551·515·4 : 551·509·11 : 551·577(545)

Effect of High Level Divergence on the Rainfall Distribution over northwest India associated with a southwest monsoon depression

K. S. VENKATARAMAN and N. S. BHASKARA RAO

Meteorological Office, New Delhi

(*Received 3 May 1963*)

ABSTRACT. In association with a monsoon depression which recurved over east Rajasthan and moved northwards into Jammu Province, torrential rains occurred in the north Punjab and northwest Uttar Pradesh on 20 and 21 September 1962. This rainfall could not be explained in terms of the low level circulation of the depression alone, which was still far away, and was found to be associated with marked high level divergence in a deep layer extending from 500 to 200-mb levels. An examination of the peculiar features of the rainfall in different areas and the associated synoptic features has shown the relative importance of the three factors, low level convergence, moisture feed and high level divergence on the rainfall distribution.

1. Introduction

Upper wind data are often meagre on days of widespread bad weather, due to the limitation imposed on pilot balloon ascents by cloud cover. So earlier investigations on the rainfall distribution associated with monsoon depression have taken cognisance of only low level features. Only during recent years, some light has been thrown on the importance of high level systems. Marked departures from the pattern of rainfall distribution, one might expect solely from the locations of the depressions, are often noticed and these are hard to explain or forecast from low level considerations alone.

A remarkable case of this type occurred in the third week of September 1962 when, with a deep depression located over east Rajasthan, very heavy rainfall occurred over the north Punjab and northwest Uttar Pradesh. The heavy rains were widespread in these areas and occurred over a period of 48 hours commencing from the morning of 20th. The rains ceased abruptly on 22nd. The torrential rains caused widespread floods in the Punjab resulting in colossal loss of livestock and property. It is said that the severity of the floods was unprecedented. As most of the rains occurred over the plains, the flooding was more due to the breaches in numerous rivulets and canals than due to over-flowing of major rivers.

2. Track of the Depression

A depression formed in the west central Bay of Bengal on the morning of 16 September 1962 with its centre near Lat. 17°N, Long. 87°E. It intensified and became a deep depression on the morning of 17th, when it was centred near Lat. 18·5°N, Long. 85·5°E. It moved westnorthwestwards, crossed coast near Gopalpur and lay with its centre near Titlagarh on the morning of the 18th and near Pachmarhi on the morning of 19th. It then took a northerly course and lay over southeast Rajasthan with its centre near Jhalawar at 0830 IST on the 20th and near Alwar on the morning of 21st. Thereafter, it weakened rapidly and moved more or less northwards becoming a low pressure area over Jammu Province on the morning of 22nd and filling up there by the same evening. The track of the depression is shown in Fig. 1.

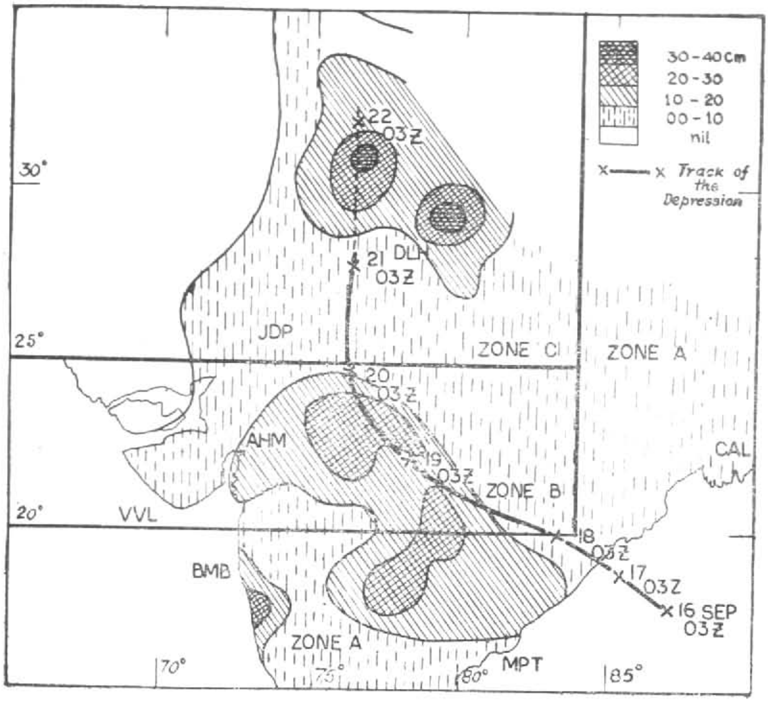

Fig. 1. 5-day cumulative rainfall

Zone A—Cumulative rainfall from 15 to 19 Sep 1962
Zone B—Cumulative rainfall from 17 to 21 Sep 1962
Zone C—Cumulative rainfall from 18 to 22 Sep 1962

3. Rainfall Distribution

Fig. 1 also gives the cumulative rainfall which fell over the Indo-Pakistan area north of Lat. 15°N, west of Long. 90°E, in association with this depression. To obtain a comparative idea of the distribution of rainfall over the different parts of the area in association with the movement of this depression alone, and to eliminate, as far as possible, the rainfall caused by other synoptic systems like a second depression which formed over north Bay of Bengal on the 20th, the area has been divided into 3 zones for giving the cumulative rainfall, as follows —

Zone A — Area south of Lat. 20°N and area east of Long. 84°E—Rainfall during the period 15 to 19 September

Zone B — Area between Lat. 20° and 25°N, west of Long. 84°E — Rainfall during the period 17 to 21 September

Zone C — Area north of Lat. 25°N, west of Long. 84°E—Rainfall during the period 18 to 22 September

The rainfall distribution shows two distinct areas of maximum precipitation, one over the central parts of the Indian Peninsula and the other over the north Punjab and northwest Uttar Pradesh.

In order to enable a better appreciation of the changes in the pattern of rainfall associated with the depression during its movement across the country, the surface synoptic charts for 0300 GMT showing isobars and 24-hour rainfall from the 18th to 22nd are shown in Figs. 2 to 6.

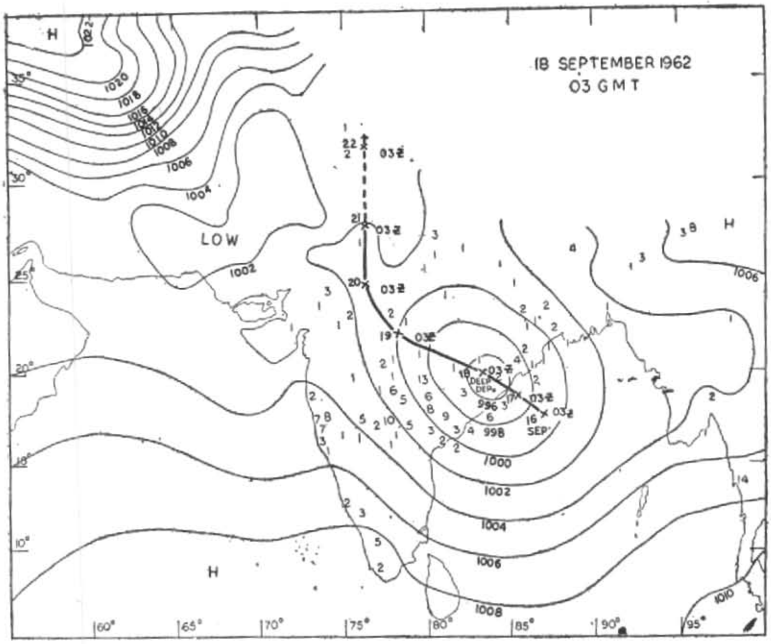

Fig. 2. 03 GMT sea level chart of 18 September 1962 with rainfall (in cm) in the preceding 24 hours

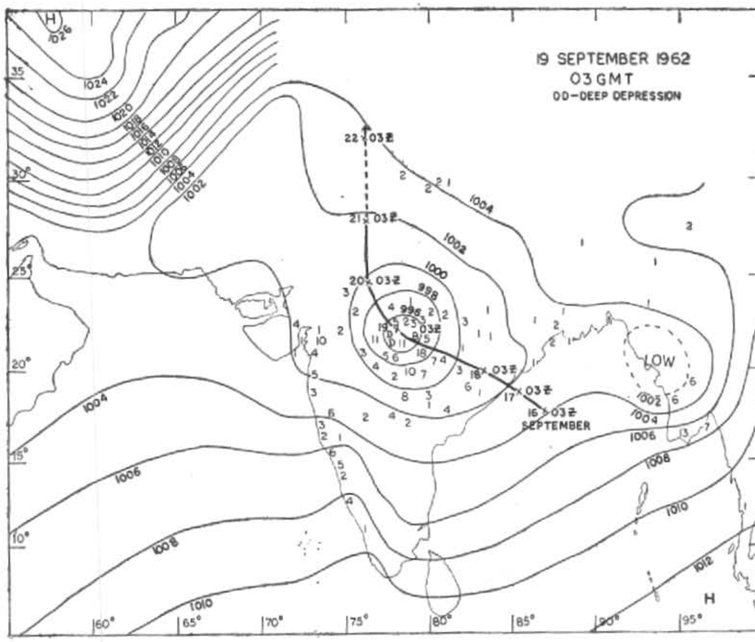

Fig. 3. 03 GMT sea level chart of 19 September 1962 with rainfall (in cm) in the preceding 24 hours

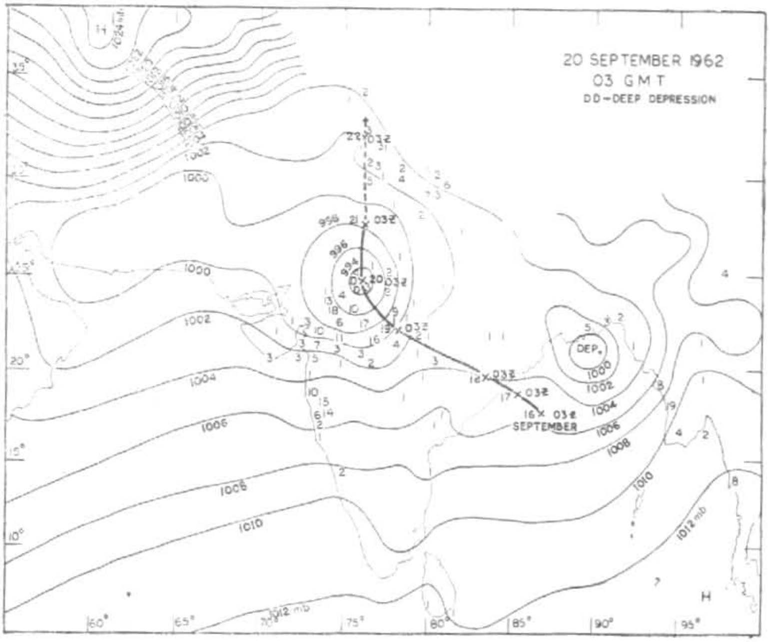

Fig. 4. 03 GMT sea level chart of 20 September 1962 with rainfall (in cm) in the preceding 24 hours

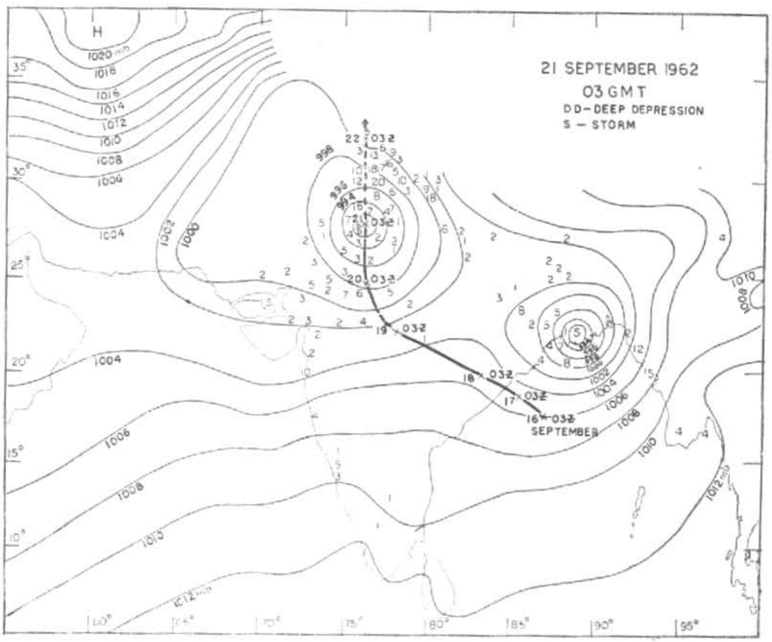

Fig. 5. 03 GMT sea level chart of 21 September 1962 with rainfall (in cm) in the preceding 24 hours

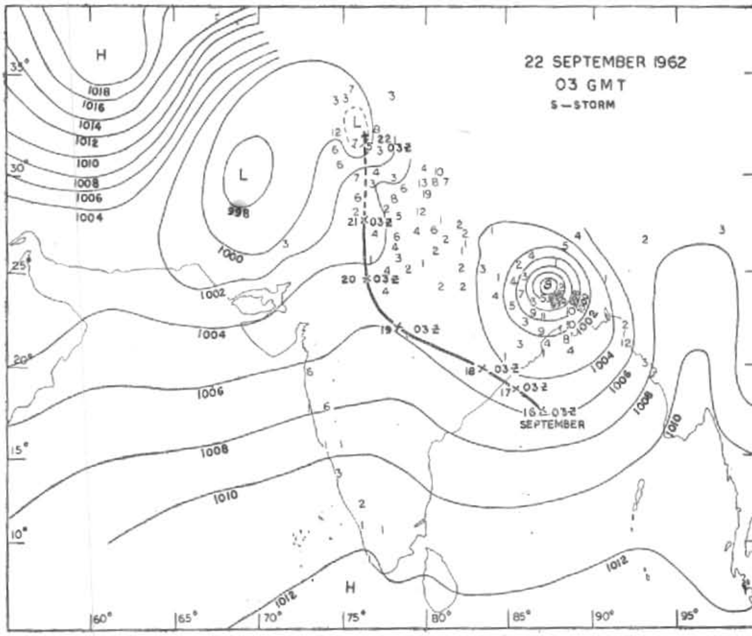

Fig. 6. 03 GMT sea level chart of 22 September 1962 with rainfall (in cm) in the preceding 24 hours

It is well known that the heaviest rainfall occurs in the southwest sector of the depressions in the southwest monsoon season. As seen from the track of the depression, the area of heavy rainfall over the central parts of the country is well in keeping with the normal distribution of rainfall associated with these depressions. (The heavy rain on the west coast is due to the influence of orography).

It is also normal to expect heavy falls over the Western Himalayas, when a depression recurves and approaches these mountain ranges. But in the present case, the area of heavy rainfall to the north has some unusual features, namely,

(*i*) The heaviest falls occurred over the plains and hence orography seems to have played very little part,

(*ii*) The heavy falls were widespread and occurred over a fairly large area,

(*iii*) The heavy rains started on the morning of 20th, when the depression was about 500 miles away to the south and continued till the morning of 22nd, when the depression was rapidly filling up,

(*iv*) While the heavy rainfall upto the 20th occurred in the southern sector of the depression, the heavy rain on the 21st occurred in the northern sector, and

(*v*) The area between the two belts of heavy rain (the one over the central parts of the country and the other to the north, *vide* Fig. 1) received omparatively very much less rainfall even though it was directly on the track of the depression and also nearer the sources of moisture than the area of heavy rain to the north.

These features cannot easily be explained in terms of the convergence associated with the depression. The chief features of the synoptic conditions at different levels in

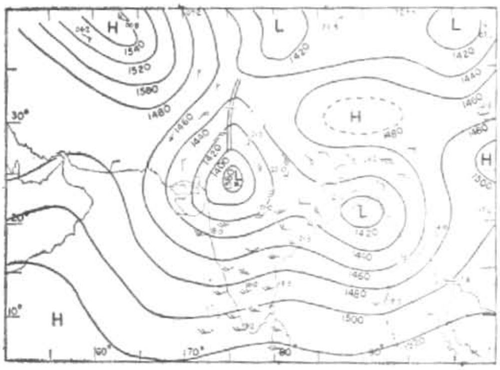

Fig. 7. 850-mb level constant pressure chart for 00 GMT on 20 September 1962

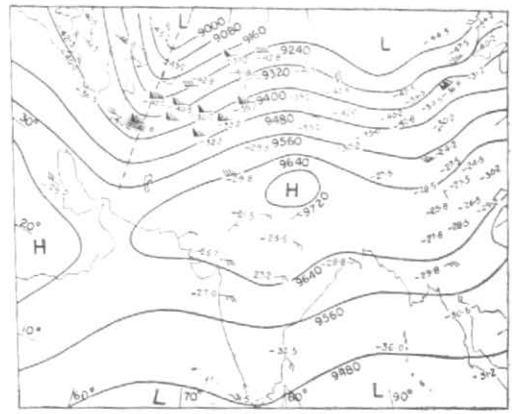

Fig. 8. 300-mb level constant pressure chart for 00 GMT on 18 September 1962

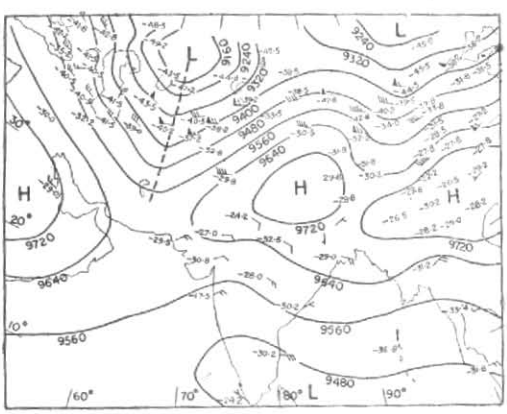

Fig. 9. 300-mb level constant pressure chart for 00 GMT on 19 September 1962

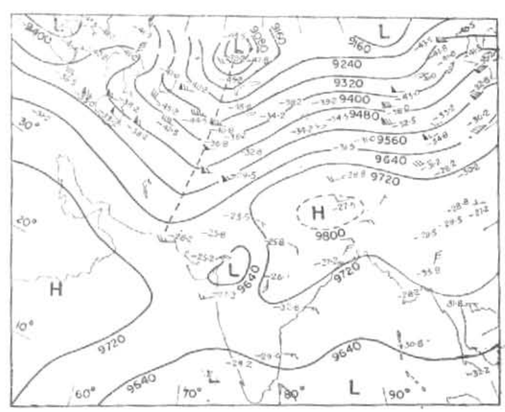

Fig. 10. 300-mb level constant pressure chart for 00 GMT on 20 September 1962

the upper air which played an important role are discussed below.

The Low Level Circulation

The 850-mb constant pressure chart of 00 GMT of 20 September is shown in Fig. 7. The noteworthy features on this chart are the two intense systems of cyclonic circulation—one associated with this depression over east Rajasthan and neighbourhood and the other over the north Bay of Bengal associated with another depression which formed there on that day. Under the combined influence of these systems, the circulation was vigorous over the country and deep layers of highly moist equatorial maritime air were being drawn into northwest India.

The only other feature was the feeble troughing over the Punjab extending from the northern apex of the cyclonic circulation over east Rajasthan with a shear line running roughly along Long. 75°E. This line is shown on Fig. 7, by two solid parallel lines. This extension of the area of cyclonic vorticity was the only indication of the possibility of heavy rains to the north as early as 20th, as far as the low level circulation is concerned.

The dry northwesterlies were apparently being drawn into the circulation over the West Pakistan area. Thus the northern half of the shear line marked on Fig. 7 also seems to coincide roughly with the line of air mass discontinuity between T_c and E_m air.

High Level Circulation

The high level circulation (at 300 and 200-mb levels) on the 18th over the Indo-Pakistan and Tibetan areas showed the normal features of seasonal circulation, with a high over Tibetan plateau centred near Lat. 33° N, Long. 82° E, easterlies to the south of Lat. 30° N and westerlies to the north of the high. The necessary high level divergence for maintaining/helping the development of the low level convergent system (depression) was apparently being provided by a wave in the high level easterlies over the Peninsular India. While the data are too meagre to provide adequate chart coverage at 200-mb level and above, the 300-mb contour charts on the mornings of 18, 19, 20 and 21 September shown in Figs. 8, 9, 10 and 11 respectively, suggest the passage of an easterly wave across the Peninsula during this period.

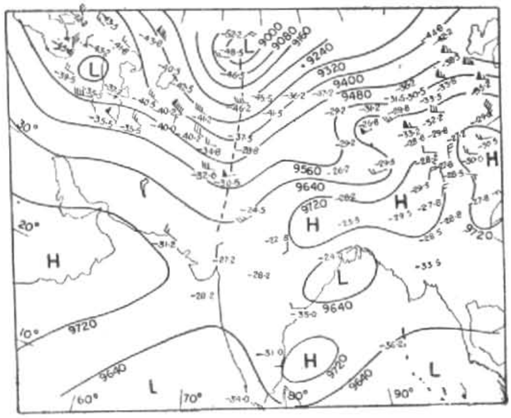

Fig. 11. 300-mb level constant pressure chart for 00 GMT on 21 September 1962

However, the dominant feature of the circulation at the higher levels was a well marked trough in the westerlies extending from 6 to 12 km above sea level. It lay over Iran and neighbourhood on the 18th, with its axis at 00 GMT roughly along Long. 58°E at 300-mb level. The positions of the axis of the westerly trough are marked by broken lines on the 300-mb charts. As can be seen, the trough moved steadily eastwards, its axis reaching about Long. 74° E by the 21st.

It is well known that zones of strong covergence and divergence can be found in the upper air associated with certain systems in strong zonal currents at high levels. The relationship between divergence and vorticity is given by the formula —

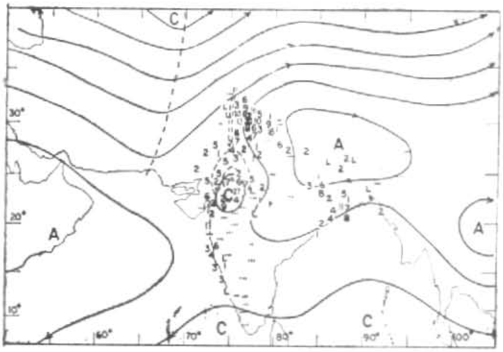

Fig. 12

Continuous lines with arrows show stream lines at 9·0 km, and the broken lines give the low and shear line at 850-mb at 00 GMT on 20 Sep 1962. The rainfall recorded on 21 September 1962 is also plotted, with amounts ten cm and above circled

$$\frac{d}{dt}\,(q+f) = -\,(q+f)\,\text{div}\,V \qquad (1)$$

where q is the relative vorticity and f is Coriolis parameter. Thus any flow pattern that increases the vorticity of air will make it converge.

Ramaswamy (1956) discussed the importance of divergence associated with waves in the strong westerlies found over northern India during the winter and spring months of the year. The change of cyclonic curvature to anticyclonic curvature from the trough to the downstream ridge leads to divergence of air along the forward sector of the trough. Koteswaram and Srinivasan (1958) have pointed out that not only the changes in curvature but also the changes in the horizontal shear associated with Jet type flow will lead to formation of areas of strong divergence and convergence. The right entrance area of the Jet, because of its increasing anticyclonic shear along the stream line and the left exit area because of its decreasing cyclonic shear, are areas where divergence of a significant order of magnitude can be anticipated.

On the 20th morning, when the heavy rainfall was just commencing over the north Punjab, the trough in the westerlies lay with its axis roughly along a line joining Tashkent to Quetta. Thus the whole of the area north of Lat. 30°N and east of the trough line was favoured by upper air divergence associated with the forward sector of the trough. As will be seen from Fig. 10, the influence of the trough did not extend to the south Punjab, Rajasthan and west Uttar Pradesh due to the peculiar configuration of the pressure field at these levels.

Secondly, under the influence of the trough, the westerly jet stream was pushed southwards and Srinagar reported relatively strong winds at the higher levels (55 knots at 9 km and 70 knots at 12 km). The winds over the south Punjab and neighbourhood were weak. Thus an area of strong anticyclonic shear was established over the Indo-Pakistan area to the north of Lat. 30°N; the shear being comparable to that found near the core of a jet. As the wind field indicated an inflow into increasing anticyclonic shear over the north Punjab and neighbourhood, another factor favourable for divergence at high levels was found over the areas.

Simplifying equation (1) by neglecting the less important terms, the relationship between divergence D and the downwind variation of absolute vorticity is given by the formula —

$$D = -\,\frac{V}{Q}\,\frac{\partial Q}{\partial s} \qquad (2)$$

(Eqn. 20-54 Haltiner and Martin 1957)

where s is taken along the stream line and $Q = q + f$.

TABLE 1

Areawise distribution of low level convergence, high level divergence and moisture feed over northwest India and West Pakistan and the incidence of heavy rainfall during the period 18 to 22 September 1962

Area	Low level convergence	High level divergence	Moisture feed	Resultant rainfall
Plains of north Punjab and of northwest Uttar Pradesh	Strong	Strong	Strong	Widespread heavy to very heavy rain
Hills of the Punjab and of west U.P. and Himachal Pradesh	Weak	,,	,,	Scattered heavy rain
South Punjab, north Rajasthan	Strong	Weak or absent	,,	Do
Southwest Uttar Pradesh	,,	Absent	,,	No heavy rain
East Uttar Pradesh	Weak	,,	,,	Do
West Pakistan and Jammu	,,	Strong	Absent	No rain

Thus it is seen that while the horizontal gradients of wind speed and direction determine the vorticity field, divergence is directly proportional to the absolute value of V at that point.

The configuration of the contour lines as seen on Fig. 10 indicates a rapid strengthening of the winds to the north of Lat. 30°N and thus the absolute value of the wind speed also indicates strong divergence only to the north of Lat. 30°N.

In Fig. 12 are shown the stream lines at 9 km at 00 GMT of 20 September and the rainfall recorded during the 24 hours ending at 03 GMT on the 21st. The contour low at 850 mb on the 20th morning associated with the depression and the shear line extending northwards are shown by broken lines. As is clearly brought out by this chart, the heaviest falls occurred over the area where the low level convergence and the moisture feed were superimposed by the area of strong divergence at high levels.

Neither the high level systems nor the low level systems by themselves alone would have explained this unique occurrence as each of these covers an area several times the actual area of heavy precipitation.

The high level pattern shifted eastwards by the morning of 21st and the area of heavy rain also shifted eastwards, the heaviest precipitation occurring over northwest Uttar Pradesh on this day.

The depression weakened rapidly after the 21st morning and lay as a weak low on the morning of 22nd over Jammu where it finally filled up by that evening.

4. Conclusions

This case study has clearly revealed that heavy rainfall occurs only in those areas where the three factors — low level convergence, divergence at very high levels and moisture feed — are all present. A deficiency in any of these will result in marked decrease in precipitation. The general areawise distribution of the above factors over northwest India and West Pakistan and the consequent rainfall are given in Table 1.

In conclusion, it can be said in a general way that low level convergence and moisture feed determine the areas of precipitation and the height and strength of divergence at high levels over these areas determine the amount of precipitation.

REFERENCES

Haltiner, G. J. and Martin, F. L.	1957	*Dynamical and Physical Meteorology*, McGraw-Hill Book Company, Inc.
Koteswaram, P. and Srinivasan, V.	1958	*Indian J. Met. Geophys.*, 9, p. 301.
Ramaswamy, C.	1959	*Tellus*, 8, p. 26.