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Areal and point distribution of rainfall associated with depressions/storms on the day of crossing the east coast of India*

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ABSTRACT. An attempt has been made to study areal and point distribution of rainfall associated with depressions/storms over the coastal areas 150 miles wide and 150 miles inland, on either side of the storm tracks on the day these disturbances cross the east coast of India between Lats. 8°N and 22°N. The east coast has been divided for this study into three broad sections — Tamil Nadu coast (Lat. 8° to 15°N), Andhra coast (Lat. 15° to 19°N) and Orissa coast (Lat. 19° to 22°N). 26 disturbances have been selected which crossed the east coast at or near about 0300 GMT, the synoptic hour at which 24-hour rainfall all over the country is recorded. In the case of Orissa coast, as a test case study has been made of about 20 disturbances which crossed the coast at different synoptic hours and the results obtained from both these cases have been found to be almost similar.

1. Introduction

It has been found from earlier studies that the total number of depressions/storms which originated or moved through the region bound by Long. 50° to 100°E and Lat. 5° to 35° N has been of the order of 1055 during the 80-year period from 1891 to 1970. Out of 1055 tropical disturbances about 700 crossed the east and west coasts of India between Lat. 8° to 22° N to enter the Indian area. Of these 700 disturbances, about 77 per cent crossed the east coast alone (Fig. 1) and on an average 7 disturbances have been crossing the east coast per year. However, the maximum number of disturbances that have crossed the east coast in any single year during the last 80 years have been of the order of 12 (*i.e.*, in the year 1927 and 1933) while the minimum number has been of the order of 2 (*i.e.*, in the years 1901 and 1957).

These disturbances while crossing the east coast of India cause intense rainfall over the coastal areas as well as over those areas which fall along and near their tracks. Rainfall distribution (areal and point) along the east coast of India has been studied on the day a tropical disturbance crosses the coast. For a proper understanding of rainfall distribution associated with these disturbances the east coast from 8° to 22°N has been divided into three broad sections— (*i*) Orissa coast from Lat. 19° to 22°N, (*ii*) Andhra coast from Lat. 15° to 19°N and (*iii*) Tamil Nadu coast from Lat. 8° to 15°N.

2. Review of earlier work on the distribution of rainfall associated with depressions/storms

Several workers have studied the distribution of heavy rainfall associated with depressions/storms over the Indian area during different seasons and months. Ramakrishnan (1940) studied the rainfall associated with 7 post monsoon depressions/storms and came to the conclusion that there are two distinct separate areas of heavy rainfall one of which lies near the storm track and the other on its right. Boothalingam and Srinivasan (1950) studied 5 storms of pre-monsoon season and found that heavy rainfall occurs mainly to the south of the track but has an extension ahead of the storm. Ratnam and Sarker (1966) studied the rainfall distribution of a number of depressions and storms both during pre-monsoon and post monsoon seasons over south India and their finding was that it was difficult to draw any uniform conclusions. However, in a number of cases they did find that heavy rainfall did occur on the left side of the tracks. Mukherjee *et al.* (1966) also studied this problem in detail and found that whenever depressions/storms travelled directly towards Tamil Nadu coast in the month of October, heavy rainfall of the same order not only occurred over Tamil Nadu coast but it also occurred over large areas of Andhra coast towards northeast.

*Preliminary results of this study were presented at 'Water Resources' Symposium held at Bangalore in May 1971 and at the technical sessions of 7th Forecasting Officers' Conference held at Poona in March 1972.

TABLE 1

Monthwise distribution of depressions/storms which crossed the different sections of the east coast during 1891 to 1970

Section of the east coast (*vide* Fig. 1)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Orissa coast (Lat. 19°-22°N)	—	—	—	—	4	44	91	111	80	21	4	—	355
Andhra coast (Lat. 15°-19°N)	2	—	—	1	4	6	5	1	37	29	12	—	97
Tamil Nadu coast (Lat. 8°-15°N)	5	—	2	3	8	—	—	—	1	21	38	10	88

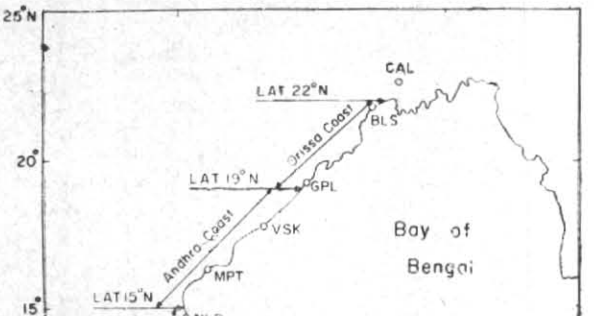

Fig. 1

Map showing three sections of east coast of India

As regards distribution of heavy rainfall associated with monsoon depressions Pisharoty and Asnani (1957), using the technique of composite charts, showed that heavy rainfall area extends to about 300 miles ahead and about 300 miles behind the centres of these disturbances and the width of heavy rainfall area is about 250 miles to the left of the storm track. Almost similar results were obtained by Lal (1958) while studying rainfall distribution around slow moving disturbances. Abbi *et al.* (1970), while examining major rainstorms in the Mahanadi basin, found that the centres of heavy rainfall in almost all the cases lay in the southwestern sector about 200 to 300 miles ahead of the pressure centres. Recently, Desai (1972) has shown that heavy rainfall in monsoon depressions occurs only in southwest quadrant and heavy rain can occur even within about 40 miles of the centre under suitable conditions. According to Ramaswamy (1967) the incidence of heavy rainfall to south of the track is due to lower tropospheric convergence taking place between the south westerlies and deflected easterlies.

3. Depressions/storms crossing the east coast of India

While preparing Table 1 it has been observed that maximum number of disturbances that crossed the Orissa coast in one single year have been of the order of 9 and that happened in the year 1927. Similarly the maximum number of disturbances that crossed the Andhra and Tamil Nadu coasts in one year have been of the order of 3 and 4 respectively. In the former case it happened on 13 occasions (*i.e.*, in the years 1897, 1904, 1915, 1923, 1929, 1933, 1945, 1947, 1949, 1956, 1962, 1966 and 1969) while in the latter case it happened on 3 occasions (*i.e.*, in the years 1943, 1946 and 1966).

Due to absence of dense network of self recording raingauge stations along the east coast, the distribution of rainfall associated with depressions/storms crossing the east coast at any hour cannot be studied in a satisfactory manner. To avoid this difficulty, this study is based upon the rainfall data of fairly dense network of ordinary raingauges (both IMD Observatory stations and State raingauges) whose rainfall data are recorded daily at 0830 IST (0300 GMT). In view of this, only such disturbances have been selected for this study which actually crossed the east coast at or near about 0830 IST and continued to travel at least for the next two or three days so that the track was well defined after crossing the coast.

A list of disturbances which crossed the different sections of the east coast at 0830 IST was picked out from the scrutiny of relevant literature on depressions/storms. In the case of Orissa and Andhra coasts 10 such disturbances were obtained during the periods 1931-1950 and 1921-1950 respectively. Disturbances which crossed the Orissa and Andhra coasts in recent years (*i.e.*, 1951 onwards) could not be considered as the daily rainfall data of State raingauges in Orissa State are not available in the printed tables.

The number of disturbances which crossed the Tamil Nadu coast at about 0830 IST is extremely meagre. During the entire 70-year period (1891 to 1960) only 6 disturbances could be selected for this study. A list of selected disturbances for all the three sections of the east coast is given in Table 2.

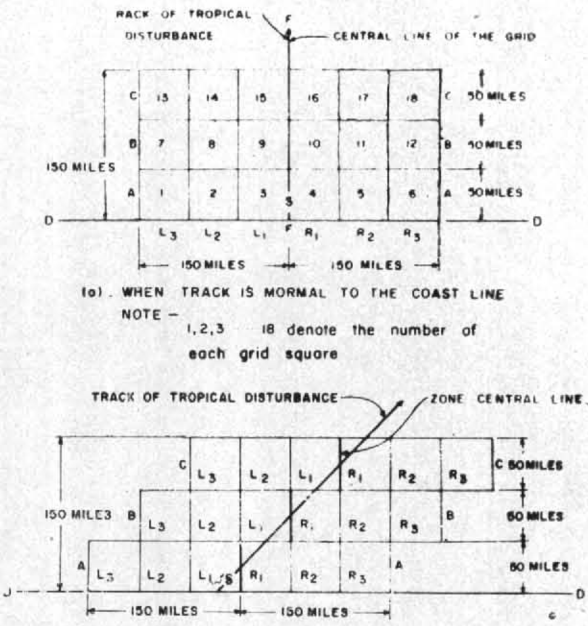

Fig. 2

Grid used for the study of areal distribution of rainfall over different sections of the east coast

4. Grid used for rainfall analysis of depressions/storms

A special grid shown in Fig. 2 (a and b) was employed for the analysis of these disturbances. The grid has been described in detail by Dhar and Mhaiskar (1970) while making a preliminary study of space-time distribution of rainfall over the coastal Orissa. Briefly speaking, the grid used is of rectangular shape whose sides are 300 miles long and 150 miles wide. It is divided into 18 squares of 50-mile width (Fig. 2a). The three horizontal zones of the grid (A, B and C) are 300 miles long and 50 miles wide and can slide left or right parallel to the base line DD. The three vertical columns on the left and right sides of the central line FF of the grid have been labelled as L_1, L_2 and L_3 and R_1, R_2 and R_3 respectively. For studying the areal and point distribution of rainfall due to depressions/storms, the grid was used in the following manner.

(*a*) The approximate point on the east coast where a disturbance crossed inland was first determined by a reference to storm track maps (India met. Dep. 1964) and *Indian Daily Weather Reports* for the corresponding years. Track of the disturbance was then drawn for the next two or three days through the point of crossing the coast on a large scale base map of the area showing the network of State and India met. Dep. raingauges and orography of the area.

(*b*) A tangent was drawn to the coast line at the point of crossing the coast on the base map.

(*c*) The base line DD of the grid was then superimposed on the tangent. If the track was perpendicular to the coast, the grid was placed as shown in Fig. 2(a). In case it made an angle with the coast, which was the usual feature, each zone of the grid was slided right or left, parallel to the base line DD, until the mid point of the zone central line lay on the track as shown in Fig. 2 (b).

(*d*) All the raingauges falling within each grid square to the right and left of the storm track were separately noted and rain amounts recorded at each raingauge station on the day of crossing the coast were achieved. Average rain depth for each grid square was then worked out using rainfall data of all the raingauges within the grid square. However, in grid squares where some amount of orography was encountered and raingauge network was sparse average rain amounts were worked out using the isohyetal method.

(*e*) Average rain depths for all the 18 grid squares thus obtaind were then utilized to obtain rain depths for the different columns and zones of the grid using the following method.

Let $r_1, r_2, r_3, \ldots\ldots, r_{18}$ be the respective average rain depths for the grid squares 1, 2, 3, ... ,18 shown in Fig. 2(a) for a certain disturbance which crossed the coast at 0830 IST on a given date. Since all the grid squares are of the same area (*i.e.*, 50 miles $\times$50 miles), the average weighted rainfall for the grid column L_3 will be $r_{L3} = (r_1 + r_7 + r_{13})/3$. Similarly average weighted rain depth for grid column R_1 will be $r_{R1} = (r_4 + r_{10} + r_{16})/3$. In the same way the average weighted rainfall over zone

TABLE 2

List of tropical disturbances which crossed the different sections of the east coast at about 0830 IST of the day

Date of crossing	Approximate point of crossing the coast		Type of disturbance at the time of crossing
	Lat.	Long.	
Orissa coast (Lat. 19° to 22°N)			
9 Aug 1933	20°35′	86°55′	Depression
10 Aug 1934	21°35′	87°00′	„
9 Sep 1935	20°00′	86°06′	„
13 Jun 1936	21°15′	87°00′	„
4 Oct 1936	20°05′	86°30′	„
10 Oct 1938	19°30′	85°15′	„
6 Sep 1939	21°18′	86°55′	„
24 Jun 1940	20°10′	86°30′	„
11 Jul 1943	22°00′	86°48′	„
25 Jul 1944	20°50′	86°50′	„
Andhra coast (Lat. 15° to 19°N)			
17 Sep 1923	18°10′	83°42′	Depression
9 Sep 1933	18°00′	83°50′	„
18 Oct 1933	16°35′	82°00′	„
29 Aug 1936	18°15′	84°00′	„
29 Sep 1938	16°02′	81°05′	„
7 Oct 1941	17°00′	82°05′	„
16 Oct 1944	16°10′	81°42′	„
18 Oct 1945	16°28′	81°15′	Storm
2 Nov 1948	16°25′	81°45′	Depression
21 Sep 1949	16°20′	81°45′	„
Tamil Nadu coast (Lat. 8° to 15°N)			
6 Nov 1898	12°40′	80°20′	Storm
1 Jan 1909	10°15′	79°20′	„
8 Oct 1921	14°15′	80°10′	„
25 Sep 1924	13°50′	80°15′	Depression
2 Nov 1946	10°35′	79°50′	„
21 Nov 1958	13°27′	80°15′	„

A of the grid will be $r_{ZA} = (r_1 + r_2 + ... + r_6)/6$ and for zone B it will be $r_{ZB} = (r_7 + r_8 + ... + r_{12})/6$.

Using the procedure mentioned above, average weighted rain depths were worked out for each grid column and grid zone for each of the disturbances mentioned in Table 2. By compositing together respective columnwise and zonewise average rain depths for all the disturbances mentioned in Table 2, the average rain profiles for each section of the coast were prepared. The columnwise profiles are shown in Fig. 3 and zonewise profiles in Fig. 4.

5. Discussion of average rain profiles

Columnwise profiles — As stated earlier, Fig. 3 represents the average rainfall distribution in the neighbourhood of a storm track on the day of crossing the coast. It has been observed that the actual patterns of individual disturbances do not differ much from this average picture. A close examination of Fig. 3 reveals the following facts—

(*a*) In the case of disturbances affecting Orissa and Andhra coasts, the maximum rainfall occurs in column L_2 of the grid, *i.e.*, an area between 50 to 100 miles to the left of the storm track and 150 miles inland.

(*b*) In the case of disturbances which affect Tamil Nadu coast, the maximum rainfall occurs in L_1 column of the grid, *i.e.*, an area between the track and 50 miles to the left of the track and 150 miles inland.

(*c*) In all the three sections of the east coast, minimum rain occurs in column R_3 *i.e.*, an area between 100 to 150 miles on the right side of the storm track and 150 miles inland.

(*d*) Average ratios of rain depths over the two adjacent columns of the grid on either side of the storm track (*i.e.*, L_1 and R_1 columns) have the following values —

Section of the east coast	*Average ratio of rain depths*
(*i*) Orissa coast	1·6
(*ii*) Andhra coast	1·2
(*iii*) Tamil Nadu coast	1·2*

The above ratios show that in the case of Orissa coast, average rain depth on an area 50 miles wide and 150 miles inland on the left side of the storm track is 60 per cent more than the rain depth on an equivalent area on the right side of the track. In the case of Andhra and Tamil Nadu coasts these ratios are considerably less.

*The average ratio for Tamil Nadu is based upon the data of 6 disturbances only while for the other two sections of the east coast, each ratio is based on 10 disturbances.

(*e*) For each of the disturbances affecting the different coastal sections, average rain depths were calculated over the grid areas on the left and right sides of the storm track, *i.e.* over an area of 22,500 sq. miles, on either side of the storm track. Using this data, ratios of rain depths obtained over left and right sides of the storm track were then obtained for each of the disturbances mentioned in Table 2. The average ratios for each section of the coast are as follows —

Section of the east coast	*Average ratio of rain depths*
(*i*) Orissa coast	2·3
(*ii*) Andhra coast	1·5
(*iii*) Tamil Nadu coast	1·3

The above results show that as one proceeds along the east coast from south to north the average ratios increase considerably. This indicates that, by and large, the rainfall obtained on the left side of the storm track is definitely more in the case of disturbances which affect the northern sections of east coast than in areas to the south. Since northern sections are mainly affected during the monsoon months, it can therefore be concluded that during monsoon depressions/storms the areas immediately to the left of the storm tracks generally receive heavier rainfall than the areas to the right while in the case of pre and post monsoon disturbances this contrast is not so prominent.

6. Zonal distribution of average areal rainfall

Average areal rain depths obtained over the different zones of the grid (*i.e.*, A, B and C) have been plotted in Fig. 4 and smooth profiles have been drawn for each section of the east coast. These profiles show that all the three sections of the east coast on the day of crossing receive maximum rain depths in zone of the grid A. From Fig. 4 it is also seen that variation of average rain depths from zone A to zones B and C is rather steep in the case of Andhra and Tamil Nadu coasts while in the case of Orissa coast the variation is less steep. In other words, this indicates that in the case of Orissa coast, on the day of crossing of a disturbance, rainfall extends far into the interior while in the case of Andhra and Tamil Nadu coasts rainfall sharply decreases in the interior.

7. Distribution of areal rainfall when depressions/storms cross the coast at times other than 0830 IST

This aspect has been tested only in the case of coastal Orissa and it is presumed that the results from other sections of the east coast will not be much different. Some 20 disturbances (Table 3) were picked out during the period 1931 to 1950

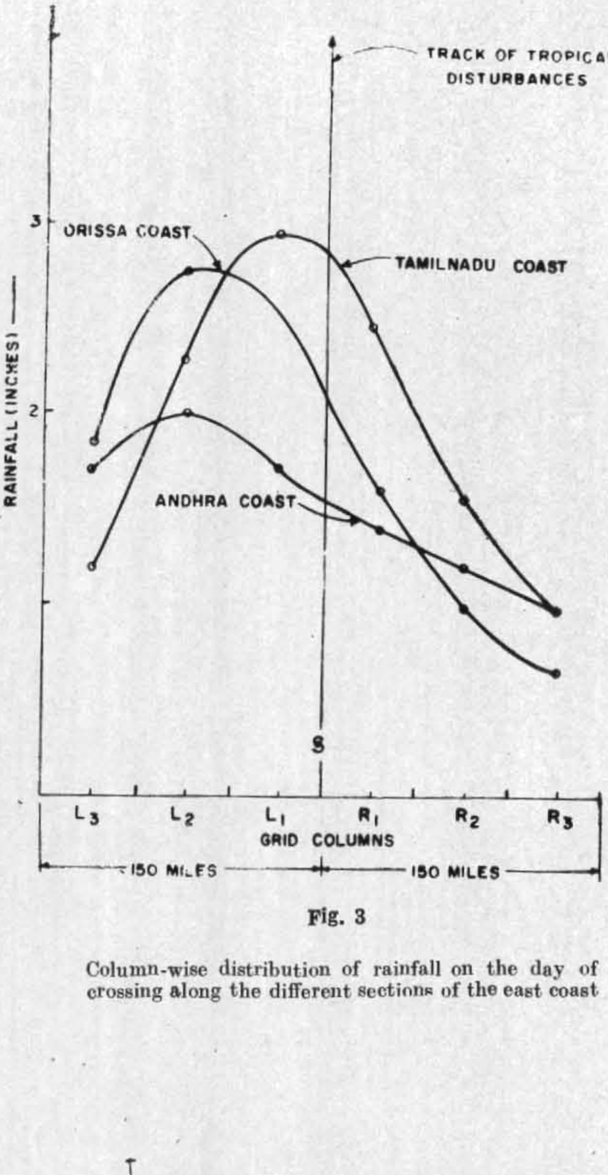

Fig. 3

Column-wise distribution of rainfall on the day of crossing along the different sections of the east coast

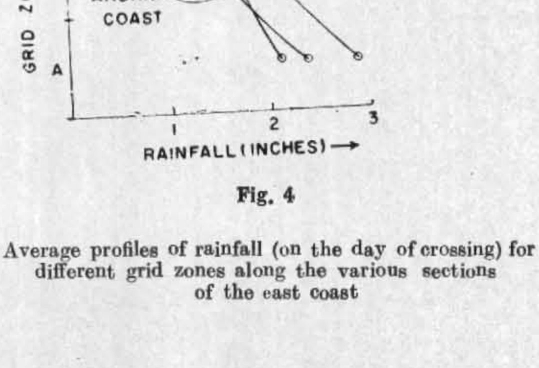

Fig. 4

Average profiles of rainfall (on the day of crossing) for different grid zones along the various sections of the east coast

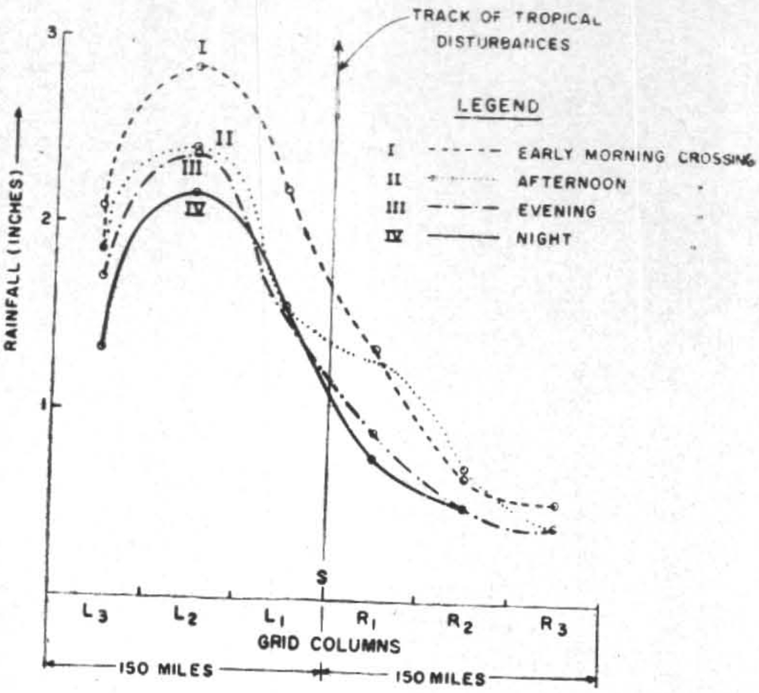

Fig. 5

Average profiles of rainfall on the day of crossing the Orissa coast at different times other than 0830 IST

TABLE 3

List of tropical disturbances (depressions) which crossed the Orissa coast at different times of the days other than 0830 IST

Date of crossing	Time of crossing	Approximate point of crossing the coast	
		Lat. (°N)	Long. (°E)
24 Jul 1936	Early morning	19°42′	85°24′
24 Jul 1937	,,	21°18′	86°54′
4 Sep 1937	,,	20°18′	86°38′
13 Sep 1937	,,	21°38′	87°30′
31 Jul 1944	,,	20°38′	86°54′
24 Jul 1946	,,	21°00′	87°00′
2 Jul 1934	Afternoon	21°32′	87°15′
21 Aug 1940	,,	20°18′	86°18′
28 Aug 1947	,,	21°36′	86°54′
3 Aug 1933	Evening	21°24′	87°06′
12 Sep 1933	,,	20°24′	86°36′
8 Jul 1935	,,	21°48′	87°45′
18 Aug 1946	,,	20°20′	86°35′
16 Jul 1947	,,	21°00′	87°00′
7 Jul 1948	,,	20°36′	86°54′
16 Aug 1931	Night	21°42′	87°30′
16 Jun 1933	,,	20°42′	87°00′
16 Aug 1934	,,	19°54′	86°00′
21 Aug 1934	,,	21°36′	87°20′
15 Oct 1934	,,	21°00′	87°00′

which crossed the coast at different times of the day. These disturbances have been grouped (*i*) 6 in the early morning, (*ii*) 3 in the afternoon, (*iii*) 6 in the evening and (*iv*) 5 at night.

Using the same type of analysis as mentioned earlier, average columnwise rain profiles have been drawn separately for each group of disturbances and these are shown in Fig. 5. It is evident from this figure that the average rain profiles follow more or less the pattern as the rain profiles of the morning group (*i.e.*, 0830 IST) of disturbances shown in Fig. 3. It is thus evident that irrespective of time of crossing the coast depressions/storms affecting Orissa coast follow, more or less, the same pattern of rainfall distribution as shown in Fig. 3.

8. Frequency distribution of point rainfall

Frequency distribution of point rainfall on the day of crossing the east coast was attempted in respect of zones A, B and C of the grid for the different sections of the east coast. All the point rainfall accumulations in each particular grid square of zones A, B, and C on the right and left sides of the storm track were plotted using the amount of rain as ordinate and distance to the grid square centre, right or left of the track, as the abscissa. An example of such a plot for zone A of all the three sections of the east coast (*viz.*, Orissa, Andhra and Tamil Nadu) is shown

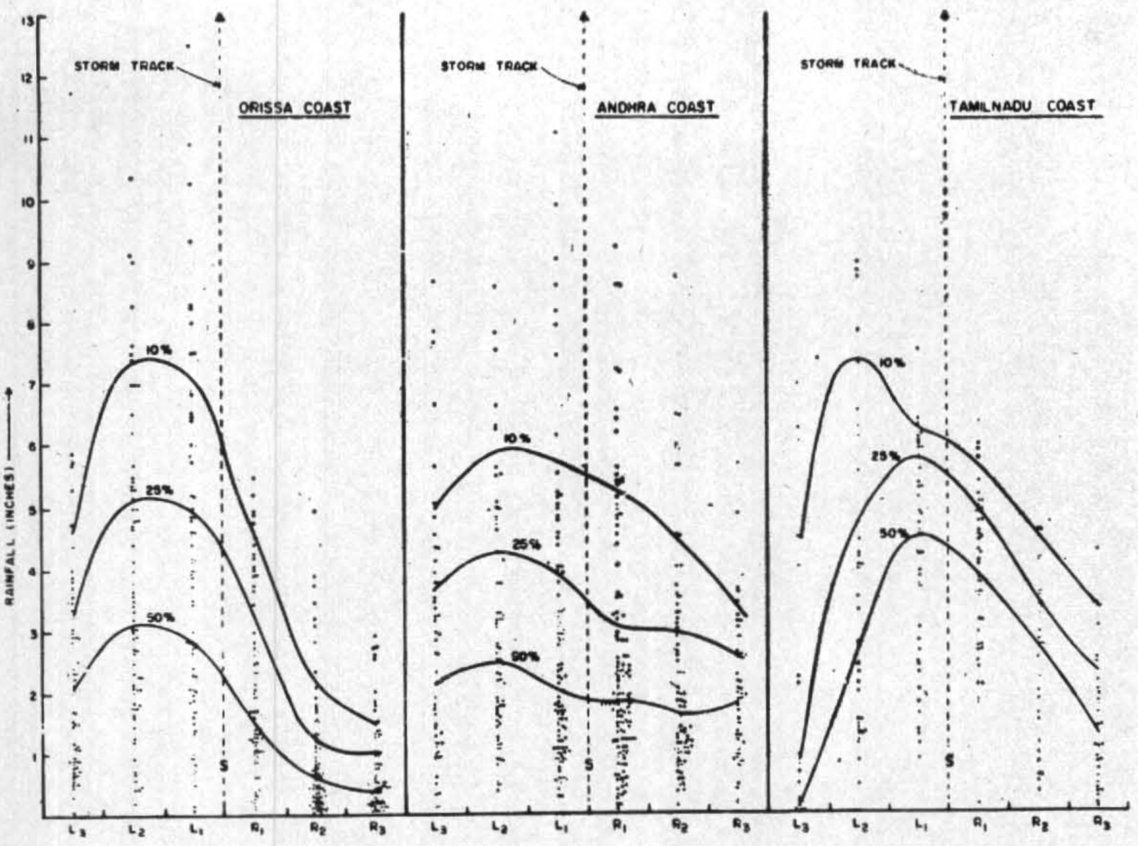

Fig. 6

Point rainfall distribution along the zone A of the grid on the day of crossing the east coast

in Fig. 6. Probability curves for 10, 25 and 50 per cent levels of occurrence have also been drawn for the three sections of the east coast. The 10 per cent curve separates all the obeserved point rainfall values in that zone so that 90 per cent of the points are on the curve or below and 10 per cent are above. Similarly, 25 and 50 per cent curves were drawn keeping 75 and 50 per cent points respectively on or below the curves and 25 and 50 per cent points respectively above the curves. It is seen from these probability profiles for all the three sections of the east coast, that the probability of occurrence of maximum rain amounts (point values) are high on the left side of the track. It is also observed from Fig. 6 that peaks in the different probability curves show that in the case of Orissa and Andhra coasts, maximum point values occur in the L_2 column. In the case of Tamil Nadu coast they occur in L_1 column upto 25 per cent probability level. Thus point distribution of rainfall along the east coast in zone A of the grid also shows similar results as obtained from curves based upon areal rainfall. Similar study was also carried out for zones B and C of the grid and almost similar results were obtained.

9. Summary and conclusions

This study has some practical utility to the design engineer besides helping the forecaster to locate areas of heavy rainfall with reference to tracks of depressions/storms. To a design engineer such studies help in the design of levees and embankments for controlling and regulating floods for coastal areas which are simultaneously subjected to floods as well as storm surges. The broad conclusions from the foregoing study are as follows—

(*i*) In the case of Orissa and Andhra coasts, the day on which a disturbance moves inland, the centre of heavy rain lies between 50 to 100 miles to the left of the storm track between the coast and 50 miles inland. In the case of Tamil Nadu coast, the heavy rain centre is closer to the storm track and lies between the track and 50 miles to its left.

(*ii*) The average ratios of rain depths over the two adjacent grid columns of width 50 miles and depth 150 miles inland (*i.e.*, columns L_1 and R_1 on the left and right sides of the storm track are — (*a*) Orissa coast 1·6, (*b*) Andhra coast 1·2 and (*c*) Tamil Nadu coast 1·2.

(*iii*) The average ratios of rain depths over the grid area 22,500 sq. miles (*i.e.* 150×250 sq. miles), on the left and right sides of the storm track are: (*a*) Orissa coast 2·3, (*b*) Andhra coast 1·5 and (*c*) Tamil Nadu coast 1·3.

(*iv*) On the day a depression/storm crosses the coast, the rainfall sharply decreases as one proceeds from the coast to the interior in the case of Andhra and Tamil Nadu coasts while in the case of Orissa coast the decrease is rather gradual.

(*v*) The probability profiles of point rainfall show that high magnitude point rainfall has a greater chance of occurrence in the grid column L_2 in the case of Orissa and Andhra coasts and in grid column L_1 in the case of Tamil Nadu coast.

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