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A study of rainfall, upper winds and divergence patterns associated with recurved monsoon depressions

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ABSTRACT. The present study was undertaken with a view to compute mean pattern of rainfall, upper winds and divergence field associated with monsoon depressions which had recurved and started moving northward. Mean charts were prepared by pooling together data of six such depressions using a moving co-ordinate system.

1. Introduction

1. 1. Depressions in the monsoon season are known to move from the Bay of Bengal in a west-northwesterly track upto central or northwest India. Meteorologists have noticed, specially in the later half of the season, a distinct northerly recurvature in quite a few cases of these depressions over that part of the country. It is expected in such cases that the associated areas of heavy precipitation and kinematic field also undergo a change.

1. 2. The distribution of rainfall around individual monsoon depressions in India has been the subject of studies by Ramanathan and Ramakrishnan (1933), Sur (1933), Mull and Rao (1949), Malurkar (1950), Desai (1951) and others. These studies show that heavy rain is mainly confined to southwest sector of the monsoon depressions moving in westnorthwesterly direction.

1. 3. Pisharoty and Asnani (1957) used moving co-ordinate system to compute composite rainfall charts by pooling data from three monsoon depressions which moved in a westnorthwesterly direction over central India. The rainfall data used were of preceding 24 hours with respect to the depression's centre of the day. They found that rainfall was confined to an area of 300 miles (ahead) and 250 miles (south) in the southwest sector of the depression.

1. 4. Mulky and Banerjee (1960) computed mean upper wind charts (at 0·6, 1·5, 3·0, 4·5, 6·0, 7·2, 9·0, 12·0 and 16·2 km a.s.l.) by pooling data pertaining to 22 depressions which moved in west-northwest direction. They found that cyclonic circulation extending upto 9·0 km a.s.l. around such monsoon depressions asymmetric along the vertical, the axis of circulation having a pronounced tilt towards the southwest sector.

1. 5. Kulshrestha and Gupta (1964), Venkatraman and Bhaskara Rao (1965) and George and Datta (1965) studied individual cases of monsoon depressions which recurved over northwest India. The first was a satellite study, in the second study the effect of high level divergence on the rainfall was studied and the third was a synoptic study of a monsoon depression. In all the three studies heavy precipitation was observed in the north sector of the depression. In the second study low level convergence topped by high level divergence was found associated with heavy rainfall areas. In the third study winds at 9·0 km a.s.l. were found to favour recurvature of the depression.

1. 6. So far no attempt has been made to study the extent of forward sector which is liable for heavy precipitation. With this aim in mind an attempt has been made in the present study to compute mean charts of rainfall, upper winds (at 0·9, 1·5, 3·0, 6·0 and 9·0 km a.s.l.) and divergence pattern at these levels for monsoon depressions that recurved over northwest or central India and moved in a more or less northerly track.

2. Technique

2. 1. To overcome the difficulty of paucity of data specially in the case of upper winds and to compute a mean model, the technique of moving co-ordinate system was used to prepare composite charts from the data of six monsoon depressions. The technique was used by Hughes and Jordon (1952) in the study of tropical storms when they were confronted with a similar problem of inadequate upper winds data. The grid used was of 10° latitude and 10° longitude (scale 1° Lat./Long. ≈1 cm). The centre of the grid coincided with the depression's centre. The direction and speed of the co-ordinate system was taken to be coincident with the direction and speed of the depression during the next 24 hours. In the present study since all the selected depressions moved after recurvature in a near northerly track, the orientation of the grid was kept north-south.

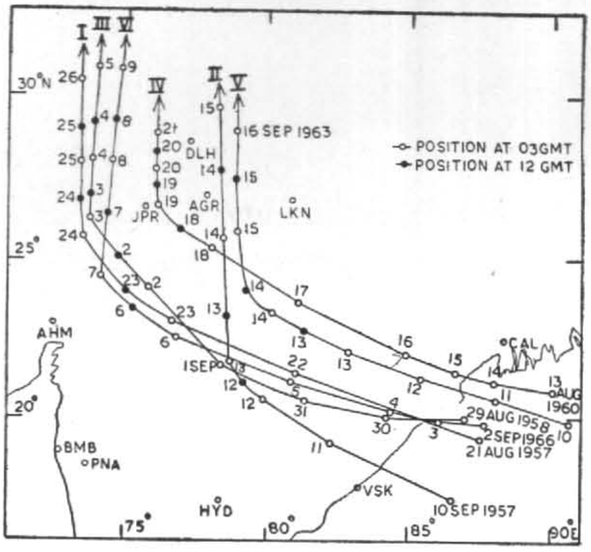

Fig. 1. Tracks of monsoon depressions

3. Data used

3. 1. Six monsoon depressions were chosen for the purpose of this study. The track of these depressions are shown in Fig. 1. All the six depressions had given widespread rain and were fairly similar in characteristics. Rainfall and wind data were extracted from the Indian Daily Weather Report of the corresponding period.

4. Method

4. 1. 1. *Rainfall pattern* — Daily rainfall of all stations within a radius of about 500 km from the centre of the depression on the following dates was plotted on W-3 special charts (Scale 1 cm ≈ 100 km).

(*i*) 24 & 25 Aug 57	(*iv*) 19 & 20 Aug 60
(*ii*) 13 & 14 Sep 57	(*v*) 14 & 15 Sep 63
(*iii*) 3 & 4 Sep 58	(*vi*) 7 & 8 Sep 66

The depression centres referred to 0300 GMT of each day and the rainfall referred to the amount recorded during the *succeeding* 24 hours. Thus, for example, the rainfall plotted around depression centre on 24 August 1957 referred to the amount recorded at 0300 GMT of 25 August 1957. This was done with the aim of forecasting heavy precipitation areas during next 24 hours based on actual observations, once the location of the depression centre and the chances of its recurvature were established. However, the amount of rainfall recorded during the preceding 24 hours with respect to the depression's centre of the above mentioned dates was also plotted for academic interest and to see if it gave any clue to the recurvature process.

4. 1. 2. The grid was divided into 100 equal parts such that each square covered an area of 1° Lat. and 1° Long. On the plotted W-3 special charts this overlay was placed with it's centre coinciding the depression's centre. The rainfall amount falling in different squares was noted and the procedure was repeated for all the 12 days. The average rainfall for all the 12 days pertaining to each square was then plotted in a magnified grid (scale 1° = 2 cm). To smoothen out the pattern, further space averaging was performed by taking mean of rainfall of the adjacent four squares (thus reducing the number to 25 from 100) and plotting it at the middle point of the four squares. Ischyets at an interval of 0·5 cm were drawn. Figs. 2 and 3 refer to the mean rainfall during succeeding and preceding 24 hours respectively with respect to the depression's centre of the day.

4. 2. *Wind pattern* — A process similar to one used for the processing of rainfall data was adopted for the collection and processing of upper wind data at 0·9, 1·5, 3·0, 4·5, 6·0, and 9·0 km a.s.l. at 0000 and 1200 GMT for the above 12 days. The centre of the grid coincided with the depression's centre of the day and time. Winds pertaining to each square were vectorially averaged and plotted at the centre of the magnified grid. On the mean wind

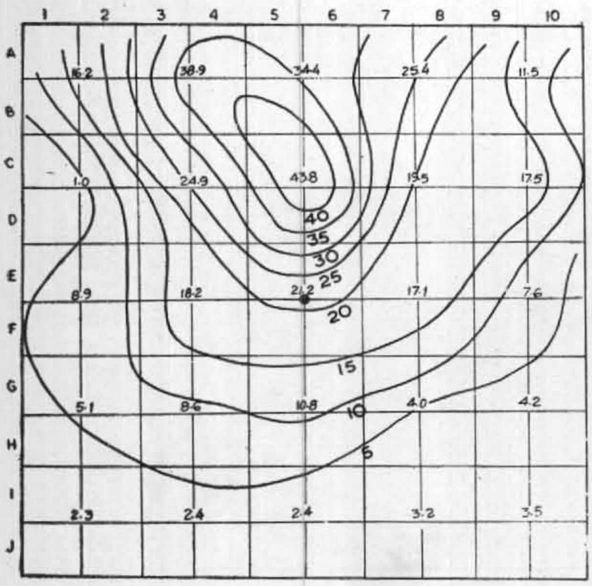

Fig. 2. Mean rainfall (mm) during subsequent 24 hours

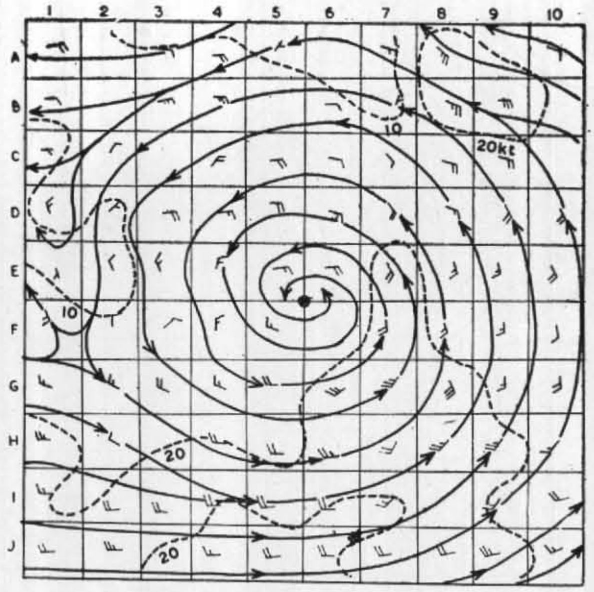

Fig. 4. Mean streamline and isotach pattern at 0·9 km

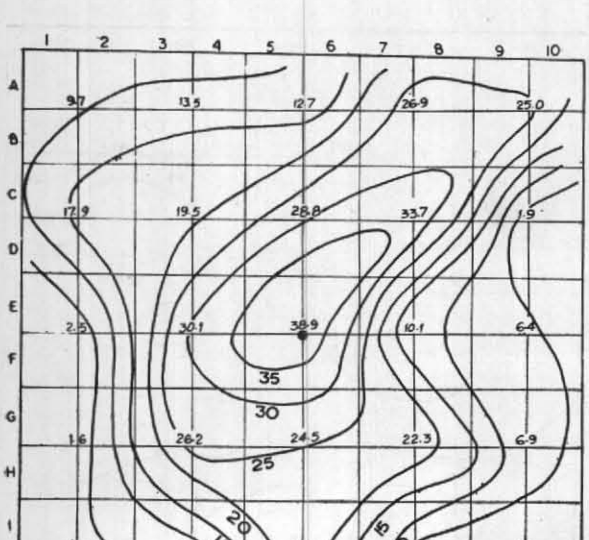

Fig. 3. Mean rainfall (mm) during preceding 24 hours

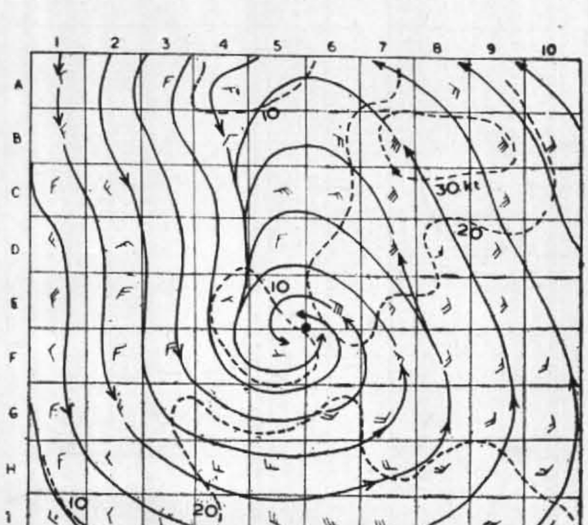

Fig. 5. Mean streamline and isotach pattern at 3·0 km

charts for the six levels streamlines and isotachs were drawn. The three mean wind charts are shown in Figs. 4 to 6 consecutively. These charts were used for the computation of corresponding mean divergence pattern.

4. 2. 1. *Divergence pattern* — Bellamy (1949) chose geographically fixed triangles at the vertices of which upper wind data were available and computed the fractional increase/decrease in the area of such triangles to find divergence/convergence. In the present study equilateral triangles were chosen. The grid area of 10° Lat. and 10° Long. was divided into 46 equilateral triangles with base of all the triangles having west-east orientation. Out of these only 23 erect triangles were considered for computation. The height of each triangle was 180 km (≈100 n. miles) on the scale of the grid. Winds were interpolated at the vertices of such triangles. Computed divergence was plotted at the orthocentre of the triangles and isopleths were drawn. The mean divergence charts for the three levels are shown in Figs. 7 to 9 respectively.

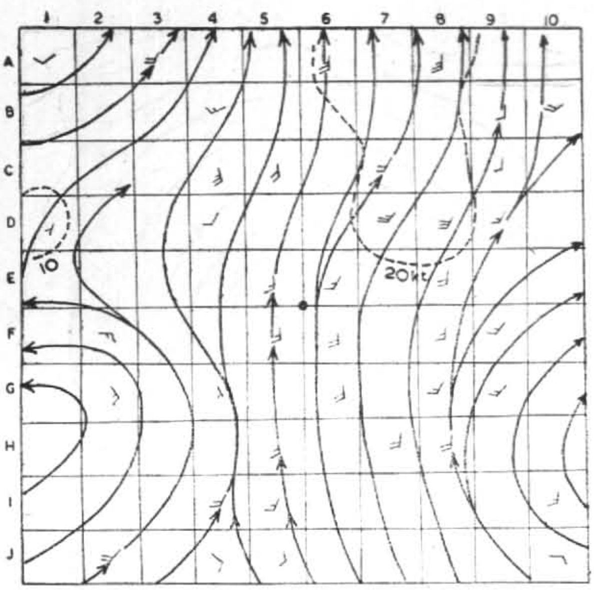

Fig. 6. Mean streamline and isotach pattern at 9·0 km

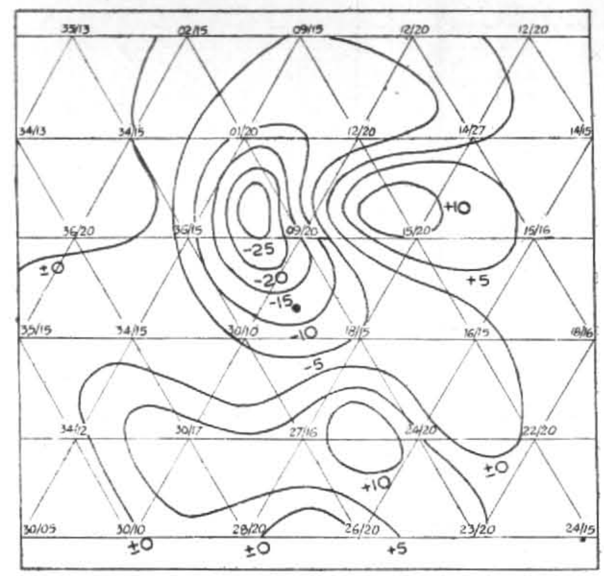

Fig. 8. Mean divergence pattern at 3·0 km

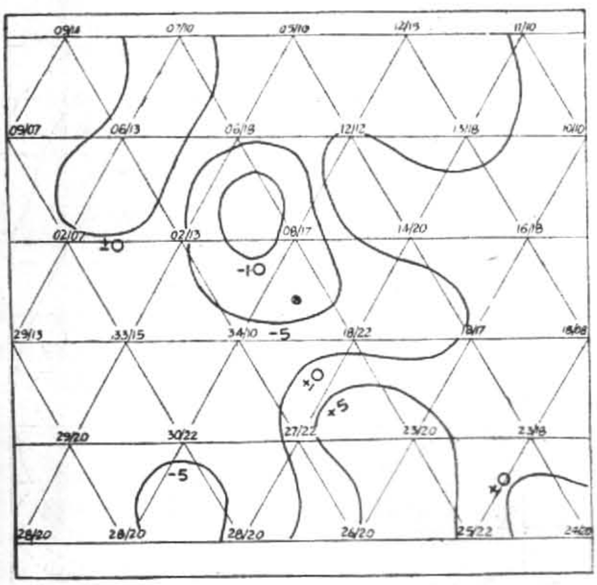

Fig. 7. Mean divergence pattern at 0·9 km

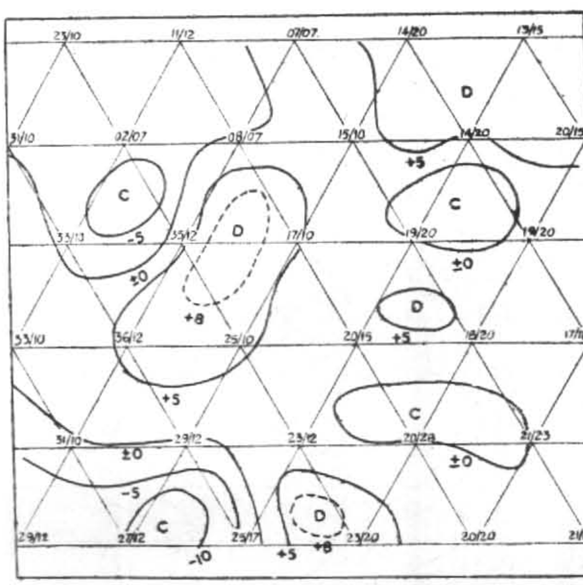

Fig. 9. Mean divergence pattern at 9·0 km

4. 2. 2. A graph was plotted to show vertical section of divergence at a point 200 km north-northwest of the depression centre (Fig. 10).

5. Description and discussion of patterns

5. 1. *Future rainfall pattern* — The plot of subsequent 24 hours rainfall showed rainfall of 3 cm and more confined to the forward sector of the northward recurved track. The area of such precipitation extended 500 km in length (ahead and 300 km in width (west-east direction) with greater area and higher amounts of precipitation recorded in the left as compared to the right forward sector (Fig. 2). The extent of heavy precipitation found in the case of recurved monsoon depressions is comparable with the area 500 km ahead and 400 km to the left of the track found by Pisharoty and Asnani (1957) for depressions which continued to move along the normal west-northwest track.

5. 2. *Past rainfall pattern* — Rainfall of 3 cm and more was found around depression centre elonga-

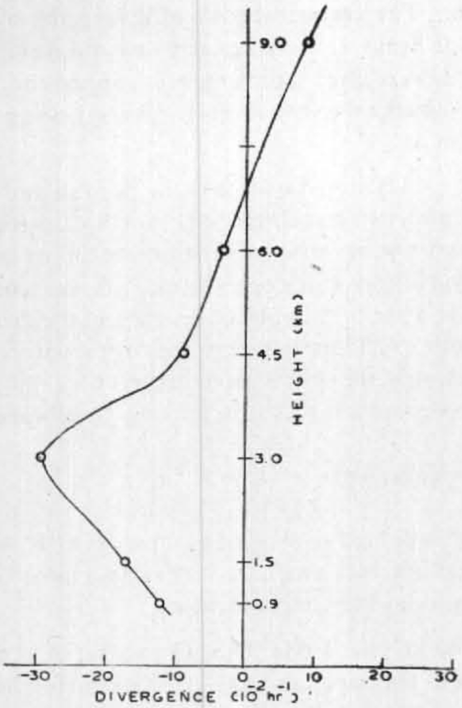

Fig. 10. Vertical section of divergence at a point 200 km NNW of depression centre

ted and oriented from northnortheast to south through the depression centre. The curved pattern and the location of higher amount of rainfall to the right of the track followed thus gave indication of the recurvature process (Fig. 3).

5. 3. 1. *Upper wind patterns : Streamlines*— A spiralling cyclonic circulation was seen extending from 0·9 to 6·0 km a.s.l. The centre of the circulation coincided with depression centre at the surface upto 3·0 km a.s.l. From 4·5 km it was found to be tilting northnorthwestward with height and at 6·0 km a.s.l. the centre of the circulation was at a distance of about 100 km (1° Lat.) northnorthwest of surface centre. It is of interest to note that in the case of depressions which moved westnorthwestward Mulky and Banerjee (1960) found the tilt towards southwest sector which once again was the sector of maximum rainfall.

5. 3. 2. *Trough in zonal westerlies* — An upper air trough extending between 4·5 and 9·0 km a.s.l. and sloping westward with height was located to the northwest of the depression centre. Ananthakrishnan and Bhatia (1958) and others have shown that the location of this westerly trough to the northwest of the depression centre is a favourable situation for recurvature of monsoon depressions. The present study thus confirms their findings.

5. 3. 3. *High level steering* — According to the concept of 'High level steering' the wind at the steering level controls the motion of the disturbance. The steering level is defined as the height at which the cyclonic circulation associated with the system disappears (Dunn and Miller 1960). In the present study the cyclonic circulation associated with the depressions, on an average, extended upto 6·0 km a.s.l. Aloft at 9·0 km a.s.l. wind over sea level depression centre was found to be southerly and was at the periphery of an anti-cyclonic circulation lying further east, just beyond the edge of the grid. It is noteworthy that in the case of depressions moving westnorthwestward Mulky and Banerjee (1960) had found that wind at 9·0 km a.s.l. in the area to the right of the track was eastsoutheasterly. Thus it becomes clear from both these studies that the streamlines at 9·0 km a.s.l. would be extremely useful in predicting the motion of the depressions during the next 24 hours whether recurving or otherwise.

5. 4. 1. *Two-layer divergence concept* — Marked convergence was found in the north and northwest sector of the depression between 0·9 and 4·5 km with a sharp maximum at 3·0 km a.s.l. Pattern was rather diffused at 6·0 km. But at 9·0 km a.s.l. marked divergence was found over the area where convergence was found upto 4·5 km a.s.l.

5. 4. 2. The vertical section of divergence at a point 200 km northnorthwest of depression centre showed convergence extending upto 7·0 km a.s.l. and divergence above it. Magnitude of convergence was found to increase upto 3·0 km reaching a maximum at this level. It reduced sharply between 3·0 and 4·5 km a.s.l. and then gradually upto the level of reversal. This two-layer pattern came out to be similar to one found in the case of extra-tropical disturbances (Fleagle 1948).

6. Conclusions

6. 1. Widespread heavy precipitation after recurvature takes place in the northern sector. Rainfall of 3 cm and more in 24 hours succeeding the time of observation extends 500 km ahead (north) and 300 km perpendicular (west-east) to the track with higher amounts and wider area located in the left forward as compared to the right forward sector.

6. 2. Rainfall during 24 hours preceding the time of observation gives indication of recurvature of the depression by virtue of it's curved pattern and the fact that higher amounts of precipitation are recorded to the right of the track so far followed.

6. 3. Cyclonic circulation extends upto 6·0 km a.s.l. with a tilt of the axis of circulation with height towards northnorthwest which is the region of heavier and wider rainfall activity.

6. 4. Between 4·5 and 9·0 km a.s.l. a trough in the westerlies is located to the northwest of the depression field. It confirms the inference drawn from individual case studies that recurvature is favoured by such waves in the westerlies.

6. 5. Southerly wind was found at 9·0 km a.s.l. over the depression centre at the surface. It indicates that the concept of "steering of disturbances by high level winds" is also applicable to the recurvature of monsoon depression and could be used as a valuable tool to forecast such recurvatures.

6. 6. The vertical section of divergence over the area of heavy rain brings out a two-layer model with lower layer convergence topped by upper layer divergence, the level of reversal being about 7·0 km a.s.l.

This study has shown that the rainfall and upper wind patterns associated with northward recurved depressions are very similar to those of westnorthwestward moving depressions, if we compare them relative to the surface centre and the direction of motion. Thus it seems that recurvature does not change the internal structure of a monsoon depression so long as it is moving northwards.

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DISCUSSION

U.K. BOSE : What was the basis for the forecast of rainfall shown on diagrams ? How far north were the depressions followed ?

AUTHOR : For 'Future rainfall pattern' rainfall recorded during the succeeding 24 hours was considered while for 'Past rainfall pattern' rainfall recorded during the preceeding 24 hours was considered with respect to the depression's surface centre of the day.

Data for two days for each storm, after they had recurved, were considered, till they had reached upto about 28°Lat.