon, rainfall is not continuous but occurs in spells lasting for about 5 to 7 days. These spells of active monsoon cause an increase of rainfall in the plains of India while the rainfall usually decreases in the southeast Peninsula and the foothills of the Himalayas. During spells of weak monsoon which sometimes last over a couple of weeks, rainfall decreases over the plains while it increases over the southeast of the Peninsula and in the Sub-Himalayan regions. The distribution of rainfall during a typical 'weak monsoon' and 'strong monsoon' day are shown in Figs 14 and 15 respectively.

4.5.3 The monsoon gradually weakens in September and starts withdrawing from Northwest India. Unlike the advance of the monsoon which is a rapid process, the withdrawal is a slow and steady process. The monsoon withdraws from Northwest India by the third week of September and from West Uttar Pradesh, Gujarat and West Madhya Pradesh towards the end of the month and by the middle of October, the monsoon withdraws from most of the country, except over southeastern Peninsula.

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N.B. : Practically every work in meteorology has some references or relevance to the rainfall. In this bibliography only such of these papers which have a direct bearing to the forecaster for whom this article is intended are mentioned.

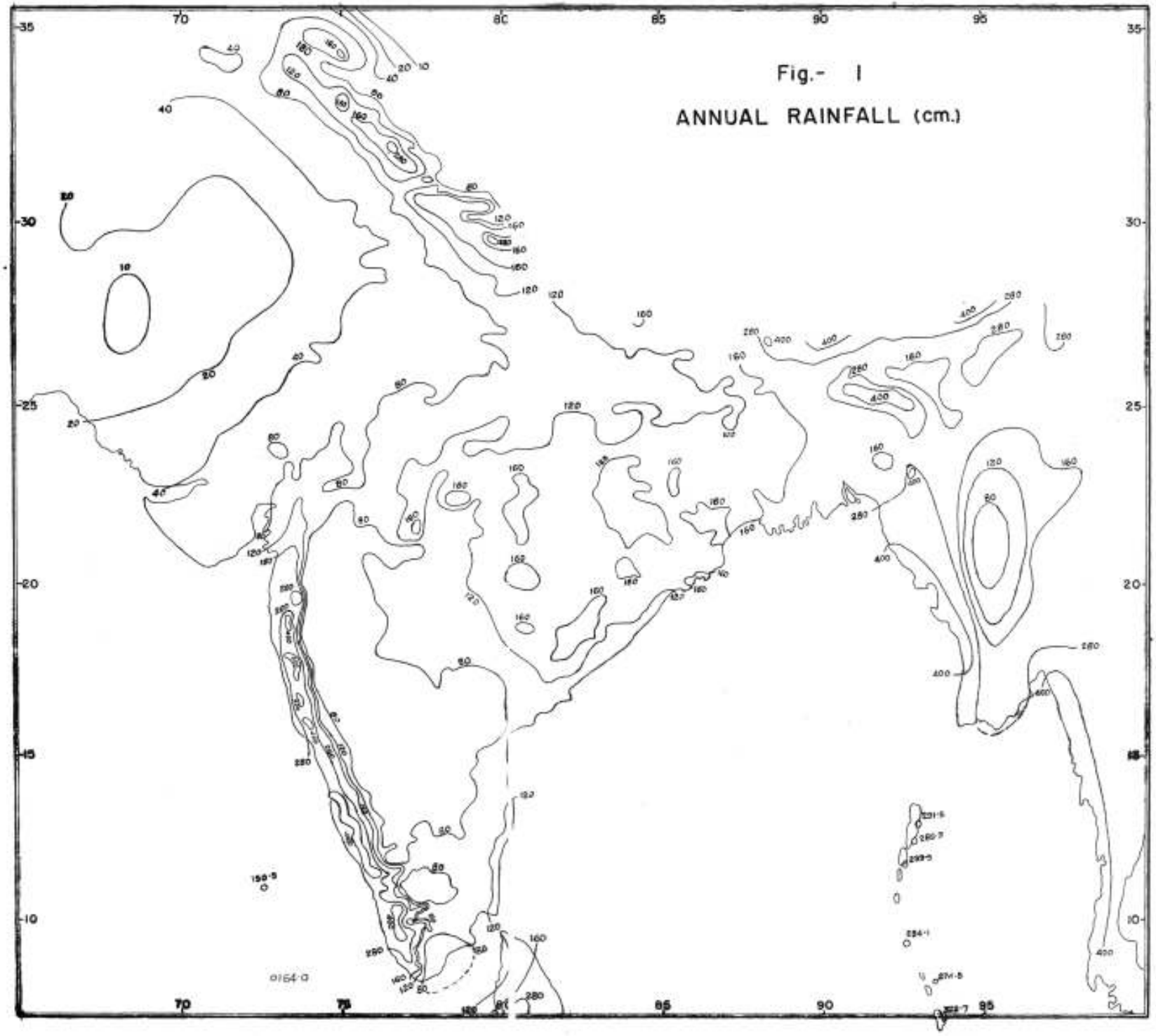


Fig.- I
ANNUAL RAINFALL (cm.)
70
75
80
85
90
95
35
30
25
20
15
10
0164-0

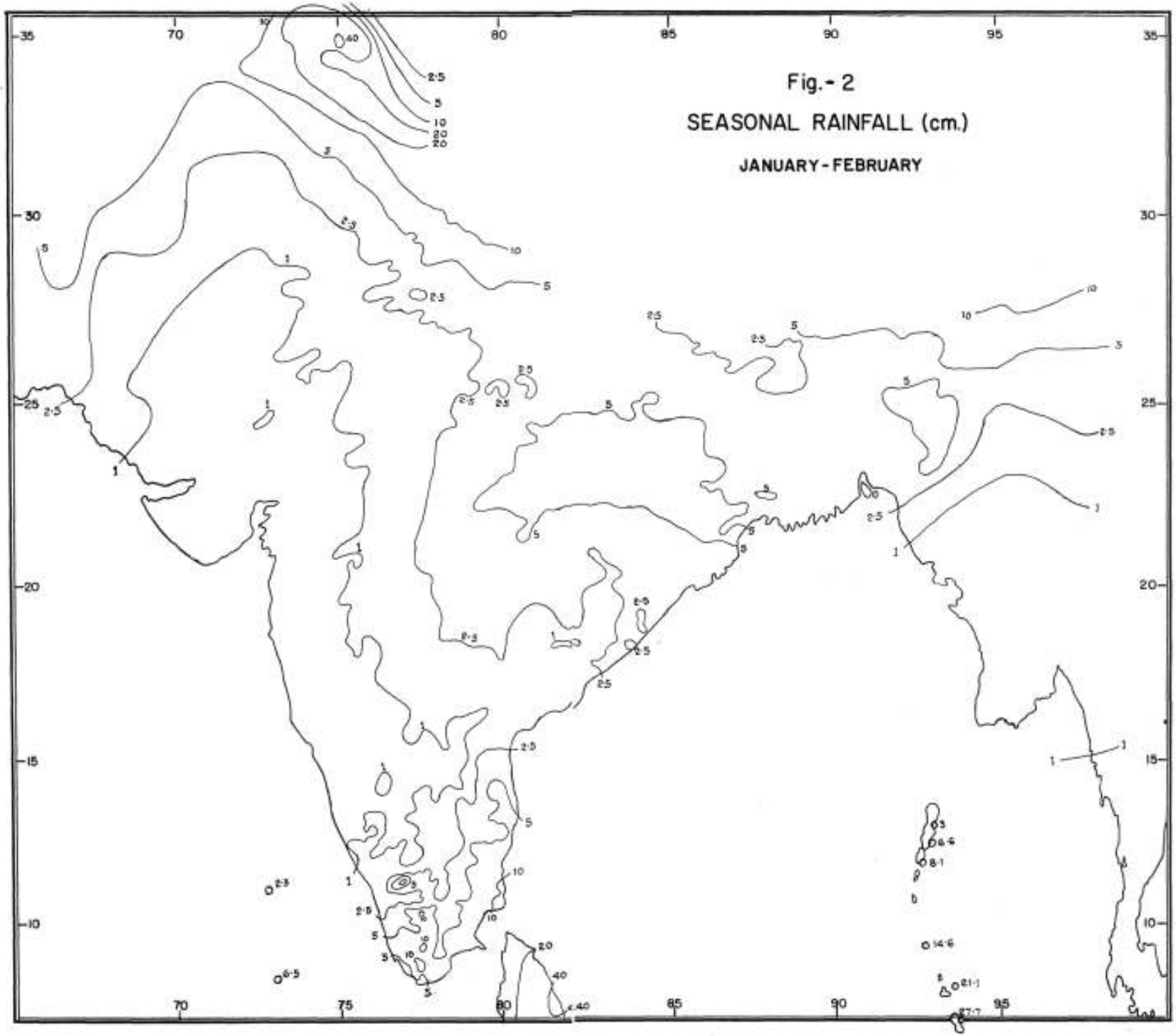


Fig.- 2
SEASONAL RAINFALL (cm.)
JANUARY - FEBRUARY

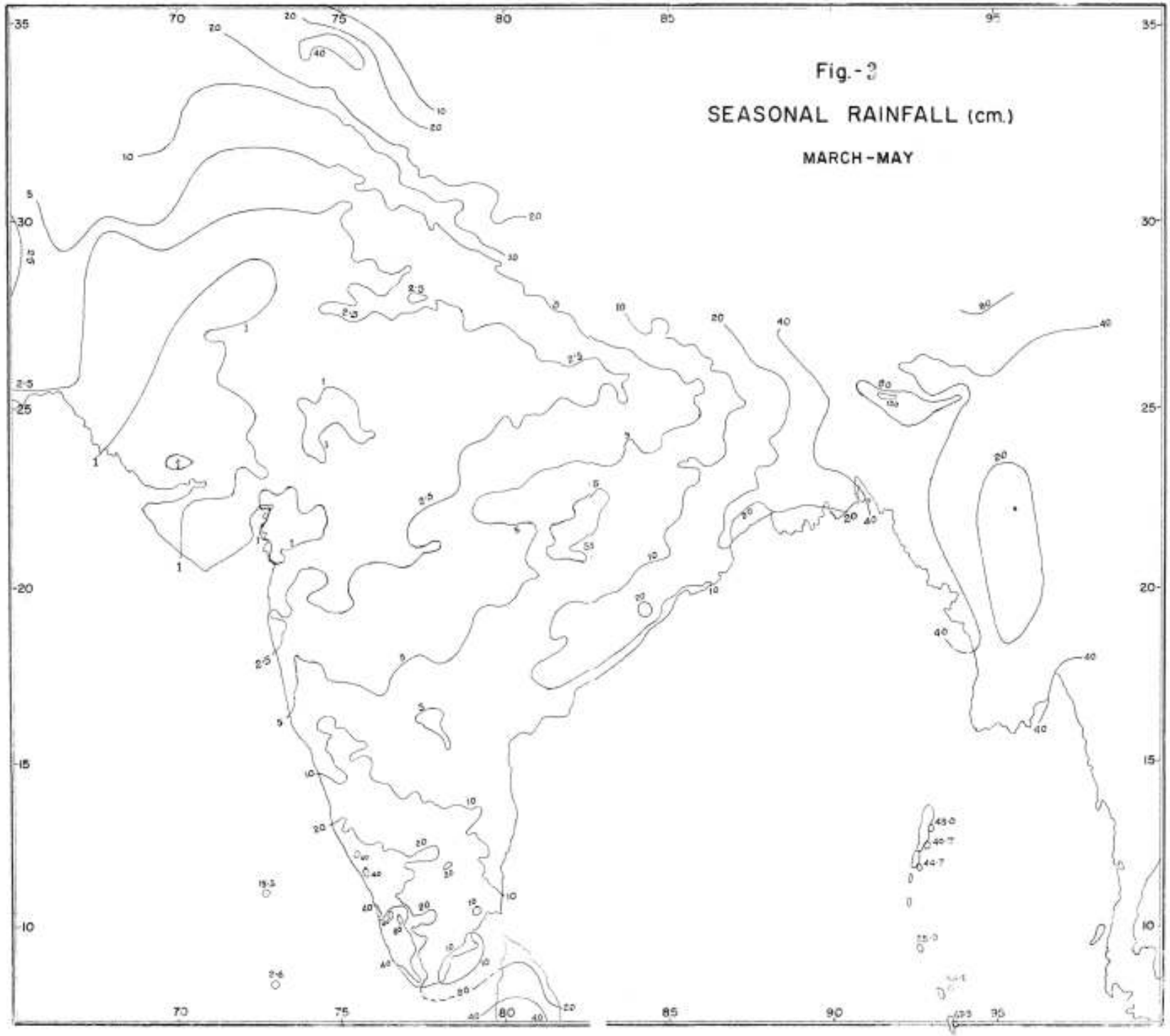


Fig.-3
SEASONAL RAINFALL (cm.)
MARCH-MAY

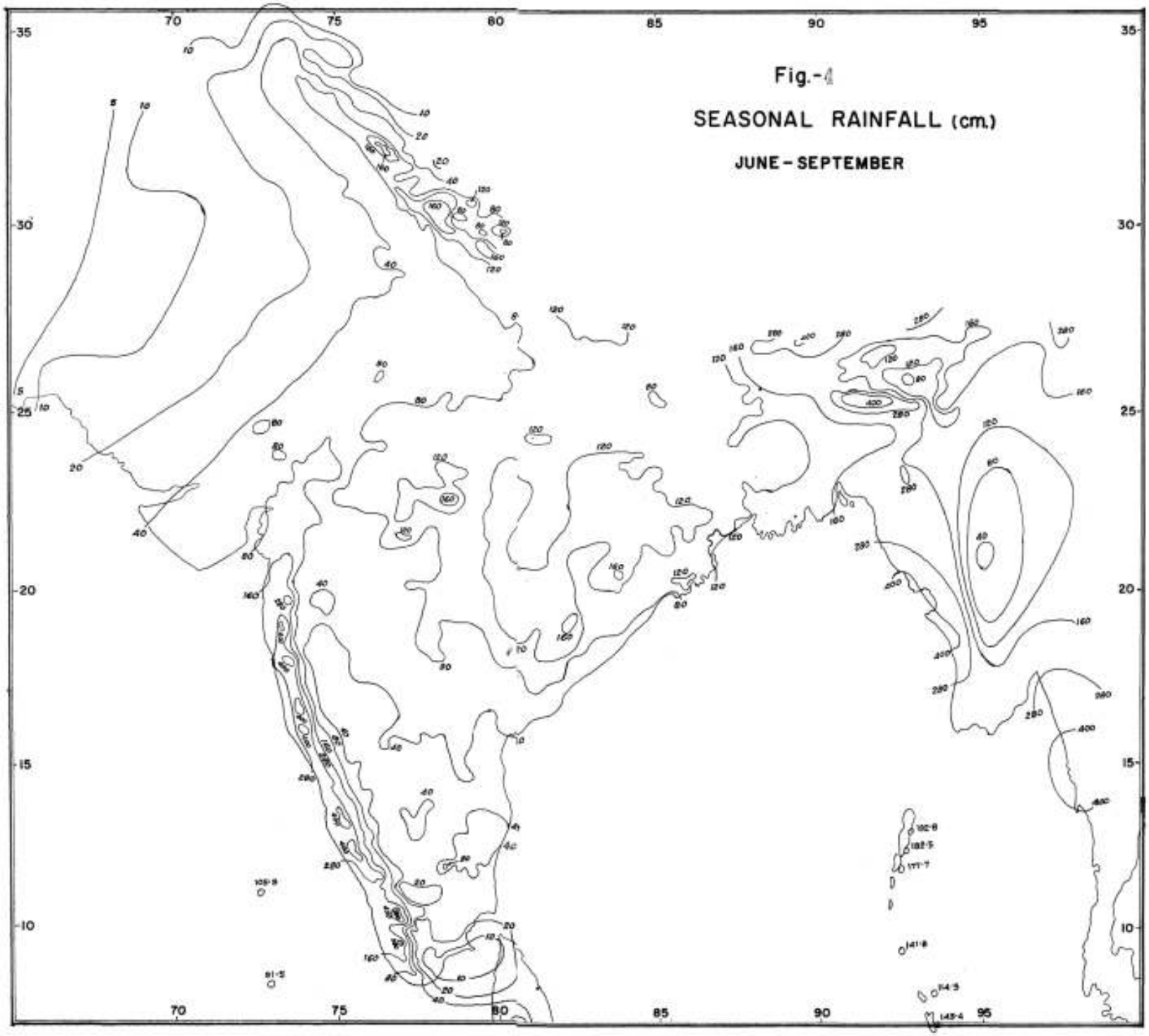


Fig.-1
SEASONAL RAINFALL (cm.)
JUNE - SEPTEMBER
35
30
25
20
15
10
70
75
80
85
90
95

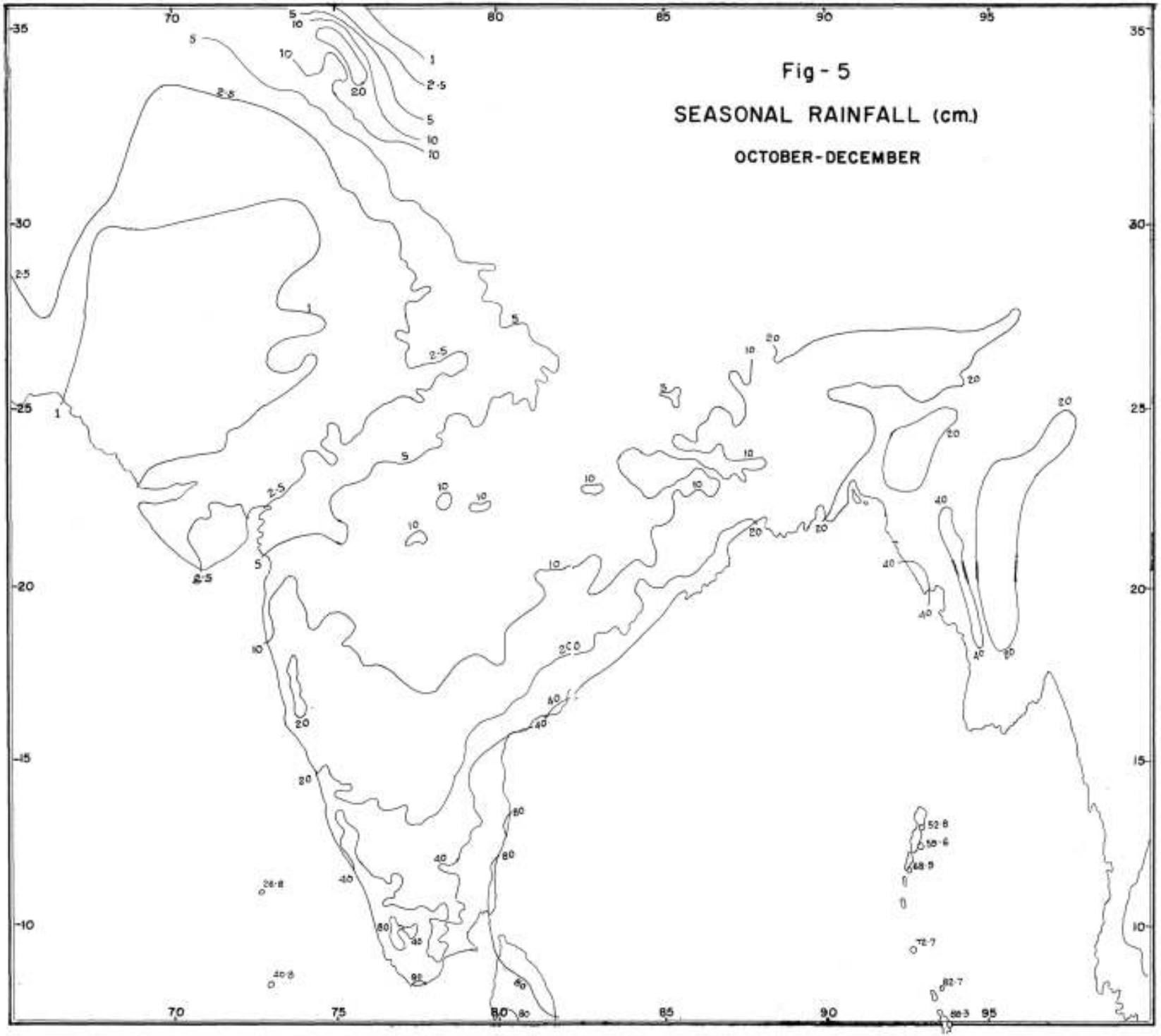


Fig - 5
SEASONAL RAINFALL (cm.)
OCTOBER-DECEMBER

FIG. 6 : COEFFICIENT OF VARIABILITY - ANNUAL RAINFALL

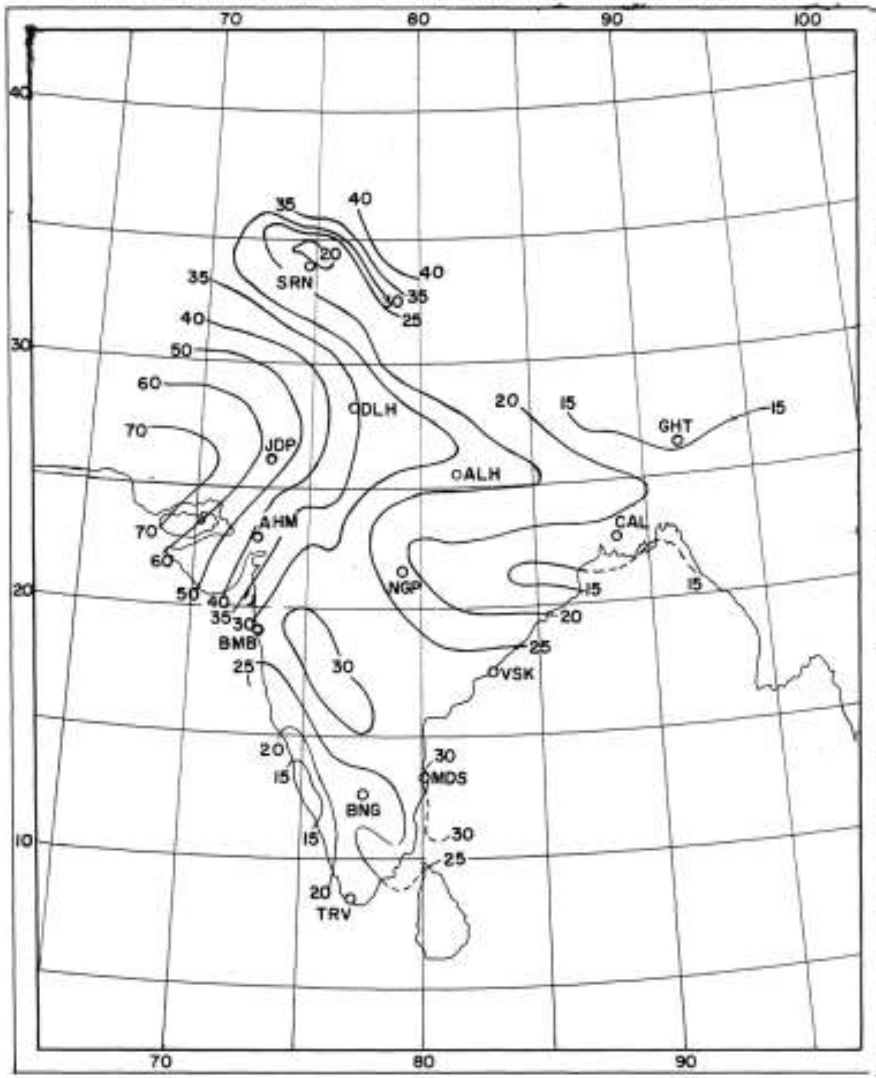
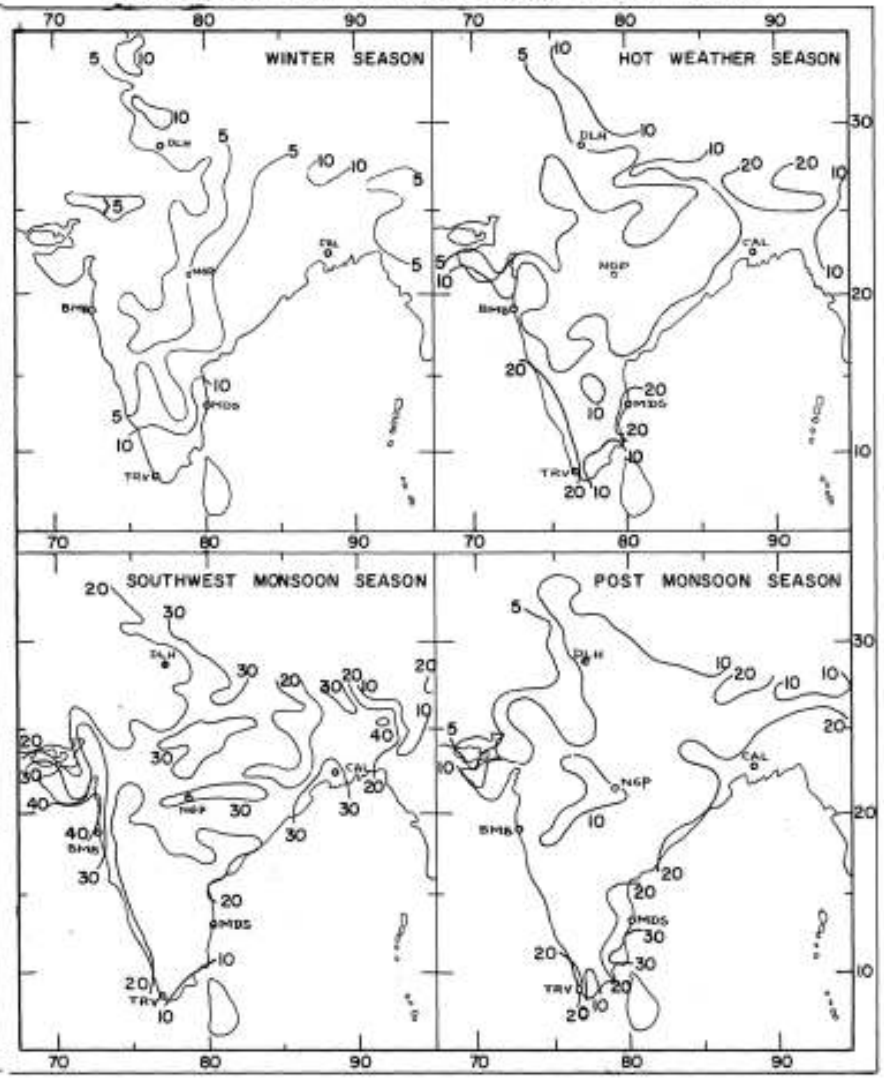


FIG. 8 : HEAVIEST RAINFALL (CMS.) IN 24 HOURS



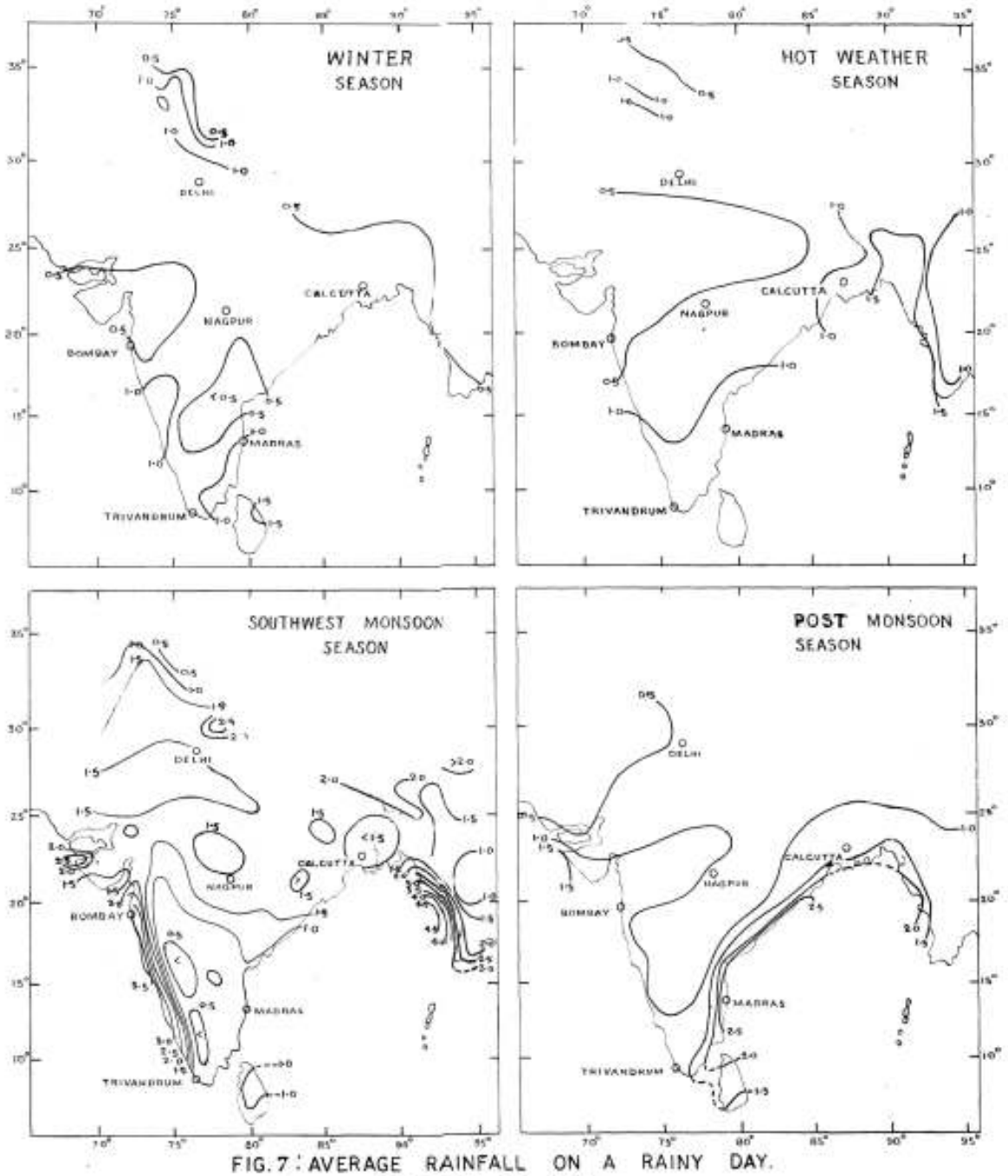


FIG. 7 : AVERAGE RAINFALL ON A RAINY DAY.
(Rao and Rao 1957)

ISOPLETHS OF HOURLY RAINFALL (Cm)

MAHABALESHWAR

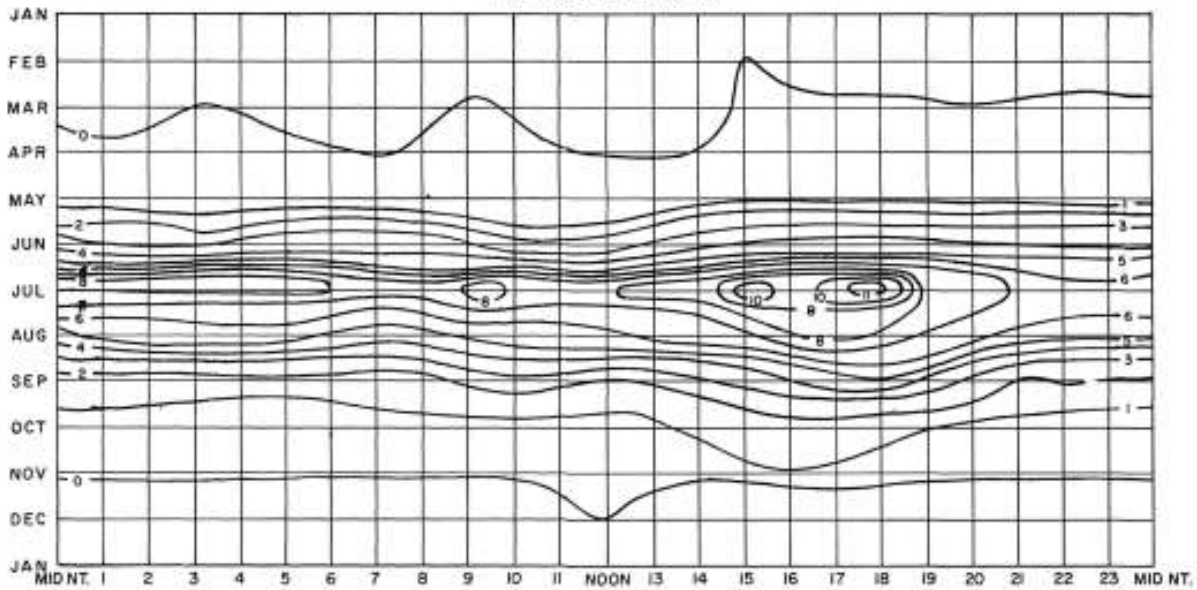


FIG. 9 (i)

BOMBAY

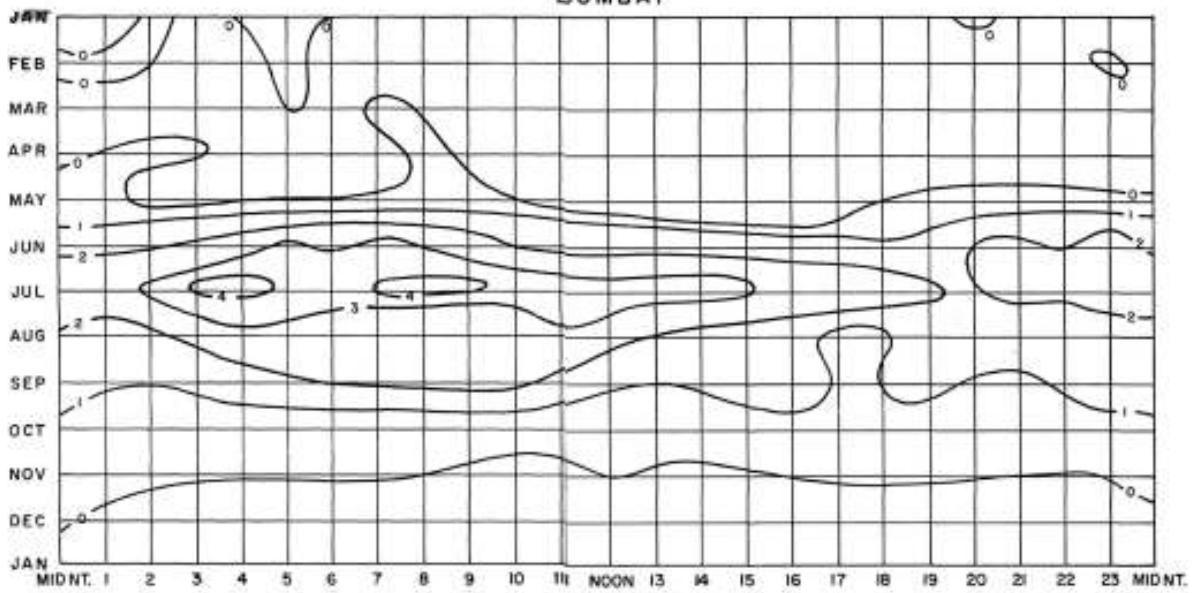


FIG. 9 (ii)

ISOPLETHS OF HOURLY RAINFALL (Cm)

POONA

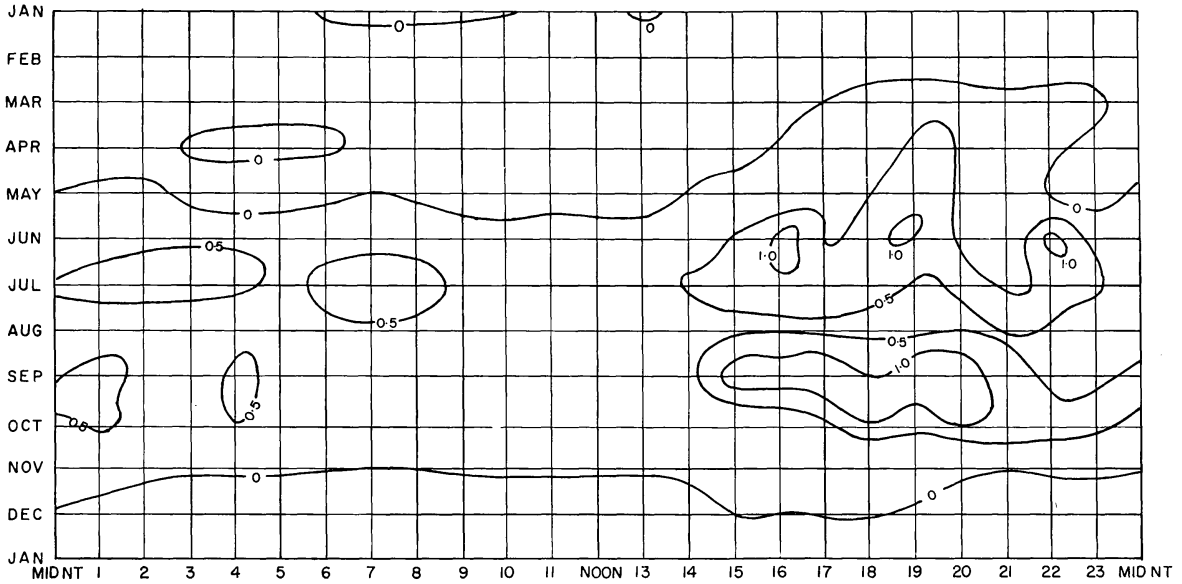


FIG.9(III)

HYDERABAD

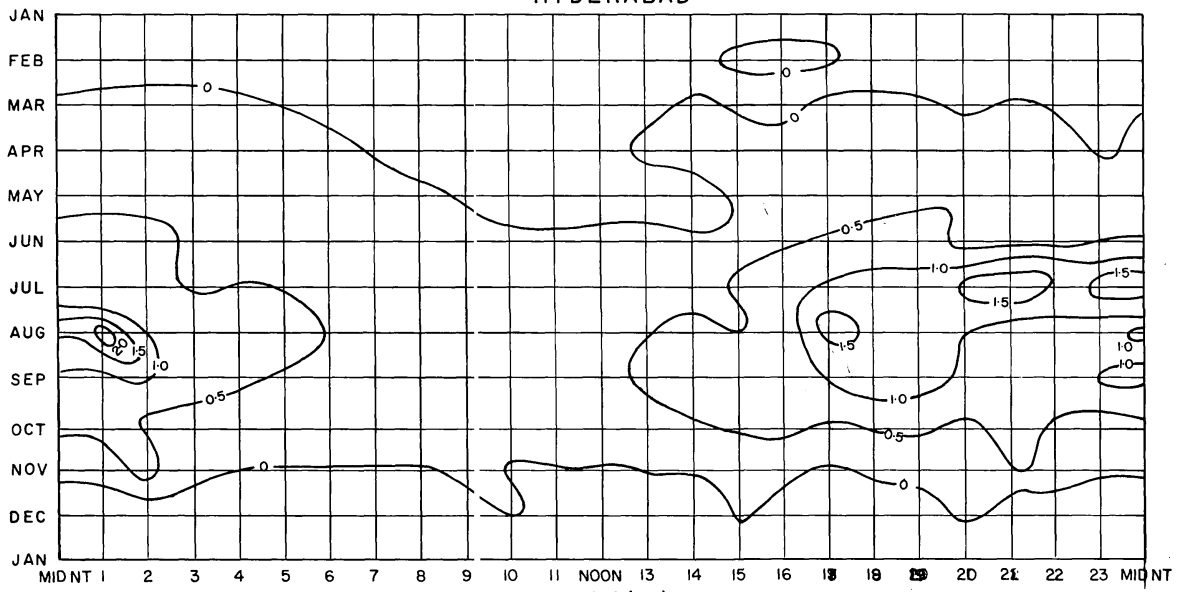


FIG.9(IV)

ISOPLETHS OF HOURLY RAINFALL (Cm)

CALCUTTA

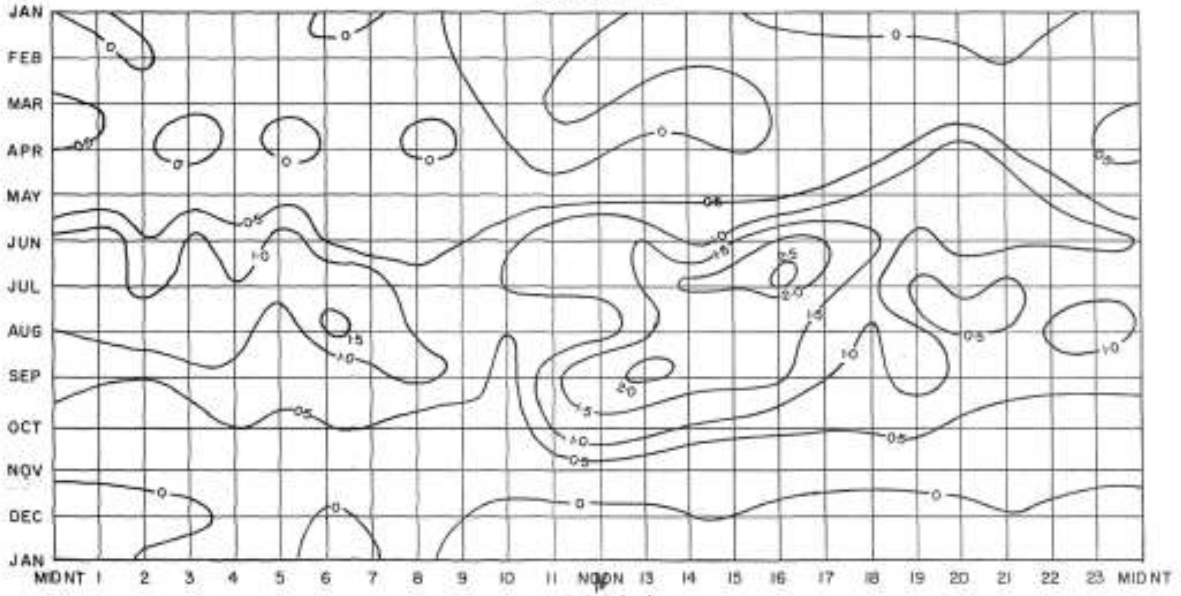


FIG.9 (v)

NEW DELHI

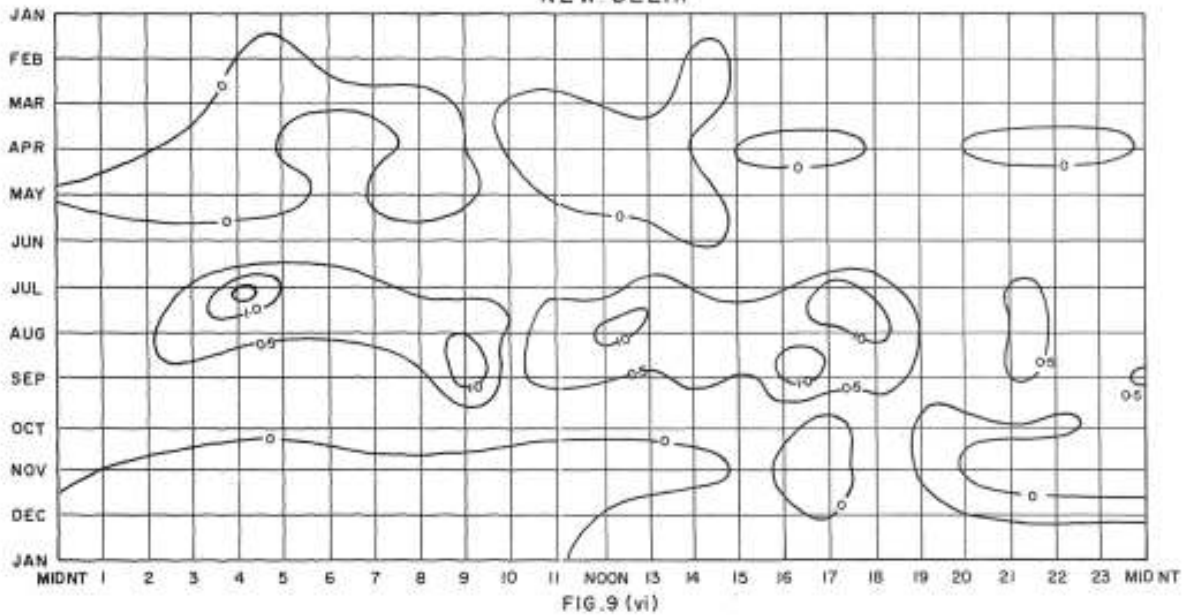


FIG.9 (vi)

FIG. 10: PERIOD (HOURS I.S.T.) OF MAXIMUM AND MINIMUM RAINFALL

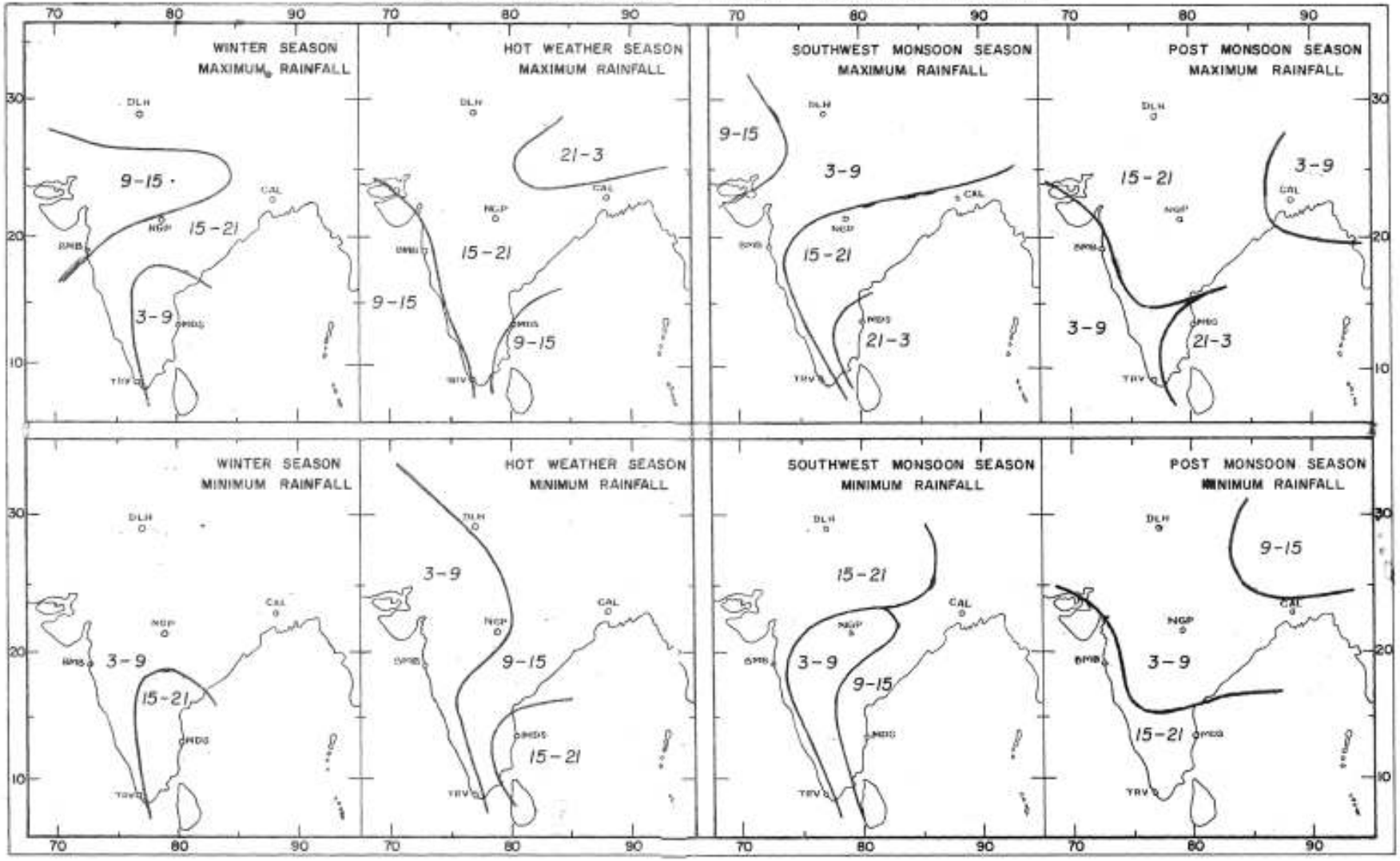


FIG. 11 MAXIMUM RAINFALL (CMS.) IN 1 HOUR

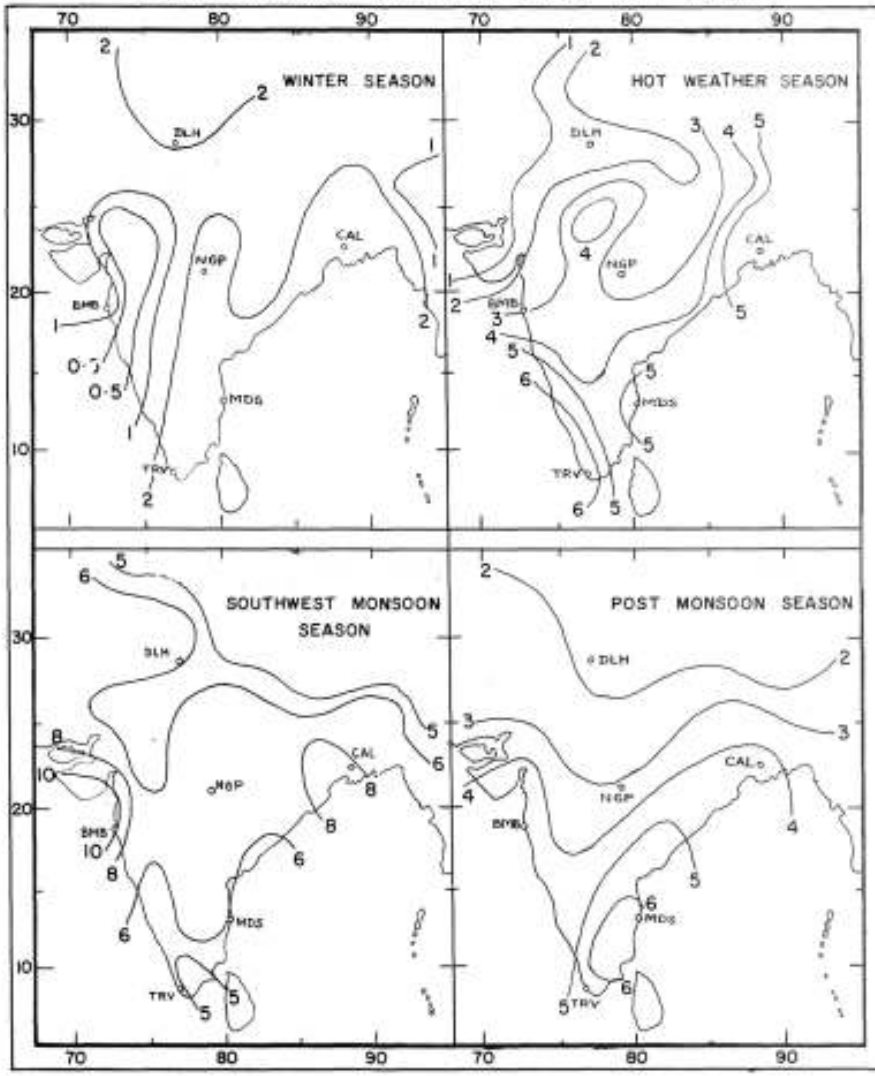
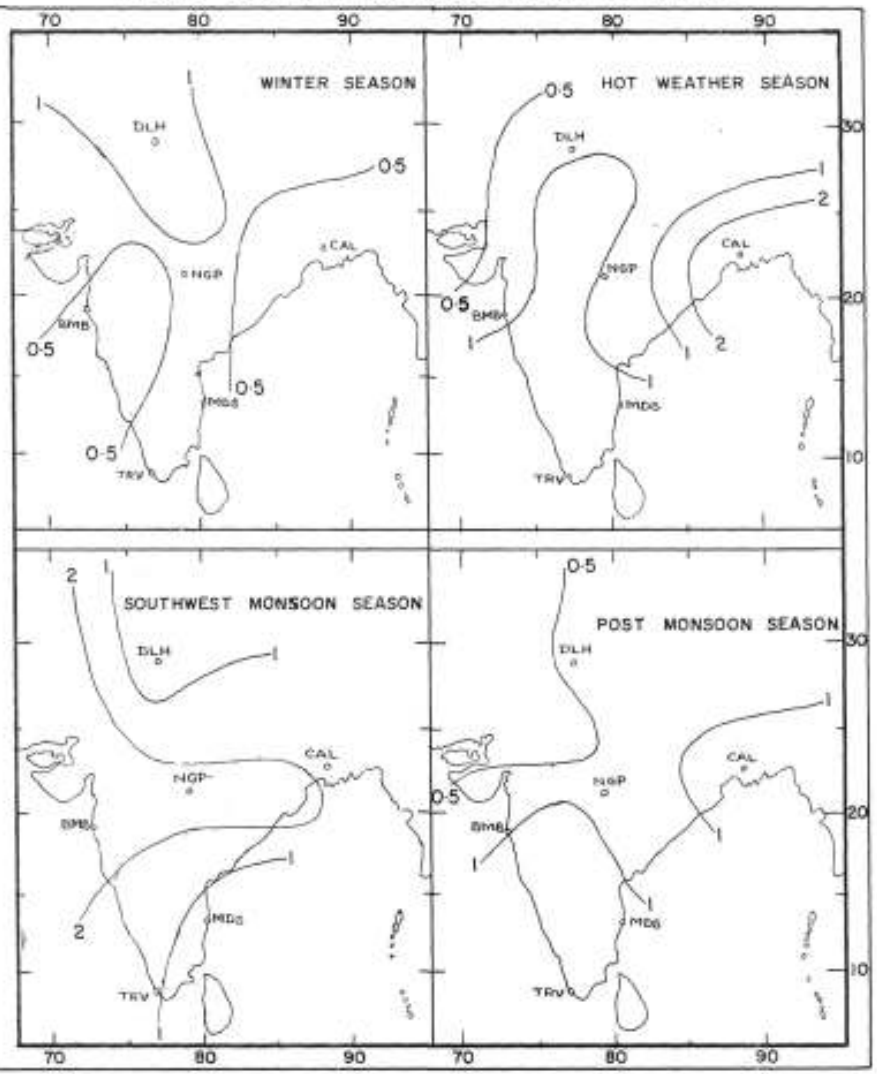


FIG. 12 MAXIMUM RAINFALL (CMS.) IN 5 Mts.



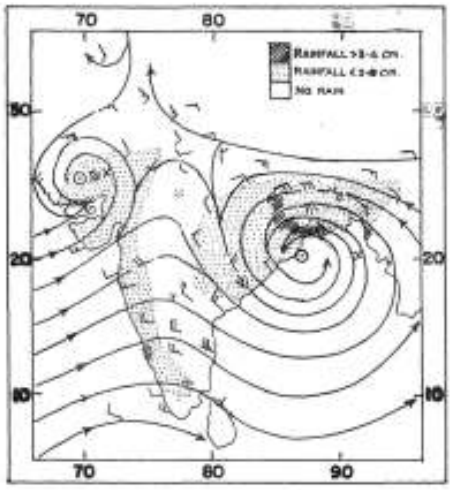


Fig.13 : Distribution of rain past 24 hr. ending at 03 GMT and streamflow at 00 GMT at 1·5 km. asl on 13-9-1961. X = Position of storm centre at sea-level at 03 GMT on 12-9-1961, and ⊙ = corresponding position on 13-9-1961. (Raghavan, 1964.)

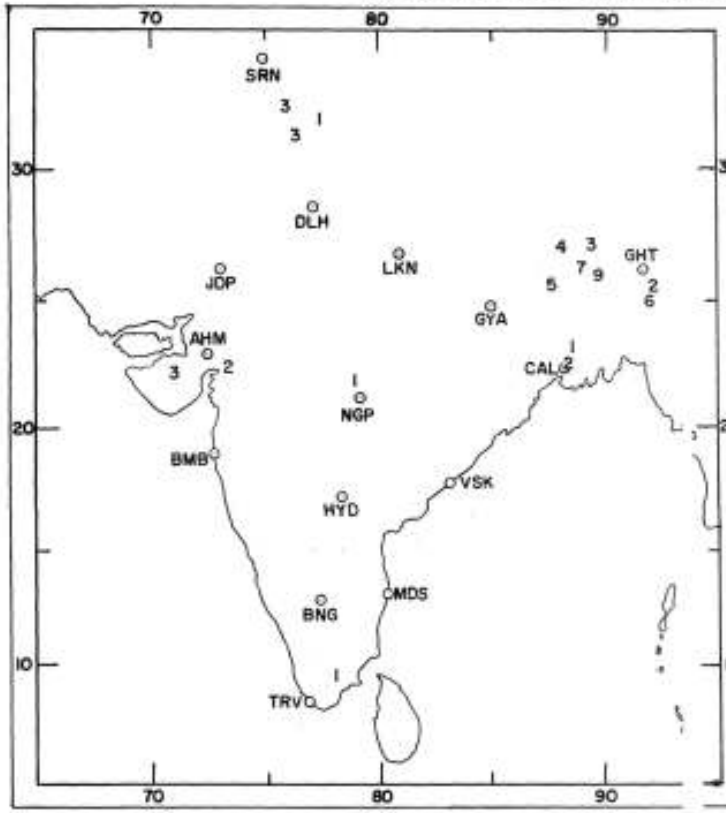


FIG.14 : RAINFALL DISTRIBUTION ON A WEAK MONSOON DAY 15-9-15 6.
(ONLY RAINFALLS ≥ 1 CM. ARE MARKED)

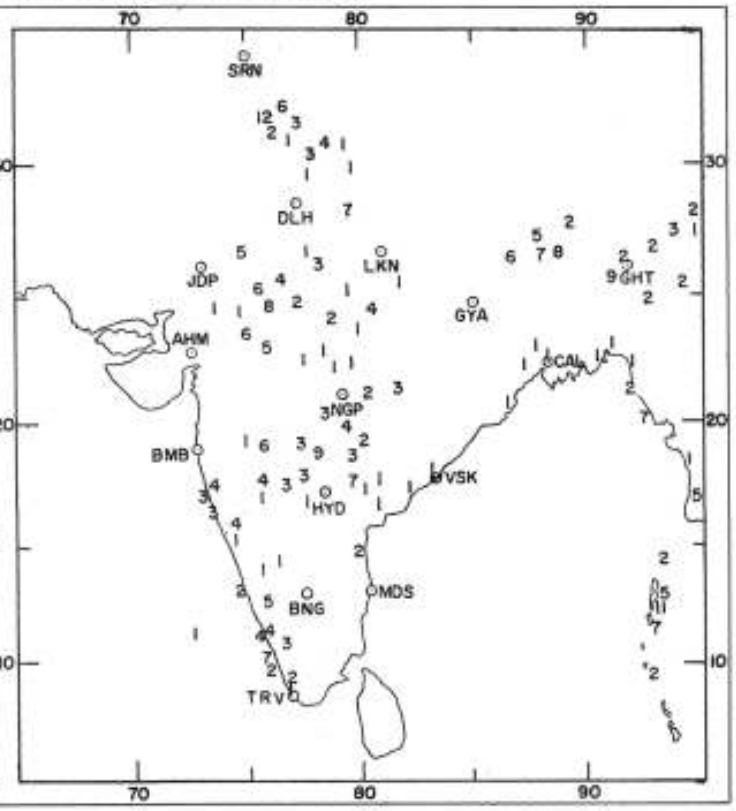


FIG.15 : RAINFALL DISTRIBUTION ON A STRONG MONSOON DAY 15-9-1961.
(ONLY RAINFALLS ≥ 1 CM. ARE MARKED)