551·508·85 : 551·515·4

Radar observations of a thunderstorm

H. MITRA

Meteorological Office, New Delhi

(*Received 13 November 1954*)

ABSTRACT. The paper describes the results of a study of a winter thunderstorm which occurred at New Delhi between 2150 IST of the 14th and 0030 IST of 15 January 1953 due to the passage of a western disturbance. The radar echoes as seen on the scope of a 3-cm AN/APQ-13 set have been explained with the help of the available surface and upper air data. The mechanism of formation and decay of the main thunderstorm cell and its associated secondaries have been described with the help of radar photographs taken at short intervals.

1. Introduction

At the Meteorological Office, New Delhi, arrangements are in progress to make systematic observations of different types of weather with the help of centimetre radars. The type of equipment and a preliminary account of such observations has already been published (Mathur and others 1954). In the present paper a special study of a moderate thunderstorm which passed over the station on 14 January 1953 at 2245 IST is described. On this day a solitary thunderstorm cell was first noticed on the radarscope at a distance of 30 miles from the observatory site and was found to approach the station from WSW. A continuous watch was kept of this thunderstorm from 2130 IST of 14th to 0030 IST of 15th and photographs were taken at intervals of five to ten minutes.

2. Synoptic situation

Fig. 1(a) shows the synoptic situation as shown in the weather charts at 1730 IST on 14 January prepared at Safdarjung Airport. The radiosonde observation from the observatory site at 2005 IST is shown in Fig. 1 (b).

On this day an active western disturbance was moving through the extreme north of the country. Its secondary lay over south Punjab and adjoining Rajasthan. The associated upper wind circulation extended up to 15,000 ft above sea level. A marked wind discontinuity at 3000 ft above sea level ran from Lyallpur to Sikar and thence running southwards. Moist air from the Bay of Bengal was flowing round the anticyclone over Orissa and neighbourhood into the secondary western disturbance up to 5000 ft above sea level and making it more active.

Details of weather changes over Delhi recorded at Safdarjung Airport from 1730 to 0830 IST of 14-15 January 1953 indicated that medium clouds began increasing in amount towards late afternoon and the base of the cloud gradually lowered to 9000 ft by 1900 IST. By evening the sky became overcast mainly with *Ac* and *As*. Slight intermittent rain started at 2050 hours. Lightning was seen towards west at 2130 hours and a thunderstorm was seen approaching the station. The radar set was switched on at this time and a thunderstorm was noticed on the scope 30 miles away from station in WSW direction.

3. Description of radar echoes

The first picture taken at 2150 IST is shown in Fig. 2. The approaching storm was observed at a range of 23 miles towards WSW. It consisted of two distinct cells and also a third one very close to the other two; the maximum horizontal extent of the thunderstorm was a little over three miles. It approximately covered an area of about 12 square miles. A small cell, 6 miles away from the station, in a SW'ly direction, may be seen just developing ahead of the main thunderstorm.

The next picture (Fig. 3) was taken at 2200 IST. The three cells noticed earlier had merged together, but could still be identified as separate cells. The average horizontal extent of the storm was about 5 miles and now covered an area of 15 square miles. The main thunderstorm also gave

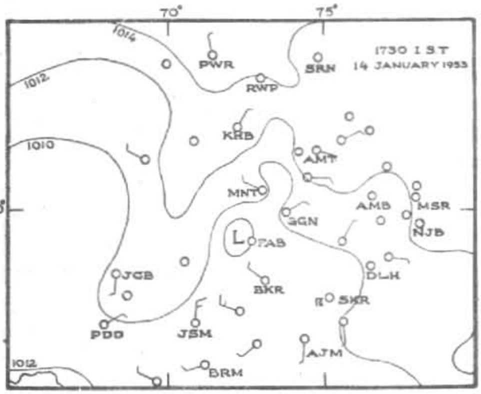


Fig. 1(a)

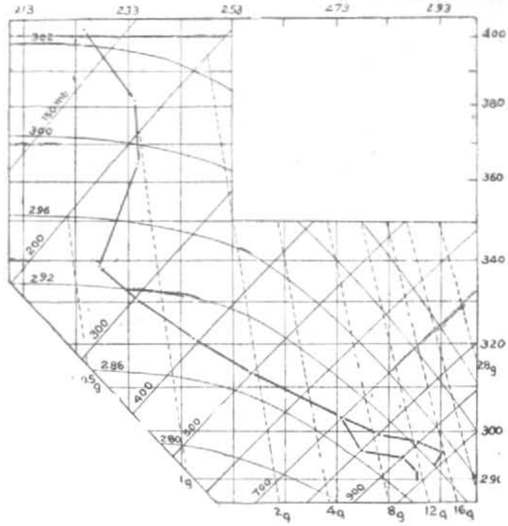


Fig. 1(b). Radiosonde observation at 2005 IST on 14 January 1953

rise to a secondary cell in its rear at a distance of 30 miles from the station in a WSW'ly direction and at about 15 miles away from it. The cell at 6 mile range towards SW became more active.

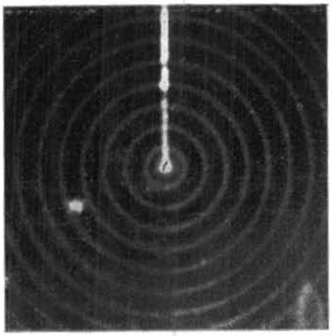
Fig. 4 shows the situation at 2215 IST. The centre of the main thunderstorm was now located at a distance of 18 miles from the station and covered an area of about 6 square miles. Two separate cells, visible earlier, had merged together and were no longer noticeable. In the rear of the main thunderstorm, 10 miles away, may still be seen the secondary which appeared to have become weak.

Two more weak cells at distances of 5 and 7 miles in the west were also visible in front of the thunderstorm. One of them had developed earlier and had moved in a NW'ly direction. The interesting fact was the very sudden development of another strong cell at 9 mile range in the NNW. It had grown within less than five minutes and indicated that either particle concentration or growth of the drops within this cell had been very rapid to give such a strong echo within such a short time. This can only be explained by very strong localised updraft in that region.

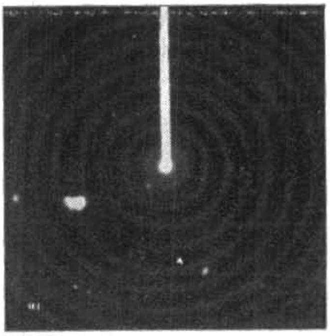
Fig. 5 was taken at 2245 IST when the storm had moved up to within 9 miles of the station. With its approach towards the station the number of secondary cells ahead of it in the direction of movement became more numerous; as many as 10 intense and 9 weak ones could be counted. These cells were clustered within an area approximately 24 square miles, the centre of which was about 7 miles from the main cell along its direction of movement. The cellular structure of these secondaries was very clear; the largest one had a diameter of about a mile and the smallest one about half a mile. Many of them were probably in cumulus stage of development while others seem to have attained the mature stage.

The pattern of these secondaries from this time onwards changed very rapidly. At 2250 IST the main storm was about $7\frac{1}{2}$ miles away. The cells formed earlier became more intense; numerous new ones also appeared. The intense ones had probably attained their mature stage. The process of growth of these secondaries had been very rapid with the approach of the storm towards the station. It was also noticed that these secondary cells oriented themselves approximately along an ellipse which rotated in a clockwise direction. At this time the occurrence of thunderstorm and rain was reported from Safdarjung. The radar echoes, therefore, preceded the rain by about five minutes.

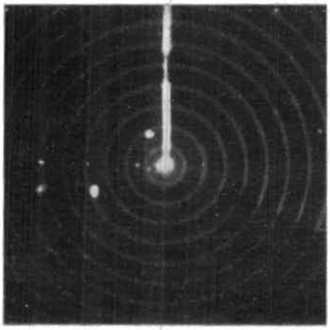
Fig. 6 shows the photograph taken at 2255 IST. The main storm was still seven miles away and comprised of several cells now. The secondaries which developed on account



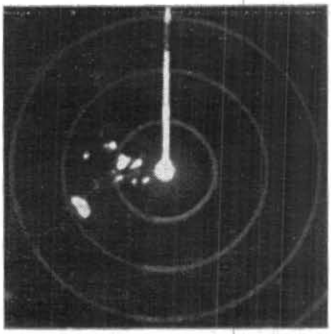
2150 Fig. 2 (50,5)



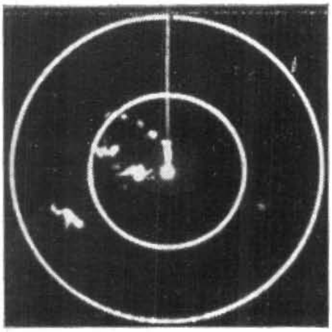
2200 Fig. 3 (50,5)



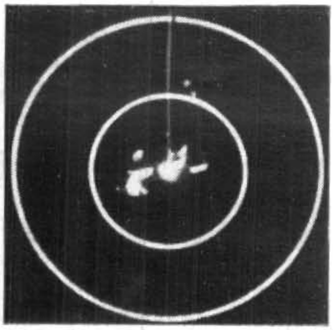
2215 Fig. 4 (50,5)



2245 Fig. 5 (20,5)



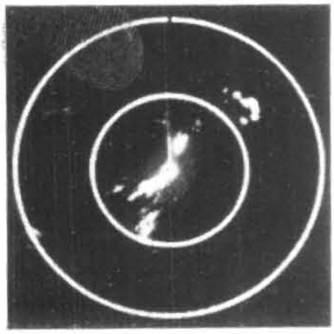
2255 Fig. 6 (10,5)



2308 Fig. 7 (10,5)

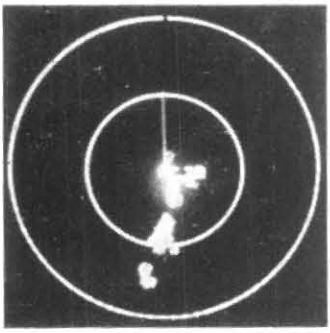
2320 Fig. 8 (10,5)

NOTE : The figures at the left bottom of each picture show the time in IST. Figures in brackets at right bottom show the range and spacing of markers in nautical miles. The vertical line at the top indicates north



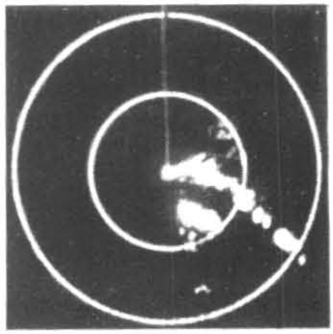
2325 Fig. 9 (10,5)

2355 Fig. 10 (10,5)

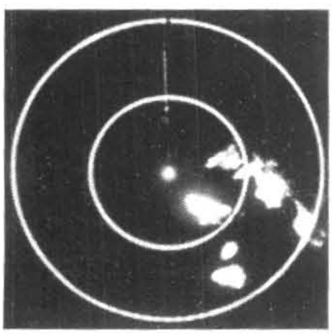


2400 Fig. 11 (10,5)

0010 Fig. 12 (10,5)



0015 Fig. 13 (10,5)



0020 Fig. 14 (10,5)

0030 Fig. 15 (20,5)

NOTE: The figures at left bottom of each picture show the time in IST. Figures in brackets at right bottom show the range and spacing of markers in nautical miles. The vertical line at the top indicates north of the approaching storm appeared in NW'ly direction and had arranged themselves in an elliptical form with the major axis normal to the direction of approach of the main storm. Towards the north, extending about 2 miles from the station, was a narrow region of thunderstorm activity; three more relatively stronger cells were also visible. The cellular structure of these cells was very marked; the bright patches represented the regions of strong vertical currents whereas the intervening dark spaces between adjacent cells were regions of downdraft.

Fig. 7 was taken at 2308 IST; the main cell was now probably absorbed by the cells towards NW and it was not possible to identify it from the others from this time onwards. Dissipating cells towards NE with dark centres may be noticed particularly. The number of secondaries which had developed on account of the main cell now formed new regions of thunderstorm activity.

Figs. 8 and 9 taken at 2320 and 2325 IST show development of a number of new thunderstorm cells from SW of station while those formed earlier were dissipating towards NE. In Fig. 10 taken at 2355 IST these cells could be seen in fully developed stage. As many as eleven cells were clearly visible extending over a length of about 9 miles towards south of the station. Other cells towards NE had dissipated by this time.

Fig. 11 taken five minutes later at 2400 IST shows that the cells noticed earlier had combined themselves to form more intense and larger areas of thunderstorm regions. Fig. 12 was taken at 0010 IST of 15th. The large patch of echo noticed at 5 mile range towards south was still identifiable; a new line of thunderstorm activity had extended from the station towards SE. Fig. 13 shows the situation at 0015 IST. The patch towards NE had dissipated away. The line type thunderstorms noticed earlier had extended a little beyond 10 miles. The patch towards south was still there and the squall line type of thunderstorm seems to be rotating in anticlockwise direction with respect to the station. It was also observed that nothing could be detected beyond 12 miles. This however does not mean that there were no echoes further beyond. The attenuation along the line of thunderstorm activity might have been severe enough to cut off completely the received power from that direction.

Fig. 14 was taken at 0020 IST when the thunderstorm had ceased over the station and the sky was clearing. The storms were moving away in NE'ly direction; two distinct and separate regions of thunderstorm activity may be seen, one in the front and another in the rear. In the front one, four separate areas could be seen. In the earlier picture at 0015 IST, only one big area was visible with a small echo towards the south of it. It was noticed that these latter ones had developed into two more intense areas.

The next picture (Fig. 15) was taken at 0030 IST. The separate regions noticed earlier have merged themselves into two distinct thunderstorm regions and were seen moving away towards NE.

4. Effect of wind field on the movement of the thunderstorm

It is difficult to forecast or even to observe movement of individual thunderstorms from synoptic charts as these are rather small scale phenomena. The usefulness of radar in this respect is obvious. By plotting the positions of radar echoes from the PPI scope on local weather map at successive intervals of time the movement of the system can be watched, or by photographing the trace, the movement can be analysed later. The former is very useful from the point of view of short range forecasting and local warnings.

The convective phenomena in an unstable air mass which ultimately culminates into thunderstorm usually occurs over a wide area and a large number of cells or echoes are observed on the radar scope over the region. Two kinds of motion are normally associated with them, the general drift of the system as a whole and the movement of individual cells within the system.

In the case under study, a single thunderstorm cell was first noticed approaching the radar site from a distance of 23 miles. This thunderstorm approached to within 5 miles

TABLE 1

Time of observation (IST)	Horizontal extent of thunderstorm (sq. miles)	Bearing from station (°)	Speed (miles/hr)
2150	9·0	247	
			10
2200	15·0	248	
			13
2215	5·5	248	
			26
2230	7·5	248	
			20
2240	5·0	247	
			20
2245	2·5	245	
			13
2250	3·0	244	
			14
2257	3·5	245	
			22
2300	—	247	
			21
2308	—	243	

Mean direction = 246 degrees
Mean speed = 18 miles/hr

of station in a period of about 78 minutes before its identity was lost amongst other secondary cells. The general drift of these secondaries as a system was more or less similar to the movement of the main storm although the movements of individual cells were sometimes entirely different. As a particular example the cell towards NNE at 10 mile range in Fig. 4 was observed to have a motion which was approximately at right angle to the direction of movement of the main thunderstorm.

In this particular thunderstorm the following three typical phases could be recognised :

(*a*) Approach of the main storm to within 5 miles of radar site, between 2150 and 2300 IST

(*b*) Development of secondary cells, their movement and dissipation during the interval 2245 to 2315 IST

(*c*) Development of new thunderstorm cells from south and their movement during 2315 to 0030 IST

For analysing the movement of thunderstorm, phases (*a*) and (*c*) above, more particularly the phase (*a*), were only examined. The growth and dissipation of cells and their movement in phase (*b*) were very rapid and complex and as radar pictures were not taken at shorter intervals it was not possible to make a detailed study of the same.

Correspondence of movement of radar cloud with winds at a particular level has been studied by others. According to Brooks (1946), small radar clouds move with the winds at 5000-ft level while large clouds move with winds at 11,000-ft level. Brancato (1942) has found however, that cumulonimbus clouds move with winds at the 6000-ft level. Observations carried out in U. S. A. (*The Thunderstorm* 1949) had revealed that the zone of correspondence between air and radar cloud movement lies in the lower layers and that the radar clouds move with the mean wind from the gradient level to 24,000-ft level. Although it would be erroneous to draw any conclusion from a single thunderstorm observation, the movement of the present radar cloud was compared with the prevailing upper winds to find out whether it agreed with any of the above findings.

Table 1 shows the speed, horizontal extent and direction of movement of radar cloud from 2150 to 2308 IST during the first phase. The speed was calculated by plotting the displacement of the centre of the echo pattern at different intervals of time. It may be observed that the speed of movement was not constant over the interval of 78 minutes and a progressive decrease in speed occurred with the diminution of horizontal extent of radar cloud. The highest speed occurred when the radar cloud was decreasing from the greatest horizontal extent attained by it at 2200 IST. The sudden increase in speed from 2257 to 2308 IST may probably be attributed to proximity of newly developed adjacent cells which had absorbed the main storm in the dissipating stage.

The mean speed and direction of radar cloud movement were compared with radar wind from the observatory site at 2005 IST. This wind and earlier pilot balloon wind at 1430 IST and later at 0220 IST after the passage of the thunderstorm are shown in Fig. 16. Fig. 17 shows the difference in direction and speed of radar cloud with winds at various levels. It can be seen that the speed of the radar cloud was less than the wind speed at all levels except upto 2500-ft and that the zone of correspondence in direction was near about 20,000-ft level; the zone of correspondence in speed lay in the lower levels, from 3000 to 12,000 ft. The best agreement both in direction and speed was, however, between the levels 18,000 to 22,000 ft and that the radar cloud was moving slower than the mean wind at this level and was displaced clockwise with respect to it by as much as 20 degrees.

The freezing level on this day determined from the radiosonde ascent from the observatory site was approximately at 12,000ft. The differences with wind direction at this or at 5000, 6000 or 11,000-ft levels are, however, large. Therefore, there appears to be no correspondence in the movement of this thunderstorm with winds at the levels mentioned above.

During the third phase of the storm it may be seen from Figs. 8 to 11 that new cells were forming from the south of the station. These cells subsequently developed into line type thunderstorms whose maximum extent was about 12 miles at 0015 IST. Individual cells along this line had a northerly movement while the line of thunderstorm itself tilted with respect to the radar site in an anti-clockwise direction. This tilting and the displacements of the line at various intervals of time can be seen clearly in Fig. 18. The cells in the line had a movement which was normal to the direction of displacement of the line. Both the lines of thunderstorm activity were advancing with an average speed of 18 miles per hour. The tilting of these lines is considered due to vertical transport of horizontal momentum downwards. This would be clear from Fig. 19 where variation of wind vector with height has been plotted. The initial growth of cells and their movement during this phase had been from south. This is likely to be due to the southerly winds up to 12,000 ft which had been more effective during cumulus stage of development of the thunderstorm in steering the cells northwards. After the mature stage was reached, relatively stronger winds at the higher levels were more effective and caused the tilting.

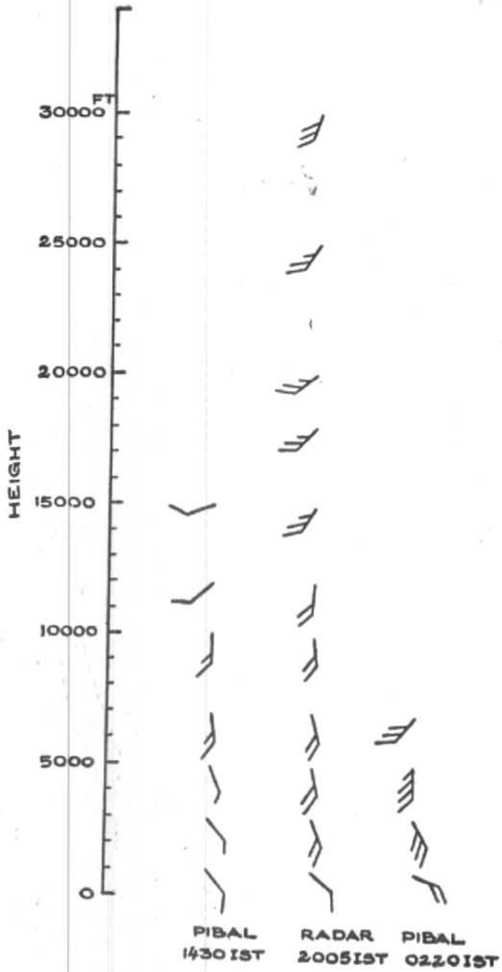


Fig. 16. Winds at New Delhi on 14.1.1953

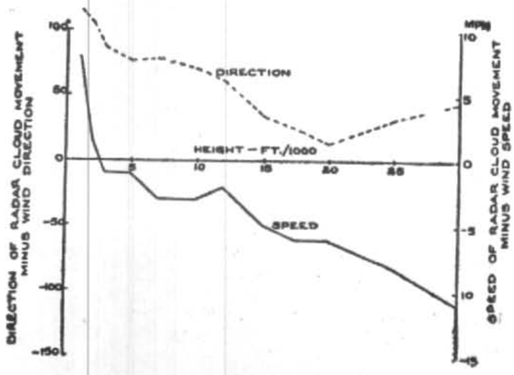


Fig. 17

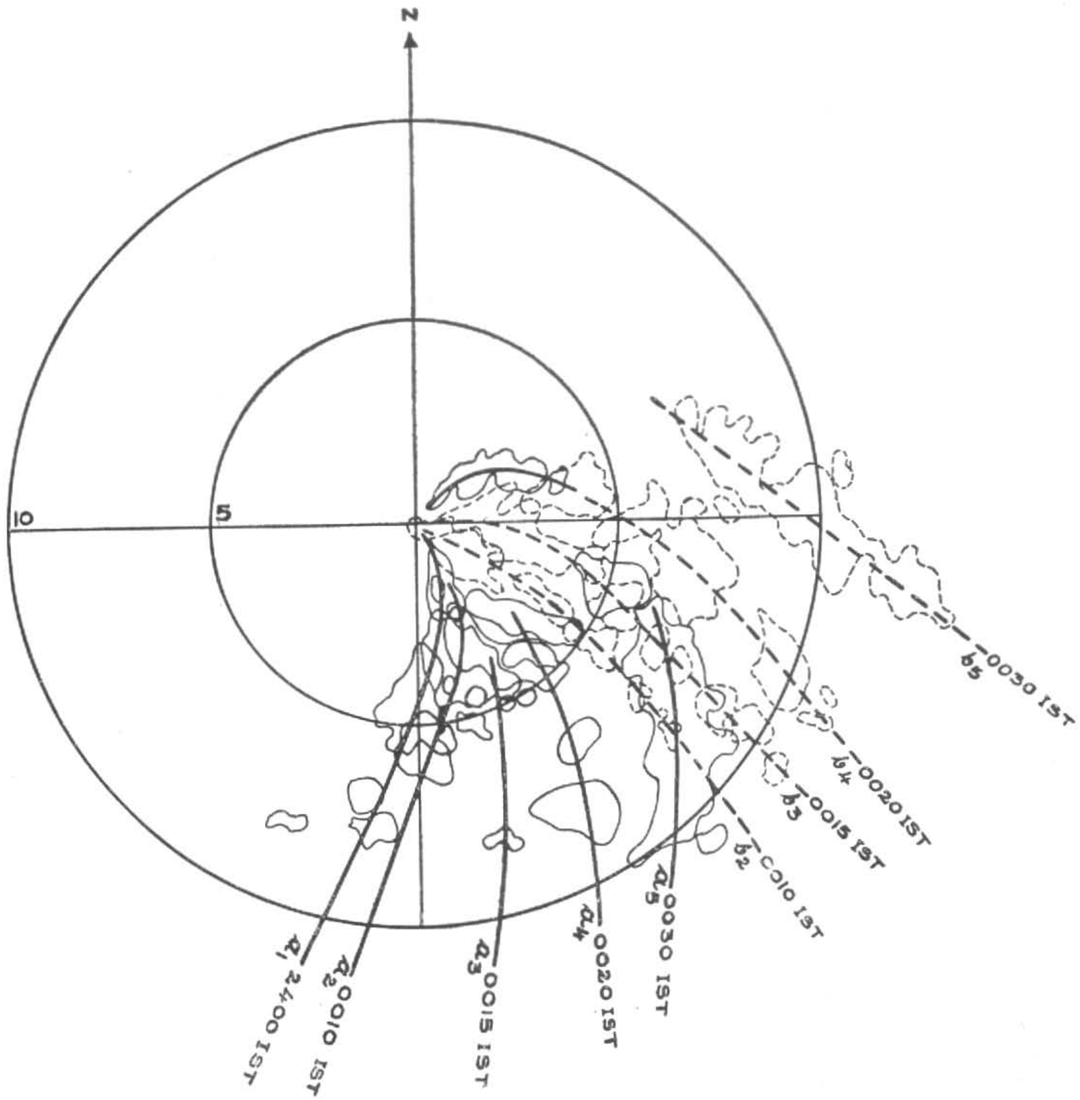


Fig. 18

5. Structure, growth and decay of the thunderstorm

One of the chief characteristics of the thunderstorm is the presence of individual areas of strong updraft or convective circulation which are detected as separate echoes on the radarscope. These individual echoes have been termed as cells on the analogy of Benard cells (Benard 1901). The cellular structure of thunderstorm echoes observed and reported by many (Jones 1950 and others) is already an established fact. In the present storm well defined cellular structures have been noticed throughout its life cycle and sometimes with finer details.

These convective circulations or cells in a thunderstorm have three distinct phases—(*a*) cumulus stage, (*b*) mature stage and (*c*) dissipating stage. In this storm, it had been found that during the cumulus stage of growth, a number of smaller cells appeared first on the radar scope. These individual cells later merged with each other to form a bigger cell or a larger region of thunderstorm activity. This has been illustrated in Fig. 20, where the outlines of individual cells as seen on the radar scope have been drawn in enlarged form corresponding to photographs shown in Figs. 10, 11 and 12. As already described, a large number of small echoes were noticed developing from south of the station at 2355 IST. The group of echoes shown within the boundary (1) at 2355 IST formed into two big cells at 2400 IST and ultimately at 0010 IST into a single large cell. The group within the boundary (2) and (3) similarly developed into larger areas by 0010 IST. Growth of such convective echoes by development of new cells at or close to the boundary of existing echo, has been reported elsewhere also (WMO RA-I (I) 1953).

While the growth of convective echoes followed the mechanism outlined above, the decay also followed the same general pattern. After the mature stage was attained, the large echo usually began to split up into a number of smaller cells as it approached the dissipating stage. This mechanism of splitting up before finally disappearing is shown in Fig. 21 where also enlarged outlines of radar echoes are reproduced from the original photographs. At 2150 IST three cells numbered 1, 2 and 3 in the above figure, were clustered together. These became larger in size at 2200 IST but by 2215 IST only one single unit could be identified. From 2215 IST this cell began to split up into a number of separate cells. At 2240 and 2245 IST the cell No. 1 had split up into cells 1 and 4. By 2250 IST further sub-divisions were noticeable, cell No. 1 split up into cells numbered 5, 6 and 7. Cell 4 got separated from the main echo.

At 2255 IST, in addition to 5, 6 and 7 another cell numbered 9, was also noticed inside the area. The cell 8 had further divided itself into cells 8, 10 and 11. Further up two more feeble cells Nos. 12 and 13 were also seen. Two minutes later at 2257 IST these cells were seen decreasing in area although no further subdivision was visible. In the configuration at 2300 IST the cell No. 5 had split up into two, namely 5 and 14, while cells 6 and 9 had merged together. This had occurred before the dissipation of the main cell and it may therefore be seen that one single cell at

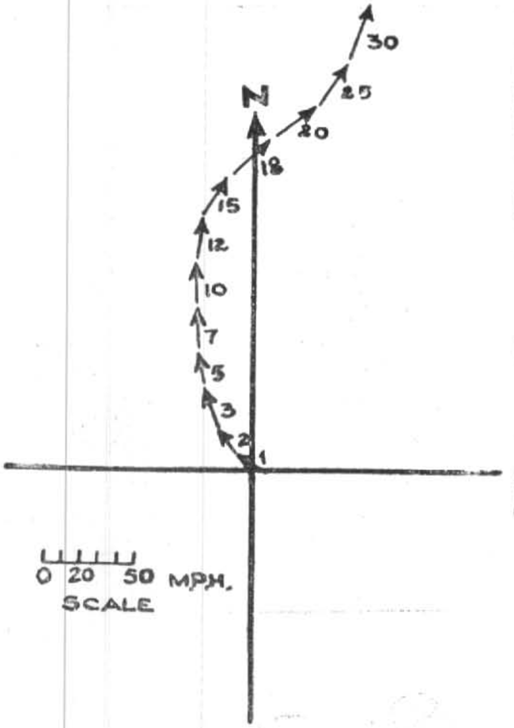


Fig. 19. Variation of wind vector with height

2215 IST had in course of fortyfive minutes subdivided itself into fourteen cells before dissipating. These transitions of cell structures were, however, very rapid at times.

Mention has already been made about the cellular structure of radar thunderstorm echoes. It was observed that these individual cells, whether they existed separately or combined themselves to form larger area of thunderstorm region, had various diameters, the minimum being about half a mile in the present case while the maximum was about two and a half miles. The average diameter was of the order of two miles. Where individual cells could not be identified inside an intensely bright area, measurement of cell diameter was not attempted. It would be erroneous to conclude that this area consisted of only one single big cell.

Apart from the types of cells noticed in the present storm as outlined above, some smaller subdivisions were also visible at times.

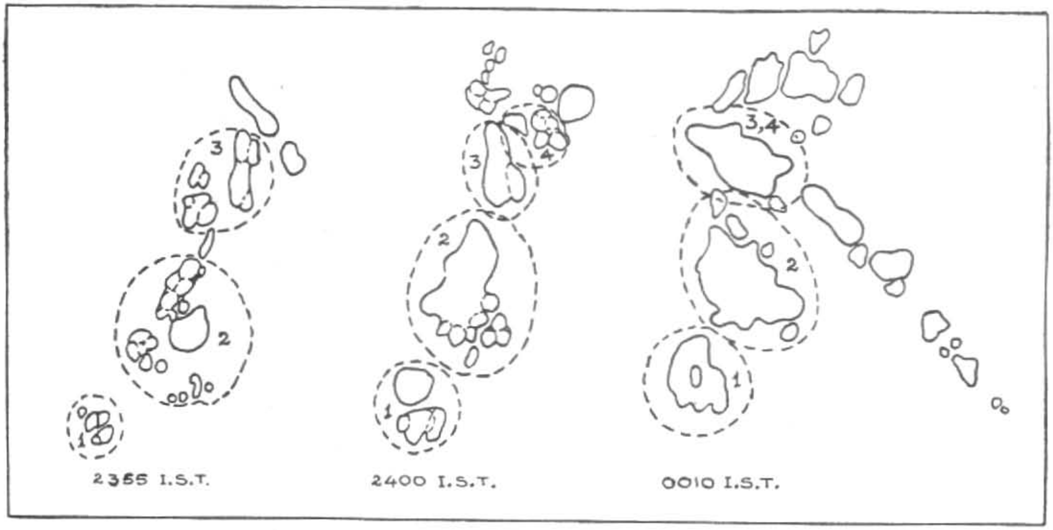


Fig. 20. Growth of thunderstorm cells

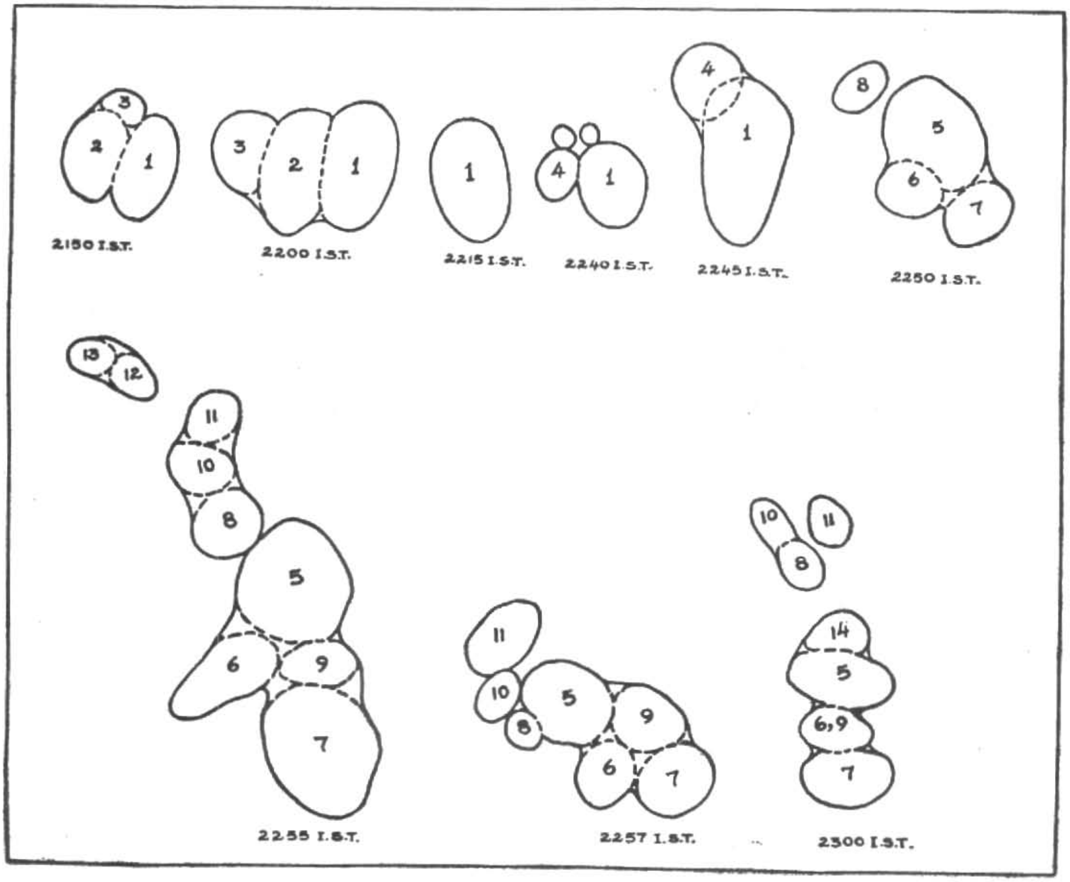


Fig. 21. Decay of thunderstorm cells

Figs. 7, 13, 14 and 15 may be seen in this connection, particularly Fig. 13, an enlarged version of which is shown in Fig. 22. At a range of about five miles towards ENE in Fig. 13 may be seen a number of small cells, circular in form with dark centres. As many as 27 may be counted easily. These cells had an average diameter of 1200 to 1500 ft. They were mostly noticed along the lateral edges of a bigger cell in the dissipating stage or when a cell had actually been dissipating. These cells, it is presumed, represented regions of smaller convective currents inside a bigger cell. A number of these combine to form larger cells usually noticed on the radar scope. It is also believed that these particular cells were in the dissipating stage; the dark core in the centre indicated that there was no hydrometeor present in the centre and the bright area around the periphery denoted that precipitation was confined only at the outer edges of the cell. This usually occurs in a cell in the dissipating stage and the pictures are in conformity with the actual conditions existing inside a thunderstorm. The complete absence of these cells in Fig. 14 also confirms that these were actually in the dissipating stage. It is, therefore, noticed that the cells of the order of half to two miles are not the smallest unit of which a thunderstorm may consist of but that these may also contain smaller subdivisions. Such finer structure and greater details can be observed by employing a radar having a smaller pulse width.

6. Changes in surface weather due to passage of thunderstorm

(a) Wind

The passage of a thunderstorm over a station is usually associated with the change in surface wind direction and an increase in wind speed. In the thunderstorm under study the surface wind recorded at Safdarjung Airport anemograph is shown in Fig 23. During the course of the passage, a maximum speed of about 33 mph was recorded at 2330 IST while a change of 135 degrees in wind direction from easterly to northwesterly had occurred. Up to 2200 IST the average steady direction of wind was easterly and it gradually backed to NW; from 2315 to 2345 IST the wind direction was steady northwesterly.

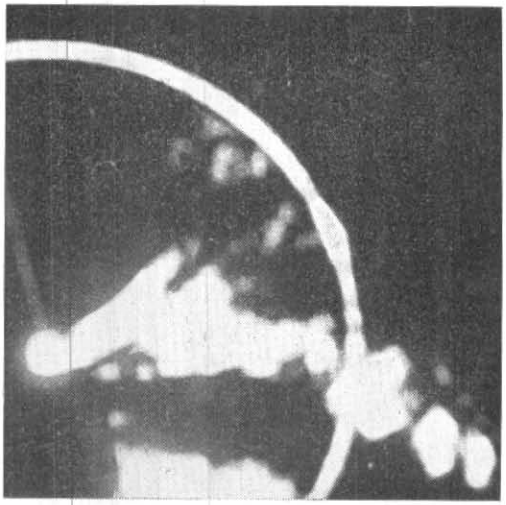


Fig. 22

The normal direction of easterly was resumed after 2400 IST.

This behaviour of surface wind can be explained by taking into consideration the positions and movements of thunderstorm cells observed on radar scope near the station. When a thunderstorm is in the early stage of development horizontal surface convergence of wind usually occurs towards the area where the updraft is in progress. This is the pattern of inflow of wind around the cell. After the mature stage is reached, a downdraft is developed and air spreads out from the cell radially in all directions. This is the field of outflow from the thunderstorm. The pattern of this field is, however, influenced by the direction of movement of cell; it is also modified by the vertical transport of horizontal momentum downwards.

At 2150 IST the thunderstorm was located about 23 miles from the station (Fig. 2). The surface wind began to change direction from 2140 IST; its speed gradually started decreasing from this instant. This change in direction was apparently due to surface convergence towards the thunderstorm and its effect was noticeable at the station when the cell was about 27 miles away. The gradual drop of the wind speed at 2200 IST as indicated in the anemogram, may be attributed to the blocking effect caused by inflow and outflow patterns of the thunderstorm.

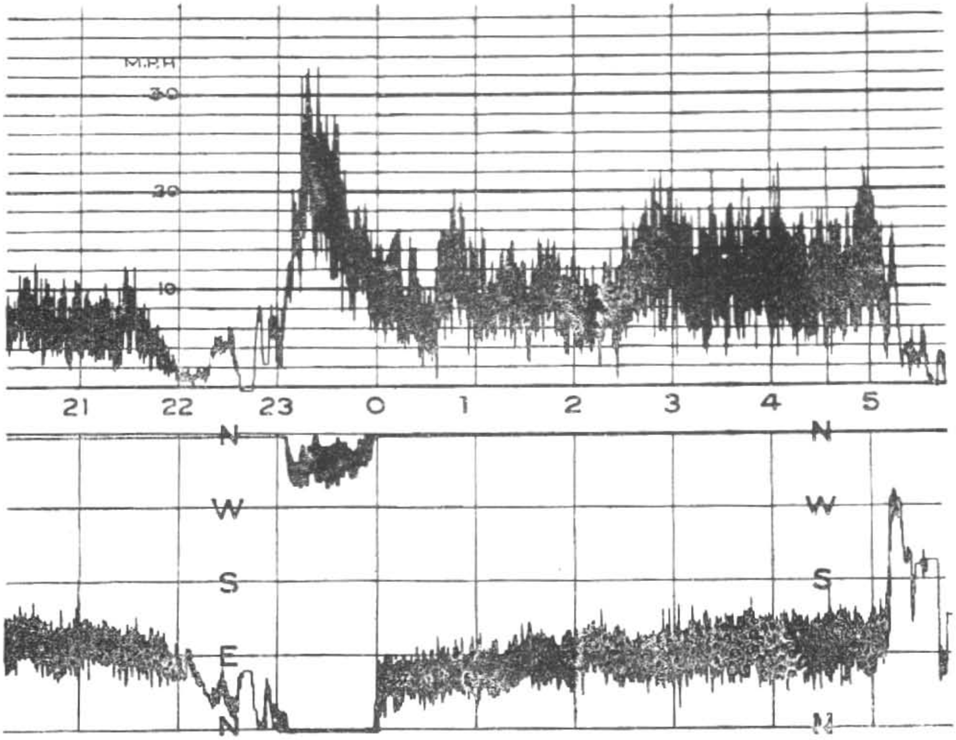


Fig. 23. Anemogram of Safdarjung Airport on 14 January 1953

The outflow gradually established itself over the former. From Fig. 23 it can be seen that at 2200 IST the wind speed practically dropped to zero, remaining so for about 10 minutes. The spreading of the cold downdraft had probably begun to occur from 2140 IST, a little earlier than the first radar photograph. The gradual nature of change of wind direction due to presence of thunderstorm at a distance may be noticed.

The position of thunderstorm cells with respect to the station at various times is shown in Fig. 26 together with the observed direction and speed of surface wind. From 2150 to 2230 IST the gradual change in direction due to convergence towards the thunderstorm may be seen. The arrival of cold dome at the station was at 2308 IST from NNW as can be seen from the anemograph, barograph and thermograph charts in Figs. 23, 24 and 25. The direction of spreading of cold air from the main cell from 2245 to 2340 IST was modified by the outflow from the secondary cells and their movement. The presence of a ridge of about 7 miles length towards northwest of the station also caused an orographic effect on the direction of recorded surface wind. At 2325 IST, due to the presence of the cell over the station, the direction of outflow was northwesterly. From 2400 to 0020 IST the thunderstorm was moving away from the station which was, therefore, in the rear of the outflow field. The surface wind direction which was originally easterly, was gradually restored after the passage of the thunderstorm.

(b) Pressure and temperature

Another feature generally associated with all thunderstorms is the passage of a discontinuity zone over a nearby station; this discontinuity zone is produced on account of outward spreading of cold downdraft. The passage of this zone at a station is normally marked by a sharp increase in wind speed, a rapid fall in temperature and an increase in surface pressure. There are many instances (Mull and Rao 1950) where the general pressure rise is not always accompanied by a temperature fall. With a view to get a

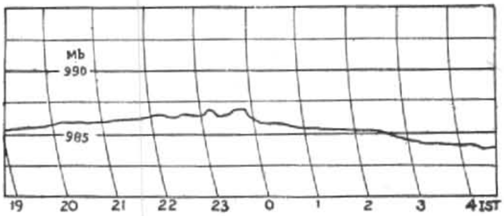


Fig. 24. Barogram of Safdarjung Airport on 14 January 1953

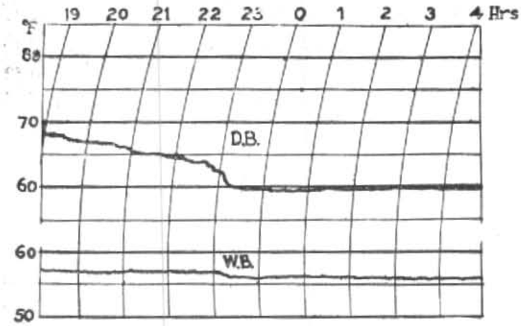


Fig. 25. Thermogram of Safdarjung Airport on 14 January 1953

clearer insight into the mechanism of thunderstorm, the barograph and thermograph records were examined together with radar pictures;

The rise in surface pressure due to cold downdraft as the cell passes from the mature to the dissipating stage has been stated (*The Thunderstorm* 1949) to be due to the following several reasons:

(*i*) increase in the mean density of the column in which the downdraft occurs;

(*ii*) impact of downdraft on the surface;

(*iii*) displacement of warm and less dense air at the surface by cold air from the downdraft; and

(*iv*) convergence at higher levels.

Assuming that the above mentioned processes are responsible for rise of pressure at surface, it is seen that fall in temperature is not the only criterion for increase of pressure at surface. Factors (*i*) and (*iv*) mentioned above are also responsible for this rise in surface pressure.

In Figs. 23, 24 and 25 the records of surface meteorological instruments are shown. It

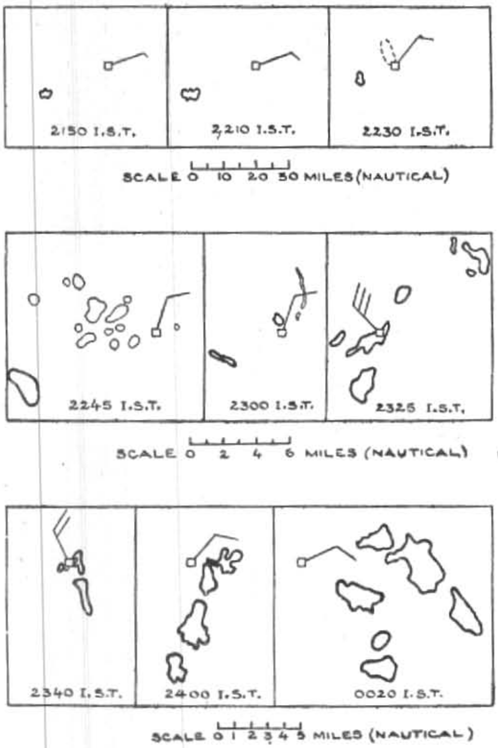


Fig. 26. Position of thunderstorm cells at various times

may be noticed that the fall in temperature, increase in wind speed and rise in pressure occur almost simultaneously at 2308 IST. These changes indicate the arrival of a discontinuity zone at the station at this time. The radar picture in Fig. 7 indicates the positions of various cells around the station at the same time. It is seen that the main cell was still 2½ miles away and there were other cells over the station which were giving rain. After 2308 IST the temperature had remained constant, but pressure registered a fall at 2320 IST and after remaining constant for about 10 minutes rose from 2230 IST, reading its maximum at 2345 IST. From the pictures already reproduced in Figs. 8 to 10 it may be seen that from 2315 to 2330 IST new cells were forming round the station. Since the cumulus stage of growth is associated with strong updraft, an expansion of air due to liberation of latent heat occurs, the fall in pressure trace without any corresponding change in temperature trace can be explained. It was estimated that the time 2330 IST was the end of the cumulus stage.

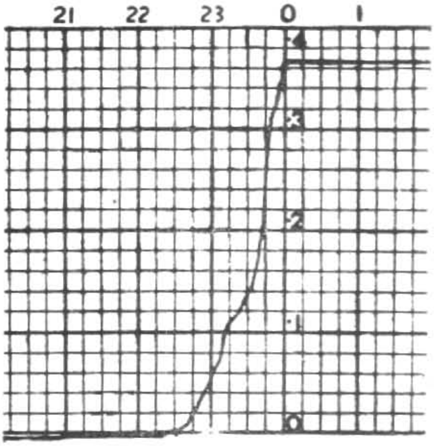


Fig. 27(a). Rainfall record of 14 January 1953 at Safdarjung Airport

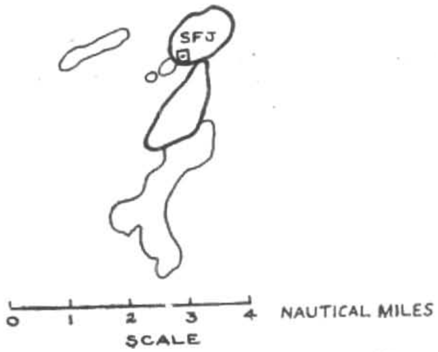


Fig. 27(b). Position of radar echoes at Safdarjung Airport at 2330 IST

It was, therefore, reasonable to expect that rain would reach ground from the cell over the station at this time. In Figs. 27 (a) and (b) reproduced the rainfall chart and the position of radar echo over the station. It is seen that the rainfall during the period was heaviest, a total of 0·16 inch was recorded in 15 minutes corresponding to a rate of 0·64 inch per hour. Other radar pictures taken at this time showed that the rate was so heavy that it caused severe attenuation and no echo could be seen beyond a range of one mile.

After the downdraft has developed, air is cooled by evaporation of rain. This cooling together with the large amount of rain causes surface pressure to rise again, which explains the rise of the pressure trace between 2330 and 2345 IST after heavy precipitation. The inferences from the radar pictures, therefore, conforms to the surface observations quite satisfactorily.

(c) *Rainfall*

It has been reported that (*The Thunderstorm*, 1949) the rainfall pattern under a thunderstorm follows closely the arrangement of cells of which it is composed. To study the rainfall pattern together with the radar echoes, it is necessary to have a very close network of surface stations equipped with self-recording raingauges. Such a network of stations was not available round the existing radar site and a quantitative analysis of rainfall pattern with radar echoes could not be undertaken. There are fifteen raingauge stations reporting the total amount of rainfall recorded during 24 hours, located around the present radar site, within a radius of 25 miles, including Safdarjung. The distribution of these stations is not uniform as may be seen from Fig. 28. The rainfall data from these stations indicated in the above figure were used in a qualitative way to examine the rainfall pattern. In Fig. 28 is also shown the path of thunderstorm and position of various cells which were formed during its passage. It may be seen from the above figure that there were only two stations, FRK and PLM, in the path of the main thunderstorm which had recorded a rainfall of 0·30 and 0·80 inch respectively. There was another station JTN about 45 miles away in the same direction as these two stations in the path of the thunderstorm which had recorded an amount of rainfall of 0·33 inch. There were three other stations, NFG, GRG, NRA in the western sector which had also recorded substantial amount of rain but where no radar clouds were observed. These stations were located beyond 10 miles of the radar site and from 2255 to 0015 IST the radar set was operated at ranges not exceeding 10 miles. It could not be, therefore, said with certainty, that there would have been no echoes over these stations during this interval. Moreover, the weather diary maintained at Safdarjung Airport indicates, that there was another spell of thunderstorm and rain between 0440 and 0520 IST. No radar watch was maintained at this hour and the rainfall recorded by these stations may also be due to this later thunderstorm.

The last radar picture of the present storm was taken at 0030 IST when the storm was

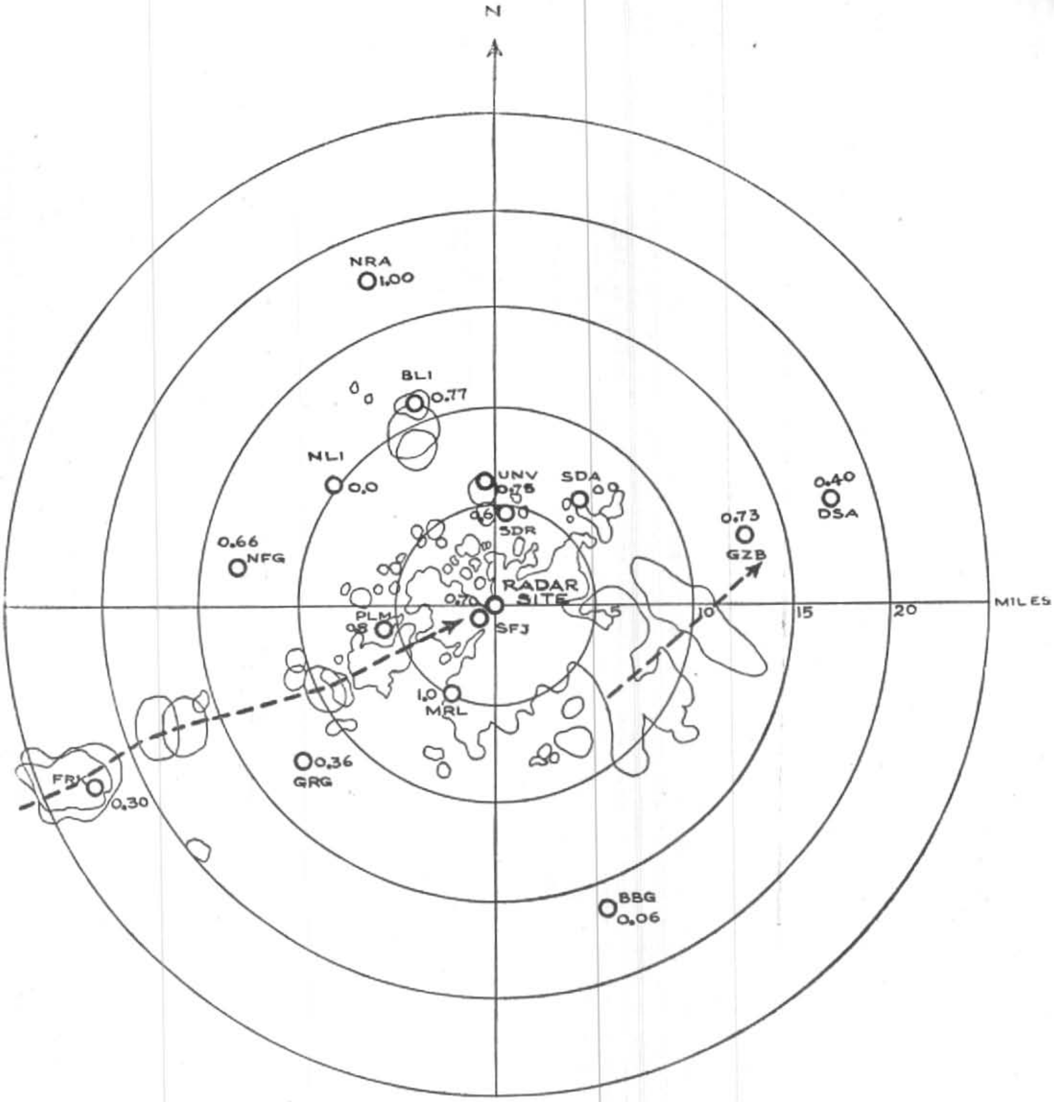


Fig. 28

Abbreviations used for stations:—Narela (NRA), Badli (BLI), Nangloi (NLI), Najafgarh (NFG), Shahdra (SDA), Sadar (SDR), University (UNV), Palam (PLM), Dasna (DSA), Ghaziabad (GZB), Safdarjung (SFJ), Mehrauli (MRL), Gurgaon (GRG), Farrukhnagar (FRK), Ballabhgarh (BBG)

seen moving away towards northeast as indicated by the arrow in the above figure. If it had actually moved in that direction the amount of rain recorded by GZB and DSA which were in its path can be explained. There was another station HPR in the path of the thunderstorm beyond GZB and DSA about 35 miles away which had also recorded a rainfall of 0·86 inch.

There is one interesting fact about the rainfall recorded at station BLI towards NNW, about 11 miles away. A solitary cell formed near this station and moved over to it. This cell had a life of about 15 minutes and was observed to be very intense (Fig. 4). A part of the rainfall recorded at the station may be attributed to this cell.

The station MRL at the edge of the area under the influence of the thunderstorm had recorded a rainfall of 1·0 inch during 24 hour period. A greater part of this rain may be attributed to the thunderstorm under study. Safdarjung is the only station in the area where a self-recording raingauge is installed and this station had recorded a rainfall of 0·36 inch during the period 2230 to 2400 IST, an average of 0·24 inch per hour. This station was directly under the path of the thunderstorm. The rainfall within the above period was due to the passage of the main thunderstorm cell as well as due to development of other secondary cells which also contributed substantially to the amount. The station BBG and a few others beyond it, not shown in the figure, had recorded only small amount of rain; no radar echo was observed as may be seen from the figure in that region. It may, therefore, be said that the radar echo, qualitatively represented the rainfall pattern observed in this thunderstorm. For estimating exact rainfall pattern it is imperative to set up a micro network of raingauge stations provided with quick-run-type rain and intensity recording gauges.

From the rainfall record of Safdarjung Airport the rate of rainfall over known intervals, wherever a change in rate had occurred, was calculated. This is shown in Fig. 29. It would be seen from the figure that there were two peaks in the rate of rainfall one at 2310 IST when the rate was 7·6 mm hr^{-1} and another at 2340 IST when the rate was 163·0 mm hr^{-1}. The latter can be considered as heavy. The duration of rainfall at a station depends upon its position with respect to the cell and also on the nature and the life history of the cell. An attempt was made to find out if these two peaks could be assigned to any particular cell passing over the station.

In Fig. 30, five pictures show the position of radar echoes round the station at different times within the above interval. The location of Safdarjung Airport is indicated in these pictures together with the outline of the observed radar echoes. Outlines of strong echoes are shown in bold lines and weak ones in thin lines. Fig. 30(a) was taken at 2308 IST and Fig. 30(b) at 2315 IST. It is believed that the rainfall rate of 7·6 mm hr^{-1} was due to the echo observed towards west of Safdarjung which moved over to it. Fig. 30(c) was taken at 2320 IST. No strong echo was observed over the station and the rain was mostly from weak cells around it. Fig. 30(d) was taken at 2330 IST and it was observed that a strong echo was over the station. The rainfall from this cell for the ensuing period was heaviest. Earlier pictures (Figs. 8, 9) showed that this cell was forming and had attained the end of the mature stage by 2330 IST. This is corroborated by the pressure trace which is also superimposed on the graph showing the rate of rainfall in Fig. 29. It may be seen that from 2310 to 2330 IST the pressure was falling. This can be attributed to the presence of strong updraft over the station as the cell was attaining its mature stage.

During the period 2333 to 2348 IST, the attenuation due to this heavy rate of rainfall was so severe that nothing could be seen on the radar beyond a range of one mile. In addition to the ordinary attenuation by rain, attenuation was also caused by the deposition of a film of water on the surface of the radome. Fig. 30(e) shows the situation at 2350 IST. The strong echo now lies towards south of the radar site and none is observed over Safdarjung. This is in agreement with Fig. 29 as the duration of heavy rain was over by 2348 IST.

7. Formation of secondary cells

The structure of the thunderstorm as revealed by the radar pictures already reproduced discloses that the phenomenon is rarely accompanied by a single cell and that new development of cells always takes place near the parent cell; these are sometimes clustered around the main cell at some stage of its life cycle. During cumulus stage of growth new developments are not so frequently observed but after the parent cell has attained the mature stage, other cells begin to appear around it. The growth of new cells around a main one had been attributed (*The Thunderstorm* 1949) to various causes, the chief among which is the under-running of cold air from downdraft which lifts up the warm air from below. In the present case, growth of numerous cells was observed in front of the main cell and at the lateral edge of it. The growth of these secondary cells had followed a certain pattern and some of the features are described in the following paragraphs. The results of observation of a few of these cells are shown in Table 2.

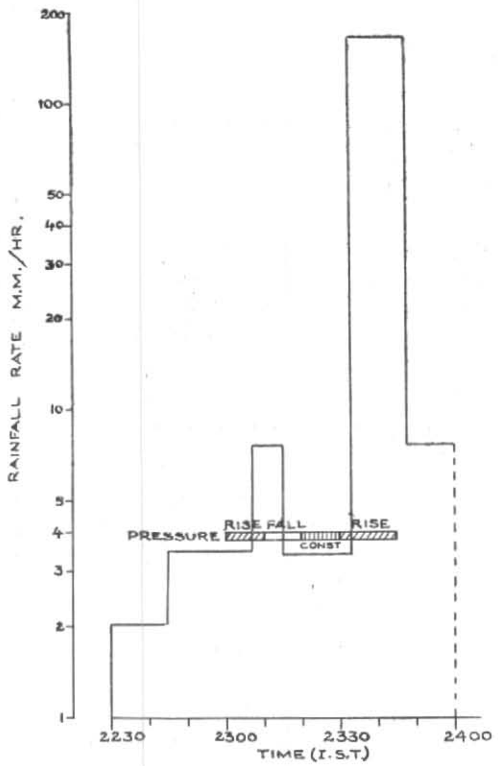


Fig. 29. Rate of rainfall recorded at Safdarjung

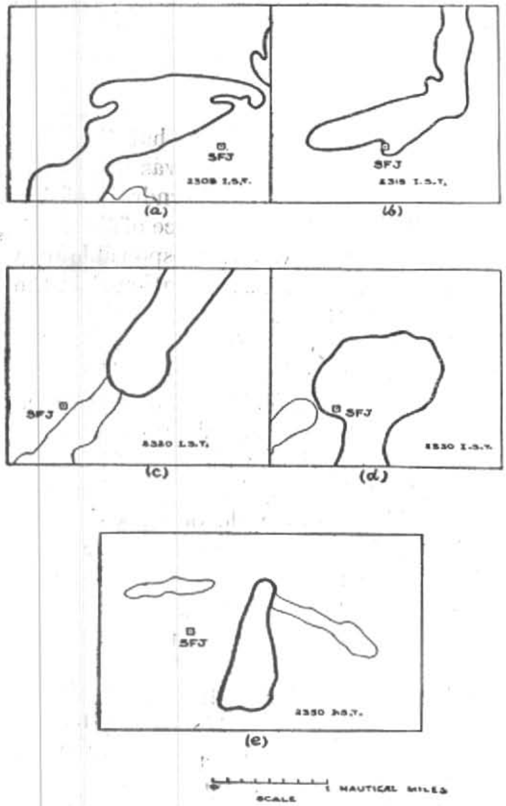


Fig. 30. Position of radar echoes round the station at different times

TABLE 2

Characteristics of Secondary Cells

No.	Duration of observation (IST)	Direction of movement	Mean speed of movement (miles/hr)	Average life (minutes)
1	2215—2225	NNW	26	15
2	2308—2330	NE	18	22
3	2355—0010	N	13	35
4	2355—0015	N	18	20
5	2320—2330	Stationary	—	10
6	2240—2300 (Group of echoes)	Clockwise	—	20

Average life of main thunderstorm 70 minutes

With the approach of the main thunderstorm cell towards the radar site, spontaneous growth of a few intense cells having a relatively short life was noticed. These cells died before the dissipation of the main cell, that is, their life cycle was much shorter than the parent cell. Some of these, in the initial stage, appeared on the radar scope when the main thunderstorm was as far as 20 miles away and were located in such a direction that it would be difficult to explain their growth by the process of under-running of cold air from the parent cell. As an example the cell towards NNW at a distance of 9 miles in Fig. 4 may be seen. It would be difficult to explain the mechanism of its growth except by spontaneous but very intense local updraft in that region. Table 2 shows that it had a life of about 15 minutes.

As the thunderstorm advanced further towards the station a number of other cells began to appear in front of it within a distance of about 7 miles. Their number also increased progressively and they became very active (Figs. 5 and 6). It also appeared that these were being pushed back by the parent cell as the system as a whole was slowly moving. Most of the cells also vanished simultaneously with the dissipation of the main storm and had an average life of 20 minutes; a few of these cells joined together and formed new regions of thunderstorm activity and behaved subsequently as an independent thunderstorm.

There is evidence to show that the chief cause of growth of these cells was the underrunning of cold air from downdraft of the parent cell although the presence of the ridge already mentioned was also responsible to a certain extent. It has been mentioned in the earlier section that the discontinuity zone arrived at Safdarjung Airport at 2308 IST. Calculations from a few charts of self-recording instruments from Palam Airport which is 7 miles from Safdarjung showed that the cold air was spreading at the rate of 10 miles per hour. On this basis, the calculated arrival time of cold air at 5 mile range where the growth was first observed to be very active, would be 2240 IST; this was approximately the time when these cells were noticed. It is, therefore, very probable that the growth of the cells noticed at a distance of about 7 miles from the parent cell was due to the lifting of the warm air by the cold air from below; simultaneous disappearance of most of these cells along with the dissipation of parent cell is also significant. But why these cells in this case had followed a particular pattern of formation is not possible to explain on account of inadequate data and the process seems to be complex.

At 2400 IST a line of fully developed thunderstorm was observed extending from station towards south upto a range of 8 miles (Fig. 11). At 0010 IST (Fig. 12) another line of thunderstorm had formed in front of the earlier one at a distance of about 2 miles from the former. At 0015 IST this had extended to beyond 10 miles (Fig. 13). Their formation is also believed to be due to the spreading of cold air from the cells in the rear and also from the group of cells near the station towards east, the outflow from which was northwesterly.

At 0015 IST two small cells towards SSE at a range of 8 miles may be seen in Fig. 13. Within next five minutes these had developed into two full grown cells (Fig. 14). Their growth was very rapid and was not towards the direction of motion of the parent cell but on one side of it. Their growth can also be explained by taking into account the direction of outflow field from the cell near the station and its rate of spreading.

In this storm, although many new cell formations were noticed in front and at the lateral edge of the parent cell, there was only one case of cell development in the rear (Fig. 3).

In all cases these new developments had been confined within a distance of 10 miles of the storm and areas in front of the direction of thunderstorm motion within a distance of 2 to 5 miles were noticed to be more suitable for new formations.

8. Acknowledgements

The author wishes to express his thanks to Mr. S. Basu and Mr. A. K. Roy for their keen and stimulating interest in the work and also acknowledges his indebtedness to Dr. L. S. Mathur under whose guidance the programme of Radar Weather investigation has been taken up. Thanks are also due to other members of staff of the Meteorological Laboratories for their assistance in many ways.

REFERENCES

Benard, H.	1901	*Ann. Chim. (Phys.)*, Tome XXIII, Ser. 7, p. 62.
Brancato, G.N.	1942	*The Meteorological Behaviour and Characteristics of Thunderstorms*, U.S. Hydromet. Sec.
Brooks, H.R.	1946	*Bull. Amer. met. Soc.*, **27**, 10, p. 557.
Jones, R.F.	1950	*Met. Mag., Lond.*, **79**, 934, p. 109.
Mathur, L.S. *et al*	1954	*Indian J. Met. Geophys.*, **5**, 2, p. 173.
Mull, S. and Rao, Y.P.	1950	*Indian J. Met. Geophys.*, **1**, 2, p. 116.

WMO Regional Association I (Africa), First Session 1953 Doc. 74.