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On some characteristic features of rainfall associated with monsoon depressions over India

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सार — 1961–74 तक बंगाल की खाड़ी और पश्चिम की ओर या पश्चिमउत्तरपश्चिम दिशाओं की ओर गमन करने वाले सभी मानसून अवदाबों को आवदाब केन्द्र के इर्द-गिर्द वर्षा के माध्य प्रारूप को ज्ञात करने के लिए संकलित किया गया है। जैसे-जैसे अवदाब अरब सागर की ओर बढ़ता जाता है वैसे वैसे प्रारूप में और वर्षा की तीव्रता में परिवर्तन होते जाते हैं। इन परिवर्तनों की जांच की गई है और उनका विवेचन किया गया है।

परिणामों से पता चलता है कि अवदाब केन्द्र के निकट भारी वर्षा की अनुपस्थिति रहती है। अधिकतम वृष्टि के प्रारंभिक क्षेत्र दक्षिण-पश्चिम त्रिज्यखंड में केन्द्र से 200 से 400 कि०मी० तक होता है जब कि उससे कम वर्षा राशि एक द्वितीयक क्षेत्र अवदाब केन्द्र के पश्चिम में 800 कि० मी० के इर्दगिर्द स्थित रहता है। ऐसा देखा गया है कि जब अवदाब पूर्व से 80° पश्चिम में होता है तब (कभी कभी माध्य अवदाब से औसतन दुगनी राशि मुक्त होती है) वर्षा पूर्व से 80° पू० में होने वाली वर्षा की अपेक्षतया बहुत ज्यादा होती है।

ABSTRACT. All monsoon depressions which formed during 1961-74 over the Bay of Bengal and moved in westerly or westnorthwesterly directions have been composited to obtain the mean rainfall pattern around the depression centre. Variations in the pattern and intensity of rainfall as the depression approaches the Arabian Sea have been examined and discussed.

Results indicate absence of large scale rainfall activity near the depression centre. A primary zone of the heaviest fall occurs in the southwest sector about 200 to 400 km from the centre while a secondary zone of comparatively less rainfall amount is located about 800 km west of the depression centre. It is seen that when a depression is to the west of 80 deg. E, it gives considerably higher amount of rainfall sometimes twice of the amount released by the mean depression on an average than when it is to the east of 80 deg. E.

1. Introduction

Because of high precipitation potential with very heavy to exceptionally heavy falls and wide spread distribution, monsoon depressions are important and have attracted notice of meteorologists from early times. Most of these studies have been made for individual depressions. For a meaningful analysis of the mean rainfall structure, data from as large a number of stations as possible should be included. In earlier years, data from departmental observatories were used and were sparse. Desai (1951) studied sequence of weather situations during 8 to 13 July 1947 and observed that the rain belt in the SW sector develops only in the later stages after the cold (Em air) currents weakens or withdraws subsequent to the formation of depression. He attributed this to an effective partitioning of a "*warm front*" between relatively cold southwest/westerly air mass and the warm easterly air mass. From a study of the depression of 29 June to 2 July 1945 Desai and Koteswaram (1951) found that replacement of NTm air by fresh monsoon air Em result in fall of temperature and heavy rains. They also found partition between NTm and NEm (the westerly monsoon current from Arabian Sea) having a slope of 1 in 30. Heavy rains occur near and to the south of the partition on the NEm side where the partition was steep. Das (1952) computed the strength of monsoon current (as measured by poleward transport of angular momentum, vorticity and divergence) for 10 and 11 June 1950 and found a rough association between the areas of convergence and precipitation in subsequent 24 hrs. The first attempt of compositing rainfall, of three depressions which moved more or less WNWwards across the country was made by Pisharoty and Asnani (1957). A similar study of two slow moving depressions was made by Lal (1958). George and Datta (1965) examined a September depression with reference to character of rainfall and other synoptic features. The compositing technique was

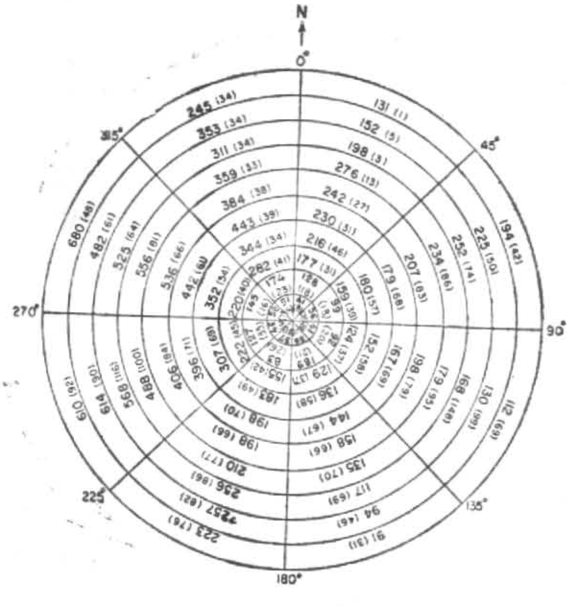

Fig. 1. Number of observations falling in each annulus analysed in the study. Figures in the parenthesis refer to the number of observations when the depression centre was west of 80°E

utilised by Bedekar and Banerjee (1969) to investigate isohyetal pattern of twelve depressions which moved across central parts of the country. Abbi *et al.* (1970) utilised voluminous data of 70 years (1890-1960) and examined the effect of depressions on rainfall along Gujarat coast. For this purpose 200 Bay depressions which moved to central and western parts of the country during July and August were considered. They found that heavy rainfall over the Gujarat coast occurs when the depressions are centred within the region enclosed between 21 deg. and 24 deg. N and 78 deg. to 82 deg. E called Reference Grid.

2. Purpose and scope

In recent years the network of departmental observatories has become more dense. Regular rainfall reports are also being received from a still bigger network of raingauges maintained by State Governments and other hydromet organisations. It was, therefore, thought appropriate to utilise this wealth of data to (1) prepare representative rainfall characteristics of monsoon depressions over India as they move across the country, (2) to determine differences, if any, between this pattern and those enunciated by earlier workers, (3) to examine changes of rainfall pattern and intensity when these depressions, on their westward march, are augmented by a fresh source of moisture from the Arabian Sea and (4) to put forth results of the analysis in a form useful for real-time application for forecasting expected zones of heavy to very heavy rainfall.

3. Basic data

This analysis spans over a period of 14 years (1961-1974). 27 depressions which formed over the Bay of Bengal have been chosen. Since after recurvature over NW India these depressions, if still active, sometimes acquire extratropical characteristics, only depressions which moved in the customary W/WNW direction, before becoming unimportant or recurving towards northeast, have been chosen. The tracks and day to day positions were collected from the publications of the India Met. Dep. A total number of 88 depression-days was thus available. The study analyses data of over 400 departmental and part-time observatories, about 50 hydromet observatories and about 100 State raingauge stations. Since the aim was to obtain a complete picture of rainfall arising only due to dynamical processes operating within the depression field, rainfalls at high altitude locations were not included in the study. The depression centres refer to the 0830 IST positions of each day and the rainfalls refer to the amounts recorded during the succeeding 24 hours.

4. Method of compositing

For the purpose of compositing, 1000 km radial distance or nearly half of the wave-length of the monsoon depression wave was chosen as the field of depression. This field was divided into 8 azimuthal sectors, each of 45 deg. width from north. Each sector was subdivided into 10 distance-zones, *viz*, 0-100 km, 100-200 km, etc, yielding 80 geometrical spaces. This arrangement was prepared in the form of a transparent overlay. This overlay was then super-imposed on 0830 hrs rainfall chart of the next day with the position of the depression centre on the previous day coinciding with the centre of the circle, and the direction of motion of the depression coinciding with the mean direction (WNW) marked on the overlay. By this process, rainfall amounts falling within each of the 80 annular spaces were collected. This was done for all the depression-days. The number of observations falling in each of the sectors are shown in Fig. 1. For each annulus, the arithmetic mean of all the rainfall reports contained within that space was computed. For the sake of analysis, this mean was assigned to the geometric centre of the space. The resulting isohyetal charts give a general portrayal of 24 hrs rainfall within a range of 1000 km from the depression centre with respect to its direction of motion across the country, during July and August months.

On each of the 88 rainfall charts isohyets were drawn, at intervals of 25 mm upto 150 mm and 50 mm for higher falls. These were superimposed on one another with the depression centre and the direction of motion both coinciding. The maximum areal extent which different isohyets occupied were thus demarcated.

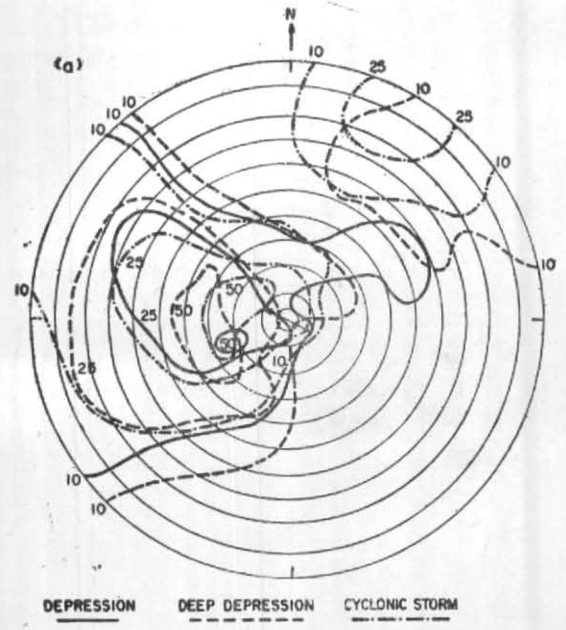

Fig. 2(a). The mean daily rainfall pattern. The arrow refers to mean direction of motion of the system

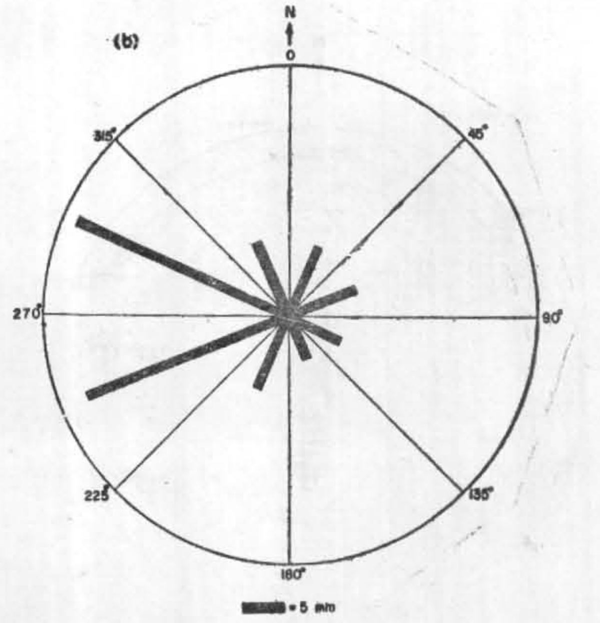

Fig. 2(b). Sectorwise distribution of mean rainfall

TABLE 1

Areal extent of 24 hr rainfall of various amounts

	Rainfall amounts (mm) equal to or more than								
	25	50	75	100	150	200	250	300	350
Area in units of 10^6 sq km	2.07	1.1	0.78	0.5	0.13	0.09	0.04	0.03	0.01
Percentage of the area of dep. field	66	35	25	16	4.1	2.8	1.3	0.9	0.3

TABLE 2

Frequency distribution of direction of motion of primary and secondary rainfall belts

Direction	Movement between					
	1-2nd day	2-3rd day	3-4th day	1-2nd day	2-3rd day	3-4th day
	primary rainfall belt			secondary rainfall belt		
WSW		1	2	1	1	
W	6	4	3	3		
WNW	9	8	1	4	6	1
NW	6	4		3	3	1

5. Mean rainfall pattern

The rainfall pattern of the mean depression is illustrated in Fig. 2(a). In the mean the principal zone of rainfall is situated in the left forward sector of depression as is well-known and has been observed by the earlier workers. Within this broad area, heaviest mean fall represented by 50 mm isohyet is located in the azimuthal zone 225 deg. to 270 deg. between about 200-400 km of the centre. Elsewhere in this zone, extending upto about 700 to 800 km the mean rainfall varies from 25 to 50 mm. A secondary maximum of 10 mm is seen in the northeast sector beween 400-600 km. A striking feature if the general absence of heavy falls in the vicinity of the depression centre. This is due to weak ascent taking place over the depression centre.

Sectorwise average rainfalls for each of the 8 sectors are depicted in Fig. 2 (b). The maximum amount of rainfall , *i. e.,* about 25-30 mm per day occurs in the left forward sectors between 225-315 deg. About 54 per cent of the rainfall in the depression occurs within this zone. In other sectors, the mean rainfall is less than 10 mm, the lowest falls occurring in the southeast sectors.

6. Areal extent of rainfall

The compositing processes also furnishes the maximum areal extent for various rainfall amounts. Areas covered by different isohyets have been determined. These areas have been expressed as percentage of the total area of the mean depression field. The results are shown in Table 1. Some of the salient features observed are discussed below. It may be reiterated that area enclosed by the isohyets represent the areas where precipitation of the specified amounts (or more) occurred at least on one of the days. They represent the upper limits of the areas of rainfall that occurred during succeeding 24 hrs, from 0830 hrs on the date on which a depression centre was located. With higher amounts of rainfall the area covered progressively diminished

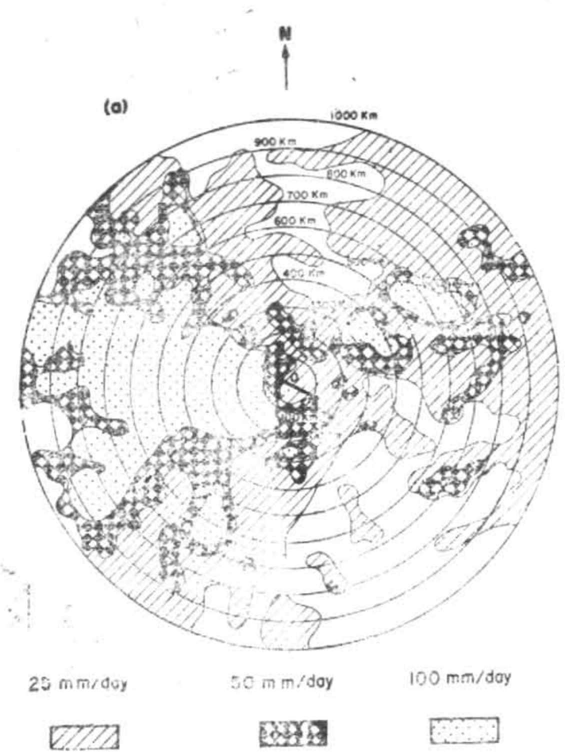

Fig. 3(a). Areal extent of rainfall. Arrow refers to mean direction of motion of the depression

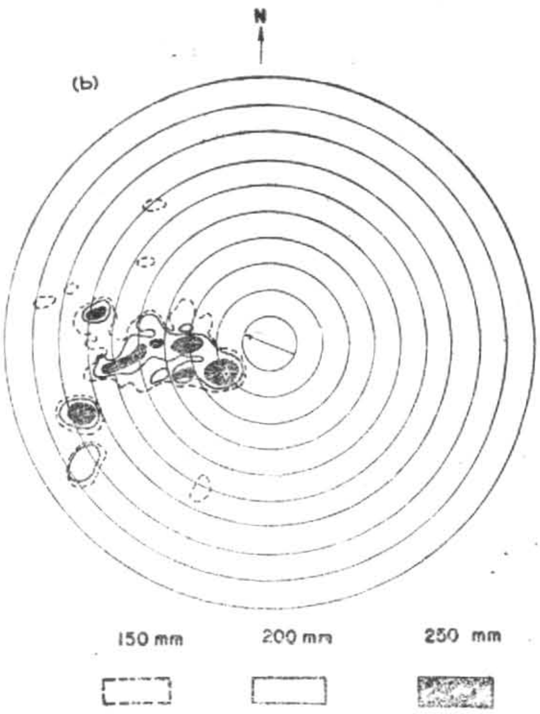

Fig. 3(b). Areal extent of rainfall

(*a*) *Rainfall* 25, 50, 75 *and* 100 *mm* — Fig. 3(a) depicts areas over which rainfalls of 25 mm, 50 mm and 100 mm per day occurred. Over a wide and extensive belt, having more or less NE/SW orientation rainfall exceeds 25 mm. Areas beyond 300 km north and about 200 km southeast of the centre generally get rainfall less than 25 mm. Rainfall of 50 mm or more per day is confined mostly in the forward sector of the depression. The 25 and 50 mm isohyets respectively occupy 2.08 and 1.10 million sq km, *i.e.*, 65 and 35 per cent of the total field of the depression. The pattern for 75 mm isohyet is found broadly similar to that of 50 mm though the area covered has diminished. Futher shrinkage continues in the rainfall belt in the forward sector of the depression for 100 mm isohyet. Thus one may expect rainfall of 75 mm or more in 0.78 million sq km (about a quarter of the field), while for 100 mm isohyets the area diminishes to 0.50 million sq km, *i.e.*, about 16 per cent of the depression field.

(*b*) 125 *mm rainfall* — Rainfall amounts of this magnitude are not normally experienced in the right forward sector. It is seen that such heavy falls continue to occur in the left forward sector though over diminished areas as compared to the areas occupied by 100 mm isohyet. About 10 per cent of depression or 0.29 million sq km, rainfall is of this or higher magnitude.

(*c*) 150 *mm rainfall* — Rainfall of 150 mm or more occurs only west of the depression centre. The extent, however, is considerably reduced and confined between 150 to 700 km from centre. Isolated cells west of the depression centre persist [Fig. 3(b)]. Rainfall of this order occupies 0.15 million sq km (or 4 per cent of the depression field).

(*d*) 200 *mm rainfall* — There is a further shrinkage in the area covered by this isohyet. The broad belt located west in the earlier cases persists but is now confined between 200 and 700 km (Fig. 3b). The cells observed ahead of the depression centre persists. Only 3 per cent of depression field which constitute 0.09 million sq km can experience this rainfall.

(*e*) 250 *mm rainfall* — The broad belt of rainfall observed above breaks down into a cellular pattern. These cells are mostly confined southwest to west of the centre lying between 200 to 400 km (Fig. 3b). Rainfall of this or higher amount occupy very little areas as is evident from the table but are nevertheless important as they produce floods.

(*f*) 300 *mm rainfall* — Amounts of 300 mm in 24 hrs are not uncommon with monsoon depression. Although no coherence in the pattern was seen, four small areas receiving this amount, are observed, all of them lying between southwest and west of the centre.

Fig. 4 (a). Mean areal extent of 25 mm or more rainfall per day

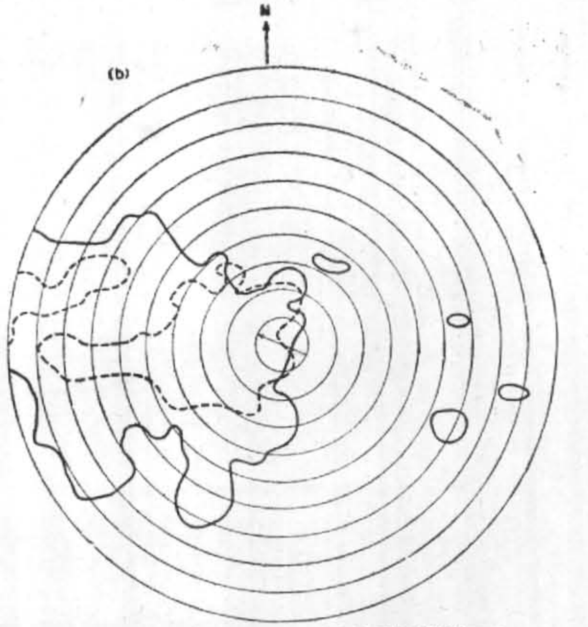

Fig. 4 (b). Mean areal extent of 50 mm or more rainfall per day

(*g*) 350 *mm rainfall* — In this analysis rainfall of this order has also been observed. Such rainfall also have preference towards the southwest sector.

6.1. *Rainfall as a function of depression intensity*

In the above analysis the three categories of depressions, *viz*, depression, deep depression and cyclonic storm have been combined together. For a meaningful apprasial of the rainfall it is necessary to obtain the mean portrayal for all the above three categories separately. For this purpose criteria adopted by India Meteorological Department were adopted. This classification takes into account the central pressure and its departure from long term normal, number of close isobars around the centre and surface wind force.

The mean 24 hrs. rainfall patterns for a depression was not found much different from what was obtained when all the three categories were combined together. As such rainfall patterns for the depression has not been discussed separately.

As may be expected the areal extent of rainfall for corresponding amount were considerably less in case of deep depression/cyclonic storm in comparison with the depression. The extensive northeast-southwest oriented belt of 25 mm observed for the depression though maintaining its identity in the forward sector breaks down into a number of cells in northeast sector in case of the deep depression and is not even seen in case of cyclonic storm [Fig. 4 (a)]. These cells to the northeast of the depression centre however are not seen for 50 mm rainfall (Fig. 4b). For cyclonic storm, the belt in the southeast sector starts breaking up for rainfall of 50 mm or more per day. The pattern for higher rainfall amounts were not much different from those of the mean depression and hence not been discussed.

The mean rainfall pattern has also been prepared for the deep depression and cyclonic storm. It is seen that in case of deep depression (Fig. 2a) though the pattern remains what was observed when all the three categories of the depression were composited, the areas in the forward sector enclosed by 25 mm and 50 mm isohyets considerably increase in extent. Besides, a distinct zone of 10 mm is now observed in the northeast sector away from the centre.

This rainfall feature is maintained in case of cyclonic storm (*vide* Fig. 2a) through the areas of 25 and 50 mm isohyets are reduced to some extent. In this respect it resembles more, the mean depression than the mean deep depression. However, in the northeast, the belt of 10 mm observed for deep depression not only persists but also encloses a cell of 25 mm rainfall.

7. Distribution of heaviest rainfall

Heaviest rainfalls recorded in the depressions during the period under study in different annular zones has also been plotted and analysed. This is depicted in Fig. 5(a). It may be seen that heaviest amounts are confined generally to the west of the depression centre. The pattern has a binary character and is discussed in a later section. Rainfall amounts of 350 mm or more are located west

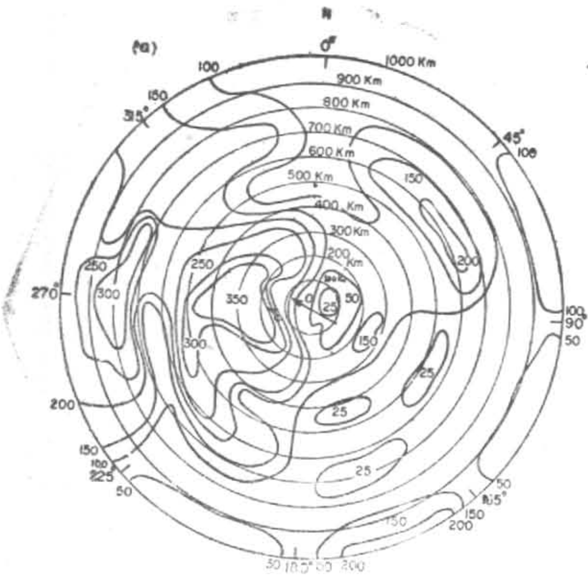

Fig. 5 (a). Distribution of heaviest 24 hrs rainfall (mm) in the depression field

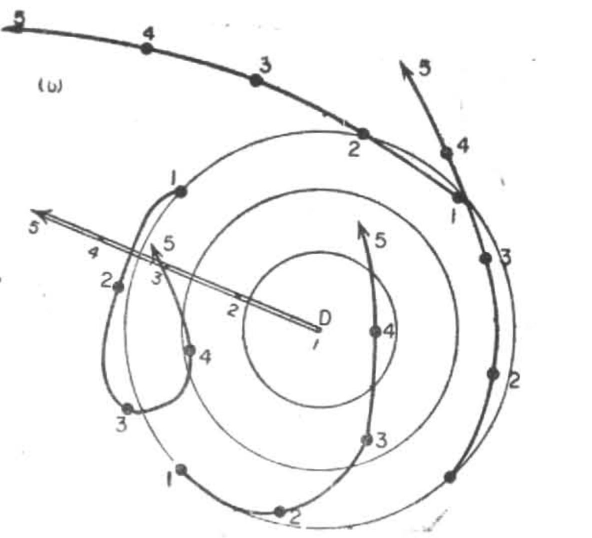

Fig. 5 (b). Showing some typical trajectories in the vicinity of a moving cyclonic centre in the northern hemisphere. Number indicates successive positions

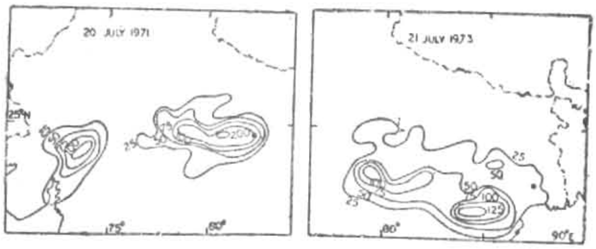

Fig. 6. Diagram showing binary character of heavy rainfall (mm). Thick dot shows position of the depression centre at 0830 IST on the previous day

of the depression at distances between 200 - 500 km. Another area of comparatively less amount but nevertheless quite heavy (*i.e.*, 300 mm) is located about 800 km west of the centre. Northeastwards, small cells of rather heavy fall (*i.e.*, 200 mm) are also observed.

(a) *Discussion on heavy rainfall*

Heavy rainfall in the left forward sector is the most outstanding feature associated with monsoon depression. Distribution of rainfall and its probable cause have been studied by many workers. It was postulated by earlier workers that the wide belt of heavy rainfall in the forward sector of the depression was due to frontal action between warmer easterly airmass to the north and westerly to the south (Ramanathan and Ramakrishnan 1932, Desai and Koteswaram 1951 etc). Mull and Rao (1949) suggested low level convergence in the isobaric channel as the cause of this heavy falls. Das (1951) on the other hand, by kinematically computing the convergence in a depression, was of the view that, all the rains may not be due to convergence. Koteswaram and George (1958) and Koteswaram and Bhaskara Rao (1963) pointed out that the heavy rainfall occurs due to warm advection in the lower and middle troposphere to the left of the track. Petterssen (1956) has examined the effect of motion of a cyclonic system on steady state stream lines associated with the system and propagating without change in its shape. His diagram has been adopted for a westnorthwest moving system when the velocity of air within the cyclonic system is smaller than that of the cyclonic system itself as is normally the case with depressions forming in the Bay of Bengal during July and August months. The resulting diagram is given in Fig. 5(b). It is evident from the figure that the trajectories indicate maximum convergence in the southwest sector and divergence in the rear sectors. This unambiguously explains as to why the left forward sector of the depression receives the heaviest falls.

The thermodynamics of the 'mean' depression studied in this paper will be analysed in order to establish, if possible, the reasons for the mean distribution of rainfall.

8. Rainfall zone in the rear sector

Pisharoty and Asnani (1957) found a zone of heavy rainfall east of the centre, about 300 miles from the centre which receive rainfall of 3 inches (75 mm) or more in 24 hrs. This was subsequently confirmed by Lal (1958). In this analysis also such a zone of rather heavy falls could be located in the left rear sector. This was contributed by only 5 per cent of the cases under study. Moreover, the amount of rainfall experienced in this sector, was never found to have exceeded 100 mm. The observations thus made by the earlier workers may

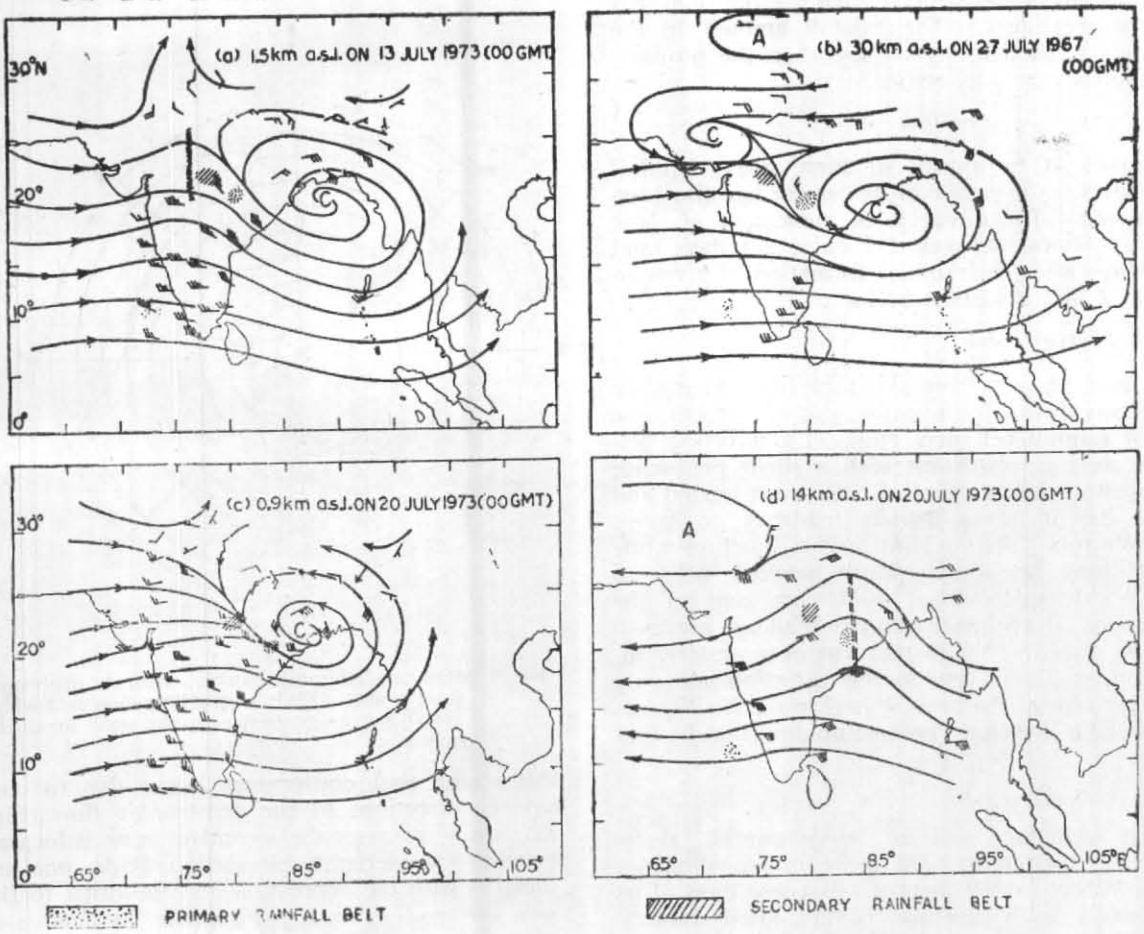

Fig. 7(a-d). Upper air flow pattern

perhaps be due to bias in the small sample and may not be considered as a normal feature of the depression.

9. Binary character of heavy rainfall

A second rainfall belt, distinct from the one observed in the southwest sector, but comparatively less intense, often develops to the west of the centre at fairly large distance. A reference to this feature was earlier made by Raman and Banerjee (1970) although Raghavan (1965) also reported though not in the heavy rainfall zone of the southwest quadrant, curved rain bands within 300 km of the centre, in case of a depression during August 1960.

In this study in nearly half of the cases analysed, the existence of two separate and distinct heavy rainfall zones have been observed. The first one called the "*primary zone*" is located near the centre, in the left forward sector. The "*secondary zone*" is mostly to the west of the centre, at a fairly large distance. In between these two zones, rainfall is less than that received within either of the zones (Fig. 6). The binary character of heavy rainfall is also reflected in the absolute heaviest fall analysis made in an earlier section (*vide* Fig. 5a). Characteristics depicting an average picture of the two zones are given below :

Type	Approximate distance from the centre (km)	Dimensions of the zone (km)	Mean rainfall (mm)
Primary	350	225×125	115
Secondary	700	175×125	90

The secondary zone is thus approximately at twice the distance as primary one from the centre of depression. This is in agreement with the analysis of heaviest falls made elsewhere in this study. The breadth of the two zones (*i.e.*, 125 km) is equal, but laterally, the secondary one is slightly smaller than the primary. Obviously the areal extent of the primary zone is more than that of the secondary. The rainfall amount in the secondary, though slightly less than the primary, is nevertheless, quite heavy.

(a) *Direction of motion*

Nature of movement of these heavy rainfall belts during the course of movement has also been examined. The direction of movement of these rainfall zones, between 1-2 days, 2-3 days and 3-4 days after their initial formation is given in Table 2 and discussed below :

(1) *Primary zone*

It may be seen from this table that during the first two days of formation and movement, the major rainfall belt may move in a direction between west to northwest with a slight preference for westnorthwest direction. Between second and third day it has a definite tendency to move WNWwards than in any other direction while after third day it may move between WSW to WNW. Frequencywise, in 41 per cent of the occasions, the primary heavy rainfall belt moves in WNW direction, in 30 per cent in a westerly direction, in 23 per cent in NW direction and only in 6 per cent of the cases, it may move WSWwards provided it does not become unimportant by that time.

(2) *Secondary zone*

The secondary zone of heavy rainfall, as its primary counterpart, can move in any direction from WNW to NW between first two days of its formation, each direction having equal chances. However, between 2-3 days the depression has a definite preference to WNW : at most it may move NW on a few occasions or WSW in exceptional cases. Nothing conclusively can be said about its movement after the third day. In terms of frequency, the secondary maxima, on nearly half of occasions move in WNW direction while in nearly a third of the cases it can move in a NW'ly direction. Occasions of its movement in WSW or W are comparatively less.

9.1. *Probable causes of binary maxima*

Attempt has also been made in this paper to find out the reasons for binary maxima. For this purpose all individual cases of the binary maxima were examined with the help of surface and upper air charts. No mesoscale system at the surface (*cf.* Das Gupta 1967) or embedded vortices within the primary circulation could be detected. Perhaps the network of stations taking upper air observations is not close enough for detection of existence of mesoscale vortices in monsoon depression. No unique synoptic situation could be found which would have explained the existence of the secondary maxima. However, in a number of cases the binary zone was found to be located between the flow from the ridge to the west to the trough in the east associated with the depression in the lower tropospheric levels. It is in this region that convergence occur due to curvature corrections to the geostrophic flow (Fig. 7a). In some cases the secondary zone is located between two separate circulation fields, one associated with the depression and the other to the west but away from it (Fig. 7b). In such cases also the eastward flow from the west often results in the ridge formation. In a good number of cases, however, the binary rainfall is due to streamline convergence in the lower troposphere between northwesterly to westerly winds and northeasterly to easterly flow associated with the depression (Fig. 7c). Divergence in the upper troposphere, if present, acts as an additional favourable situation (Fig. 7d).

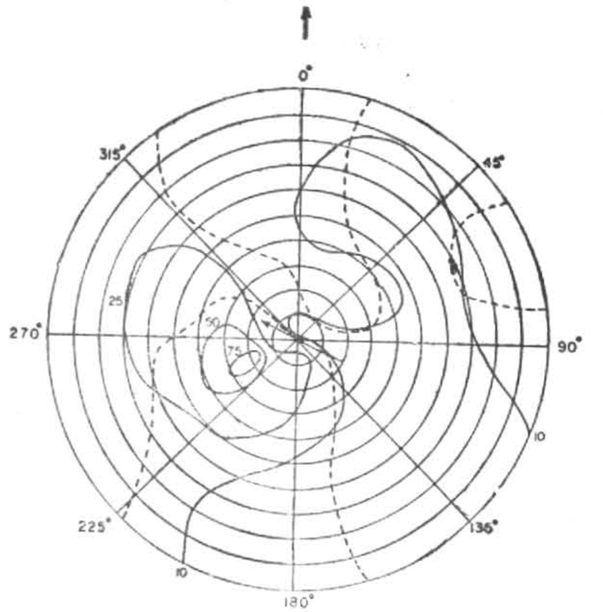

Fig. 8. Mean rainfall (mm) pattern when the depression centre is west of 80° E. Dotted lines show area where rainfall increases compared to the mean for all the depression

10. Application in forecasting heavy rainfall

Application in day to day forecasting of heavy rainfall become apparent from the rainfall features described in the earlier sections. Utilising the composite maps of section 6, probable areas of heavy rainfall and the associated expected amount can be determined for a subsequent 24 hrs period from the depression location at 0830 IST on any particular day by performing the following operation :

Presuming one is interested to locate the extent of rainfall of 100 mm or more. In the first instance, the centre of the depression, as shown in the composite map for this amount of rainfall is made to coincide with the actual centre of the depression on 0830 IST surface isobaric chart. Keeping the centres fixed, the composite map is oriented such that the arrow on it, coincides with the expected direction (west or westnorthwest) of the movement of depression centre. The most probable areas, which may receive rainfall of 100 mm or more, is then traced on the top chart from the composite diagram. In this manner, expected areas of receiving specified ranges of rainfall can be estimated from the corresponding composite chart.

Probable areas receiving heavy falls during next 48, 72 or 96 hours can also be located by merely shifting the depression centre indicated on the composite map to the forecasted position of the centre of the depression 24, 48 or 72 hours later respectively and then tracing out the maximum possible areas of heavy rainall on the surface chart.

10.1. *Verification of technique*

The results in section 6 being based on a large sample of data, it may be tempting to suggest the technique for use by forecasters. Naturally the success and failures of this technique has to be verified before it can be applied to forecasting on a real-time basis.

Verification of weather forecast has always been a controversial topic and has affected nearly the entire field of meteorology. A number of verification systems are available in literature, many of which do not permit subjectivity to enter the comparison of forecast with the subsequent observations. One such method has been suggested by Panofsky and Brier (1958) which has been utilised to examine efficiency of Figs. 3. For this purpose daily rainfall for all those monsoon depression which moved in westerly or westnorthwesterly direction during 1975-80 were considered.

The Skill Score S is given by :

$$S = (R-E)/(T-E)$$

where,

R = number of correct forecasts

E = number of forecasts expected to be correct based on some standard, such as, chance, persistence or climatology.

T = total number of forecasts.

The Skill Score was found to be as high as 0.83. Thus the technique suggested in section 6 may be used with a high degree of confidence to forecast areas of rainfall of different amounts.

11. Character ef rainfall west of 80 deg. E

In its westward march, when the depression approaches the Arabian Sea, instead of filling up, and becoming unimportant, it often regenerates and becomes vigorous. However, the general characteristics of rainfall in association with the depression once it nears the Arabian Sea have not received much attention. The only work of this kind was by Abbi *et al.* (1970). They observed that when the depressions are slow moving or are centred within 20-24 deg. N and 78-82 deg. E, they give copious rains on the Gujarat coast. Depressions whose movement coincide with strong pressure gradients over Gujarat–Maharashtra coast are also responsible for heavy falls over coastal Gujarat though they may be centred considerably east of the above area.

An attempt has been made to determine the pattern of rainfall when the depression is west of 80 deg. E. In all, 14 cases have been observed in this category. The analytical procedure adopted is the same as has been described in sections 5 and 6. The number of observations which were utilised in this analysis have been shown for each of the annular zones in Fig. 1. Some of the special features of this study are noted below :

In the mean rainfall, the pattern (Fig. 8) is similar (compare Fig. 2a), though the amount of rainfall, in general, are heavier than those observed in the earlier case. For example whereas the mean highest heavy fall in the southwest sector was 50 mm it is now more than 75 mm. Of course the location of these heavy belts remain the same, *i.e.*, 200-300 km southwest of the centre. Over a fairly large area in the left forward quadrant the mean rainfall exceeds 50 mm. The increase is mostly observed SW and north of the centre (Fig. 8) and it ranges from 20 to nearly 200 per cent of the former.

Increases are also observed when only the distance ranges are taken into account. This is conspicuous only from 100 to 400 km of the centre, the percentage increase being 20 to 60 per cent. The trend of increasing rainfall upto 400 km and subsequently decreasing, however, persists. In the inner sector (between 100 to 400 km) rainfalls are of the order of 30 mm while in the outer sector they falls to 10 mm.

Sectorwise analysis of rainfalls reveal that in the southeast sector (between 90 to 135 deg. azimuth) where a marginal decrease in rainfall is seen, the remaining sectors record increase in rainfall ranging between 10 to a maximum of 70 per cent in 180 to 225 deg. sector. Maximum rainfall amounts of about 30 mm are observed between 225 to 315 deg. while the lowest (about 5 mm) falls in the southeast quadrant (between 90 to 180 deg.). In this case also these two sectors contribute to about 52 per cent of the total rainfall.

12. Concluding remarks

Rainfall associated with monsoon depressions is dependent on a number of factors. Most important among these are :

(*i*) Intensity of depression.

(*ii*) Rate of ascent of air in different sectors of the depression circulation.

(*iii*) Moisture contents of the air, which has to be continuously renewed and replenished.

(*iv*) Topography which greatly enhance the rate of ascent of moist air.

(*v*) State of the depression, *i.e.*, whether developing or dissipating.

(*vi*) Whether the system is recurving.

(*vii*) Location of the station with respect to the depression centre.

From what have been mentioned in the preceding paragraphs, the following conclusions may be drawn :

(*i*) The immediate vicinity of the depression centre is generally free from heavy rainfall activity. The outer periphery of the circulation field also receives scanty rainfall.

(*ii*) The rainfall pattern, in a good number of cases, is distinctly binary in character. The heaviest falls occur in the southwest quadrant about 200-400 km from the centre, while a secondary zone of comparatively less rainfall amount, is located about 800 km west of the depression centre.

(*iii*) Rainfalls of 30 cm or more in 24-hr period are not uncommon in monsoon depressions and cause heavy floods.

(*iv*) Heavy rainfall in the rear sector of the depression occurs only in exceptional cases.

(*v*) When the depression moves west of 80 deg. E, the rainfall amounts increases considerably. This may be, at times, 200 per cent of that received normally.

(*vi*) The technique can be conveniently applied to demarcate expected areas of heavy rainfall of different amounts.

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