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Hailstorms near Nagpur — A radar study

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ABSTRACT. In the present study, which has been made by a Decca type 41 radar, it has been shown that the hailstorms over Kamptee situated at a distance of 10 n. miles towards northeast of the radar station had occurred due to the presence of a rotational echo with characteristic hook features. An attempt has been made to find out (*a*) the speed and direction of the movement of the rotational and non-rotational echoes and their collision courses in directional convergence, (*b*) to calculate the terminal velocity of the precipitation particles and the corresponding particle size from the streamers, associated with a prominent hook echo and (*c*) to suggest the probable time of occurrence and end of the hailstorm over Kamptee.

1. Introduction

The present study of hailstorms has been made with Decca type 41 radar, installed at Nagpur. This radar has a PPI scope, operates on 3-cm wave band and has a peak power output of 30 kw. Its beam width in the horizontal plane is 0·75 degree, and in the vertical plane 4 degrees.

This series of hailstorms confirmed by local newspaper reports occurred on 26 and 27 February 1964 towards evening at Kamptee which is situated about 10 n. miles in the direction 042° from the radar station.

In the study, the hailstorm on 26 February 1964 has been discussed in detail, while study of that on 27 February 1964 restricted to only the movement of the echoes. The synoptic situation under which these hailstorms had formed have also been discussed briefly.

2. Brief synoptic situation

The straight wind flow over North India and a part of central India with a belt of strong winds from 40 to 100 knots at 9-km level was lying over a low level (0·9 km) cyclonic vortex situated very near Nagpur in the west at 00 GMT on both 26 and 27 February 1964.

The vertical time-section of winds at Nagpur (Fig. 1) showed strong wind shear of the order of 65–70 kts on 26 February and 55–60 kts on 27 February 1964 between 850 and 300-mb levels. In the lowest 10,000 feet, the wind flow veered from northeasterly to westerly on both the days.

3. Observations on 26 February

A solid echo first observed on radarscope at 1630 IST was in the northwest of the station at a distance of about 8 n. miles. It was associated with well marked indentations in the west and also a finger like protuberance or a hook having a deep notch towards south of the echo mass. The photography of the echoes could only be started by 1643 IST. This deep notch could not be seen clearly above 8 degree elevation of the radar antenna. From 4 to 5 degrees elevation, the hook with the notch was seen quite distinctly and so further study was made at 4 degrees elevation of the antenna, after 1 or 2 minutes interval at various receiver gain settings within 25 n. miles of the station. The variation in echo size from 1643 IST at short intervals of time, at various antenna elevations has been represented in the series of photographs (Figs. 2a to 2n).

4. Discussions of radar observations

Hook activity has been studied by many authors both in India and abroad. Mull and Kulshrestha (1962) and Sharma (1965) in India have noticed hook echoes in association with hailstorms.

Browning and Ludlam (1962) and Browning and Donaldson (1963) have studied severe local storms associated with tornado and hail. The echo from such a storm had three important features (*a*) a forward overhang, (*b*) an echo free vault and (*c*) a wall, as seen on RHI during the most intense phase of the storm. When such an echo is viewed on PPI by a horizontally scanning radar with slightly narrow beam, the wall surrounding the vault is seen to be a hook echo and the echo free vault appears as an echo free notch, resembling those often seen in association with tornadic storms. Browning (1964) has given a name "Supercell" to such single large cells which remained in more or less steady state, as the storms travelled to the right of the environmental winds for period of several hours. Such super cells have been discussed by Browning (1964), as S. R. storms, *i.e.* severe local storms that travel to the right of th winds.

Neumann (1965) emphasised, while studying a severe hailstorm over Miami area, that the formation of Browning "Supercell" in the low latitudes favoured strongly the occurrence of hailstorm,

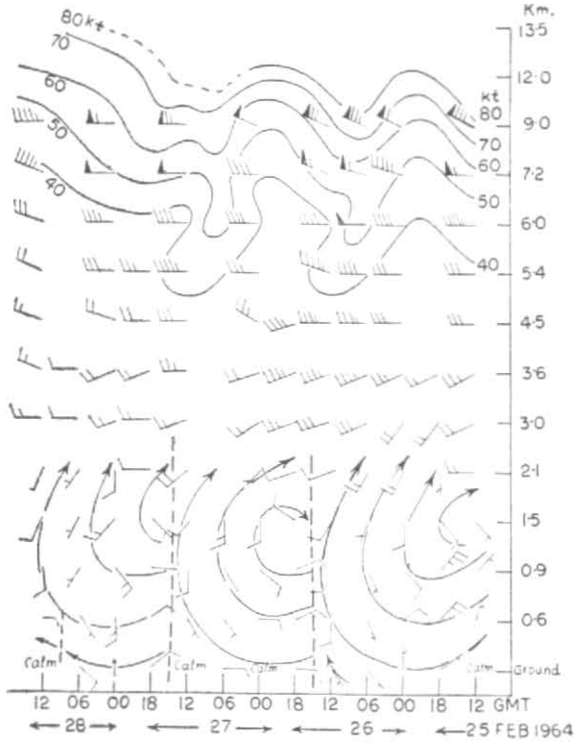


Fig. 1. Vertical time-section of wind over Nagpur

4.1. Out of the figures 2a to 2d representing the main echo from lower levels to the higher levels, the last one (Fig. 2d) shows all the special features like forward over-hang towards left hand forward flank, an echo free notch or vault and a hook or wall.

4.2. Browning and Donaldson (1963) have noticed that the strong winds behind the hook or the wall, probably due to the outflow from an intense downdraft associated with region of the most intense precipitation (rain and hail) in the immediate vicinity of the intense updraft, had the effect of inclining the wall slightly forward and to the right at low levels. The wall or the hook at 1651 IST in Fig. 2f has been seen to have turned forward towards east and filled up the notch area between the hook and the forward echo mass, known to be an echo from the forward over-hang. Soon after this was noticed, the station recorded a rise of pressure by 0·3 mb from 1650 to 1652 IST, a temperature fall of 4·2° C at about 1700 hrs and humidity rise of 4 per cent from 1651 to 1700 IST. The surface wind changed from southerly to north-northeasterly giving a first northnortheasterly gust of 36 km/hr at 1704 IST. Also the number of sferics per minute had shown a sharp increase from 50 at 1630 IST to 130 at 1655 IST and then dropped to 100 at 1700 IST showing thereby that the storm was having maximum intensity at 1655 hours. From these observations the most probable time for the commencement of hailstorm at Kamptee may be taken as about 1651 IST. The time lag of 13 minutes between the probable time of commencement of hailstorms at Kamptee at 1651 hours and the station surface wind record at 1704 IST may be attributed to the distance of Kamptee from the radar station.

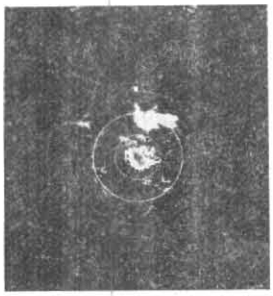
In Fig. 2g the hook turning cyclonically forward towards the notch is clearly seen at 1653 IST. Fujita (1958), while studying Illinois tornadoes of 9 April 1953 has shown that the radius of curvature of the hook increases with time and then turns cyclonically into a miniature eye at the centre of a tornado cyclone, which appears as a hole in the reduced gain pictures. This hole or the dry hole is represented in Fig. 2h. At this time (1655 IST) the updraft probably had remained so much intense that the small cloud droplets, constituting the echo free area (dry hole), owing to the high velocity within the core of the updraft, had insufficient time to attain radar detectable sizes (Browning and Donaldson 1963). Sferics data also confirm that at this time the number of sferics per minute were maximum. A dry hole was also observed five minutes after the commencement of the hailstorm at Gauhati (see Figs. 6 and 7, Sharma 1965).

Stout and Hiser (1955) have suggested that the notches might be the result of dissipation of a portion of the cloud accompanying release of hails. A blunt hook or a widened notch at 1656 IST

Full 1643 ½°/25
(a)

Full 1645 1°/25
(b)

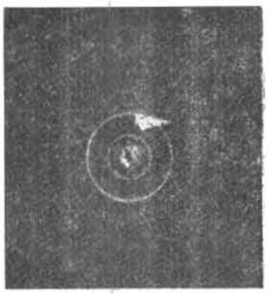
Half 1647 3°/25
(c)



Full 1649 5°/25
(d)

Half 1650 5°/25
(e)

Full 1651 4°/25
(f)



¼ 1653 4°/25
(g)

Zero 1655 4°/25
(h)

Full 1656 4°/25
(i)

3/4 1700 4°/25
(j)

3/4 1702 4°/25
(k)

3/4 1705 4°/25
(l)

Figs. 2 (a—l) — 26th February 1964

Figures below photographs indicate (from left) : Gain of the receiver, time in IST, elevation of radar antenna in degrees and the total range in n. miles

3/4 1711 4°/25
(m)

Full 1742 4°/25
(n)

Figs. 2(m—n) — 26 February 1964

(Regarding figures below the photographs please see p. 257)

(Fig. 2i) within five minutes of its being a narrow one suggests that hails might have been released by this time over Kamptee.

The major cell from 1700 IST started showing again the protuberances in its left and right hand portions. Also it moved along the same track of 110 degrees from 1656 to at least 1711 hrs after which the movement could not be made out. At 1742 hrs the echoes transformed into a bright line type echo. Sferics data show that the number of sferics per minute increased from 100 to 140 from 1700 to 1736 IST, and then went on decreasing to 40 only till 1845 hrs.

5. Movement of the echoes

The main storm cell had been moving at a speed of about 25 knots towards about 090° azimuth up to 1649 IST. The storm speed decreased to about 17 kts from 1649 to 1656 IST and the direction of its movement changed to about 110° which can be observed from Figs. 2d to 2i and then to Fig. 2k. After 1656 IST the storm had been following the direction of 110 degrees with the original speed of 25 knots.

The new echo appearing at 1702 IST at 360°/13 n. miles and the crescent shaped echo (Figs. 2k to 2m) separating itself from the main echo mass and shown by arrow had been moving towards 065 degrees azimuth at a speed of 27 kts. Their direction of movement thus deviates by 45 degrees from that of the main storm cell.

Newton and Katz (1958) have found that on the average large convective rainstorms moved about 25 degrees to the right of and 7 kts slower than the mean wind in 850–500 mb layer. Fujita (1958) has found that the hook echoes moved in a direction 25 degrees to the right of the direction of movement of echoes located in the vicinity. Neumann (1965) has found a deviaton of 10 degrees towards right of the original path of a hailstorm when it got intensified. Fujita (1965), while analysing tornado echoes of 26 May 1963, found the deviation from ENE to ESE, *i.e.*, about 45 degrees towards right. He further discussed the rotational and non-rotational echoes, and the hooks that are associated with the former type. According to him whenever an echo becomes rotational, the direction changes abruptly towards right, this then intensifies and produces heavy rain and hail. The non-rotational echoes which maintain the normal course diverge when lying to the left of the patch of the rotational echoes and converge while lying to the right.

The crescent shaped echo and the new echo, as mentioned above, which diverge from the main storm cell by 45 degrees, are the non-rotational echoes, lying towards left of the path of the main storm cell. The main storm cell is the rotational echo, associated with hook, which, after having acquired rotational characteristics, changes its course to 110 degrees from an original direction of approximately 090 degrees. As soon as it changes direction, it gets intensified and gives indications like the decrease in its speed, the increase in curvature of the hook cyclonically (Figs. 2f and 2g), release of downdraft indicated by narrowing of the notch (Fig. 2f) and strong updraft indicated by a dry hole (Fig. 2h) during the period 1649 to 1656 IST.

During this period (1649 to 1656 hrs), the updraft perhaps becomes so much strong that it begins to offer retardation to the motion of the major echo. The speed as a result, reduces to 17 kts from 25 kts.

After 1656 IST the major cell regains the original speed of 25 kts and moves in the same direction of 110 degrees. When the downdraft releases during the period 1649 to 1656 IST downward transfer of horizontal momentum occurs which perhaps, minimises the retardation offered by the updraft during the above period.

Browning and Ludlam (1960) have observed that the turret has a high vertical velocity upon first appearance at the top of the echo mass, but its horizontal velocity is much less than the wind at that level. The turret takes up the velocity of the environmental winds, when it loses the vertical momentum. Also, when the most intense portion of the downdraft reaches the ground within the region of heaviest rain — Byers and Braham (1949) and discussed by Browning (1964) —, which is found beneath the left hand part of the storm, it diverges strongly in all directions and spreads predominantly beneath the updraft. The edge of the cold outflow is overrun by the warm surface air approaching the updraft and so new cell formation occurs. These new cells were seen forming and growing in size after 1651 IST, when first observed at 8 degrees azimuth and 22 n. miles range (Fig. 2f). It is quite likely that the energy of the updraft is distributed partly in generating the new cells and partly in maintaining the flow to the major storm cell. Under such circumstances the major cell would lose the vertical momentum, overcome the retardation offered by the updraft and start moving again with the speed of 25 kts which it was following before 1649 IST. From this discussion it becomes clear that the main storm cell having characteristics like hook or wall, a dry hole or vault, a forward overhang towards its left hand forward flank and movement towards right of its actual path, was nothing but a Browning super cell which caused the severe hailstorm over Kamptee.

6. Stationary echoes

Certain echoes in the northwest at about 15 n. miles were observed to have remained stationary throughout the period of study of the storm. These echoes were weak in intensity and disappeared on low gain of the receiver. It appears that the flow of the updraft air to these echoes was not strong enough to help these echoes gain sufficient height. Therefore, with their height so small, they probably could not be influenced much by the upper level winds to follow a preferred direction of movement, on the other hand due to the combined effect of upper and lower level winds they appeared to be stationary echoes.

7. Precipitation trajectories

The radar set was scanning from 1/2 degree to 5 degrees in the vertical. The extent of the echo under study, therefore, ranges from ground to about 7000 ft in the vertical. Thus the echo analysed here presents the pattern at low levels.

As discussed by Browning and Donaldson (1963), the forward overhanging echo ahead of the storm slopes downwards to the ground towards its left flank and shows protuberances or streamers curved cyclonically a short distance beneath it. The importance of these streamers is that their form and motion enables us to infer something about the airflow in their vicinity.

The streamers are visible (Figs. 2a to 2c) in the left hand forward flank of the major echo during the early stage of the echo. The streamers in Fig. 2b give some idea of the airflow in the vicinity of the storm. The possible airflow has been drawn in Fig. 3, which is a replica of Fig. 2b. It can be seen from these figures that the curvature of the streamers in the left hand forward flank of the echo is anticyclonic, while in the right hand and the rear portions they are curved cyclonically. The anticyclonic flow in the left hand forward flank may be due to the small precipitation particles falling from the base of the overhang, which after flowing towards the main flow under the forward overhang curves up into the zone of strong updraft (Browning-Ludlam model 1962) and thus are prevented from descending from the overhanging base. The cyclonic flow in the left, right and rear portions may be due to the strong updraft ascending cyclonically upward to the highest part of the echo. Fig. 3 shows this flow at 1 degree elevation approximately upto 3000 ft above the ground.

In Fig. 2e streamers in left and right hand portions of the main storm cell have curvatures opposite in sense to each other. The curvature in the left hand portion (facing 360 degree azimuth) are in cyclonic sense while in the right hand portion (facing 180 degree azimuth) they are in anticyclonic sense. The curvatures of precipitation particles in Fig. 2b are quite different in sense from those in Fig. 2e. Probably this change in Fig. 2e is due to the initiation of the downdraft, right from 1650 IST, whose indications were observed in Fig. 2f (by shrinking or narrowing of notch).

The winds over Nagpur, as drawn in the vertical time-section of the winds in Fig. 1 veered with increasing height (or backed with decreasing height) before 12 GMT of 26 February 1964, after which hour they backed with increasing height (veered with decreasing height) upto 7000 ft till 18 GMT. In Fig. 2e the streamers facing north may be due to the descent of smaller precipitation particles following the cyclonic trajectories in the winds backing with decreasing height and those facing south due to the descent of the precipitation particles describing anticyclonic trajectories in the environments in which wind veered with decreasing height (Browning 1964). The backing winds with increasing height after 12 GMT also show the descent of the cold air mass or possibly the downdraft. The streamer (Fig. 2e) at the place where the hook lies

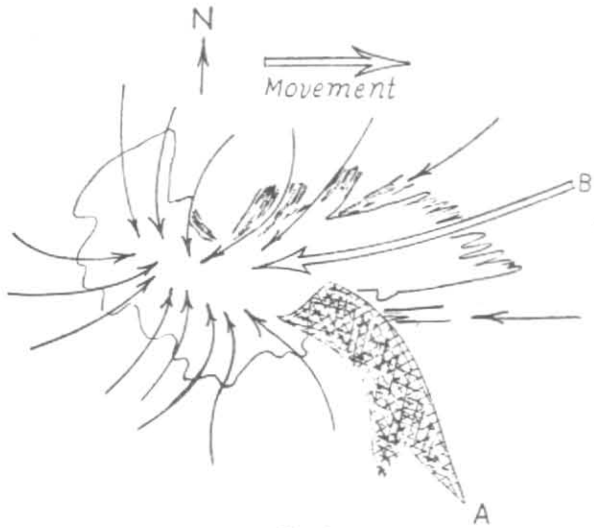
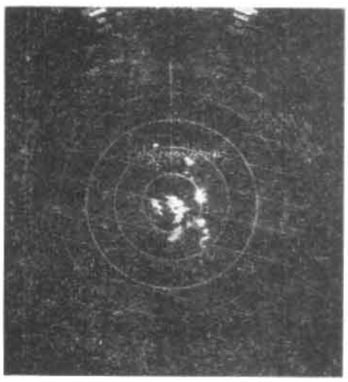


Fig. 3

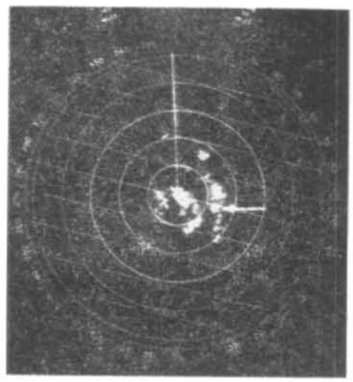
Possible position of

A — the updraft entering the storm from right hand forward quadrant

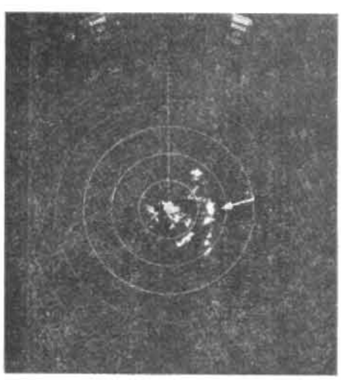
B — main flow below forward overhang which curves up into the zone of strong updraft



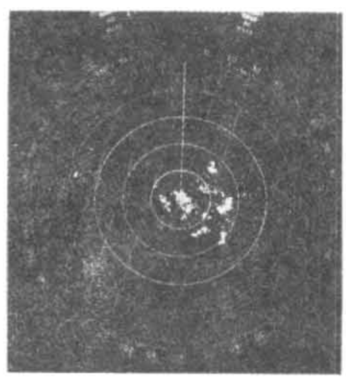
Full 1830 1°/100
(a)



Full 1845 1°/100
(b)



Full 1855 1°/100
(c)



Full 1905 1°/100
(d)

Figs. 4(a—d) — 27th February 1964

Figures below the photographs indicate (from left) : Gain in the receiver, time in IST, elevation of radar antenna in degrees and the total range in n. miles in Fig. 2d (shown by an arrow in Fig. 2e) in comparison to other streamers has lower intensity. The decrease in its intensity may be due to those hailstones having diameter larger than 3 cm, the wave length of the radar set, for which equivalent radar reflectivity factor Z_e decreases, when they acquire a wet coating (Atlas 1963).

8. Terminal velocity of precipitation particles

From the streamers (Fig. 2e), the terminal velocity of falling precipitation particles can be calculated by a method given by Marshall (1953). He has suggested that the velocity can be obtained more directly from the sequence of PPI photographs and it is not very necessary to have the pattern in the vertical section. This method has also been discussed by Battan (1959).

The terminal velocity of the particle is given by the relation

$$W = b = aZ^2/[2(x - x_0)]$$

where $(x - x_0)$ is the length of the streamer in their plane, $aZ = u$, the wind in the direction x at level Z where Z increases downward and is assumed to change linearly with height and $W = b$, the terminal velocity of the particles.

The average length of the streamers from Fig. 2e comes out to be 2000 metres. The level Z (*i.e.*, 4000 ft or 1200 metres) has been taken as the middle of the layer 2500 to 5600 ft, being scanned by radar at 5 degrees elevation and wind u at Z has been found out to be 5 metres per second.

Substituting these values in the formula we get $W = 1 \cdot 5$ metres per second. Marshall (1953) obtained 4 ft/sec as the rate of descent of precipitation particles.

The diameter of the precipitation particles can be calculated by an approximate formula $V = 200D^{\frac{1}{2}}$ given by Weickmann (1953), where V is the terminal velocity in centimetres per second and D, the diameter in millimetres. From this we get $D = (V/200)^2 = 0 \cdot 56$ mm. The terminal velocity of 500 μ drop is about 2 m/sec (Gunn and Kinzer 1949).

9. Observations on 27 February 1964

The only echo of the first group at 25 degrees azimuth and 30 n. miles range had been moving towards 110 degrees with a speed of 25 kts. In the second group of merging echoes, the echo at 080 deg had been moving towards 110 degrees with the speed of 25 kts. The second echo in same group (*i.e.*, at 120° /20 n. miles) also had the same speed but was moving towards 70 degrees and thus had a collision course of 40 deg directional convergence. They collided with each other at a place at 100 deg and 30 n. miles range at 1905 IST (Fig. 4d). The echoes in the third group also had movements towards 105 and 060 degrees and the speed of 25 kts each.

The echoes which are moving towards 105-110 degrees are rotational echoes and those moving towards 060-070 degrees non-rotational echoes (Fujita 1965). The non-rotational and rotational echoes of the second group have been shown by an arrow in Figs. 4b and 4c respectively.

The hailstorm, as reported by newspaper at Kamptee was probably caused by the rotational echo of the second combination. This was moving towards 110 degree at a speed of 25 kts. If we trace back its course along 110-290 degree axis(as also suggested by the super refraction streak running west-east in Fig. 4c), then it would have come over Kamptee at about 1755 IST (after taking into consideration its speed and extent). The tilted V shaped super refraction echoes noticed behind the non-rotational echo of first group and rotational echo of second group suggest that a single echo was present over Kamptee. After causing hailstorm there, it had split up into two echoes whose track diverged by about 45 degrees from each other. The non-rotational part seems to have merged with the rotational parts of first combination by the time the photography was attempted.

From the study it appears that on this day also a Browning super cell had remained over Kamptee and caused hailstorm there. The intensity of the storms can be compared with that of the storm on 26 February 1964. A pressure rise of 0·3 mb between 1755 and 1800 IST, a temperature fall of 5°C between 1800 and 1822 IST was recorded over the station with surface wind shift from SSE to NE and a gust from NE of 43 km/hr at 1817 hours.

10. Conclusions

(1) The hailstorms (over Kamptee) near Nagpur on 26 and 27 February 1964 occurred due to the presence of a rotational cell.

(2) The shrinking notch associated with prominent hooked echo (*i.e.*, filling up of an echo free area) may give a good indication of initiation of downdraft and consequently the commencement of hailstorm, while the widened notch, the end of the hailstorm.

(3) The terminal velocity of the precipitation particles associated with the prominent hook echo, observed on 26 February 1964 was found to be 1·5 metres per second.

(4) The rotational echoes observed on 26 and 27 February 1964 generally had been moving towards 110 degrees azimuth with a speed of 25 knots and non-rotational echoes towards about

065 degrees with almost the same speed. They were in a collision course of 45 degrees directional convergence in general.

(5) The major echo associated with prominent hook on 26 February 1964 when changed its direction of movement from 090 degrees to 110 degrees, its speed decreased from 25 knots to 17 knots.

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