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Radar observations of thunderstorms at Poona

A. MANI

Meteorological Office, Poona

and

S. P. VENKITESHWARAN

National Aeronautical Laboratory, Bangalore

1. Introduction

Radar observations of rain have been made at Poona since 1953, when a small air-borne model search radar type SCR-717-C operating on 9·1 cm was set up at the Poona Observatory. The radar has a peak power of 40 KW and a pulse length of 1·125 μ s. The antenna is a dipole-fed paraboloid mounted for rotation about a horizontal axis so that the radar beam scans the sky from horizon to horizon through the zenith giving a vertical cross-section through the atmosphere above the point of observation. The Vertical Height Indicator (VHI) display so obtained is better than the conventional Range Height Indicator (RHI), since the heights and distances are maintained in true proportion and an easier interpretation of the rain echoes immediately above the point of observation is possible. This type of display was first used by Bowen (1951) and his collaborators in Australia and has been extensively used since then, by other workers, especially Vonnegut, Moore *et al.* (1959) in their studies of thunderstorms in New Mexico.

Thunderstorms occur at Poona generally during the premonsoon months from March to June and again from September to November during the post-monsoon period. Radar observations of both pre- and post-monsoon thunderstorms have been made more or less systematically since 1953 and the present paper summarises the results of the observations of radar echoes from thunderstorms over Poona from 1953-1959.

2. Observations of two typical thunderstorms

Radar echoes from two typical thunderstorms are reproduced in Figs. 1(a) and 1(b). The first shows radar VHI photographs of a post-monsoon thunderstorm on 7 October 1953 and the second of a premonsoon thunderstorm associated with hail on 16 March 1954. In the first, the thunderstorm approached the station from the east and dissipated over the station. 63 cents of rain fell in the interval 1310 to 1345 IST and light drizzle from 1430 to 1810 IST, adding only 9 cents in nearly four hours to the total rainfall. The echo stratified at 1450 IST, a bright band forming at a height of 4·6 km by 1455 hours. It descended to 3·8 km by 1511 IST and remained there for three hours till it disappeared at 1810 IST. The freezing level that day was at a height of about 4·4 km.

On 16 March 1954, the thunderstorm moved in from the north and was associated with hail from 1800 IST. The top of the radar echo when hail started to fall was at 10·7 km above sea level, where the temperature was about —40°C. It was nearly 9 km wide at the base in the north to south direction. The top of the echo later descended till by 1827 IST it was only 5·5 km a.s.l. The rate of descent was about 14 km hr^{-1}. A new cell formed at 1827 IST to the south and grew to 8·6 km by 1847 IST. Both cells dissipated rapidly, giving on indication of stratification of the cloud or the formation of bright bands.

It is seen that, while the growth of a thunderstorm cell is rapid and similar in all cases, dissipation occurs in two ways, either slowly as in the first case or rapidly as in the second. Rapid dissipation is presumably associated with a decrease in the supply of warm moist

TABLE 1

Maximum height reached by supercooled water in thunderstorms over Poona

	Height reached by supercooled water (metres a.s.l.)	Height of 0°C isotherm (metres a.s. l.)	Mean height of supercooled water above 0°C (metres a.s.l)	Free air temperature at mean maximum height of supercooled water (°A)
Mar—Apr	9500	4800	4700	241
May—Jun	13100	4900	8200	217
Sep—Oct	7500	5200	2300	262

air from below and a rapid entraining of the colder surrounding air. In the other, generally associated with bright bands and light drizzle which persist for a long time, the entrainment is gradual, presumably due to the difference in temperatures between the cloud and the environment being small.

3. Bright bands in radar echoes

The bright bands, when they do occur in the dissipating stages of thunderstorms, generally appear not at the freezing level, but well below it and sometimes persist for as long as three hours. The bands are rather diffuse, though the general thickness does not vary erratically. They generally form at a higher level and gradually descend to a slightly lower level, in some cases by 300—500 m below and in others less.

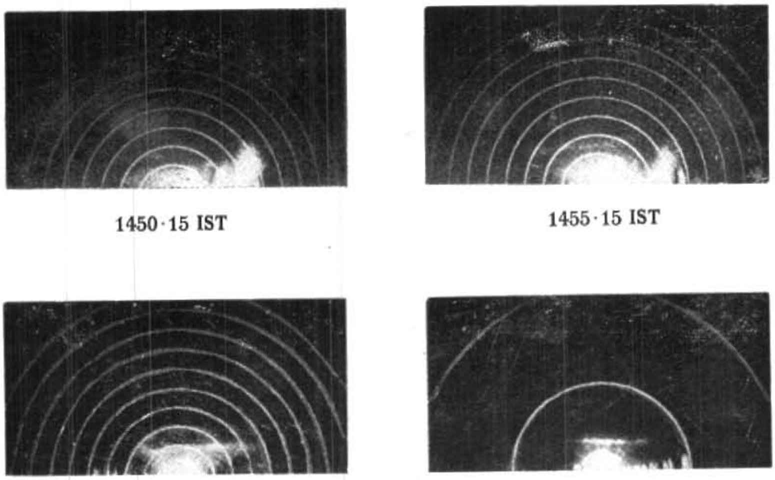
The bright bands in the post-monsoon thunderstorm seasons appear to be slightly less thick and nearer the freezing level than in the pre-monsoon season. However both their thickness and their distance below the 0°C isotherm are about thrice the value obtained in extra-tropical regions. Assuming a snow flake aggregate of 5 mm radius, falling with a speed of one metre per second, Austin and Bemis (1950) calculated the distance between the freezing level and the level at which melting is complete, to be about 1200 ft. The average value of the distance actually measured by them at Cambridge Mass., was 830 ft while Hooper and Kippax (1947) found it to be only 310 ft. The average distance of the bright band at Poona from the freezing level is about 1400 m and its average thickness about 700 m.

The distance of the bright band below the freezing level indicates the average distance the snow flakes fall before melting and should be expected to be greater for heavier precipitation which contains larger drops and for smaller lapse rates. The appreciably larger values observed at Poona are probably attributable to the larger size of snow flakes resulting from the greater extent of convection above the freezing level. Lapse rates have been obtained from radiosonde ascents on the days on which the thunderstorms occurred but since thunderstorms are short-lived and conditions inside the cell may be very different from those outside, it has not been possible to draw any inferences on the influence of lapse rate on the distance of the bright band below 0°C.

4. Radar observations of supercooled water in thunderstorms at Poona

In Table 1 are given the maximum heights reached by supercooled water in the pre- and post-monsoon seasons over Poona. It will be seen that the supercooled water reaches greater heights in May and June than in the other months. Since the heights to which the supercooled water if lifted in a thunderstorm depends on the thermal instability and the moisture supply available, it is only natural to find that thunderstorms reach the maximum heights in May and June. The last three columns give the mean height of the freezing level, the mean height of the top of the supercooled water above 0°C and the free air temperature, corresponding to the mean maximum height up to which supercooled water was visible in the radar echoes. These indicate the convective vigour of

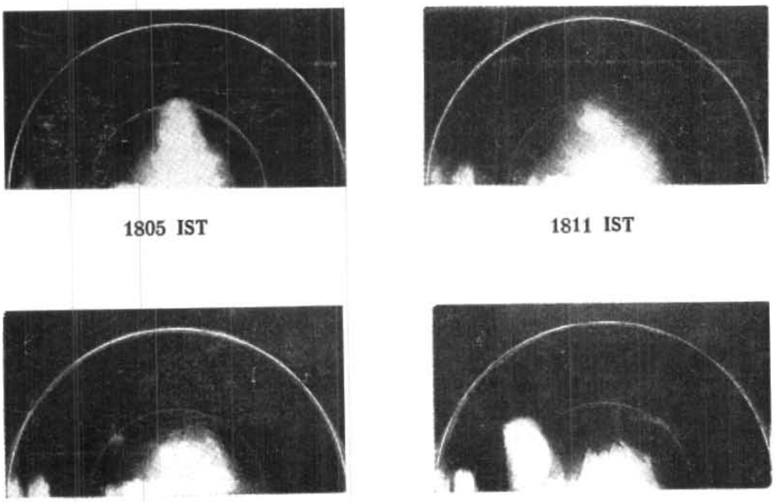
W E W E



1450·15 IST 1455·15 IST

1517·15 IST 1750 IST

Fig. 1(a). Thunderstorm on 7 October 1953

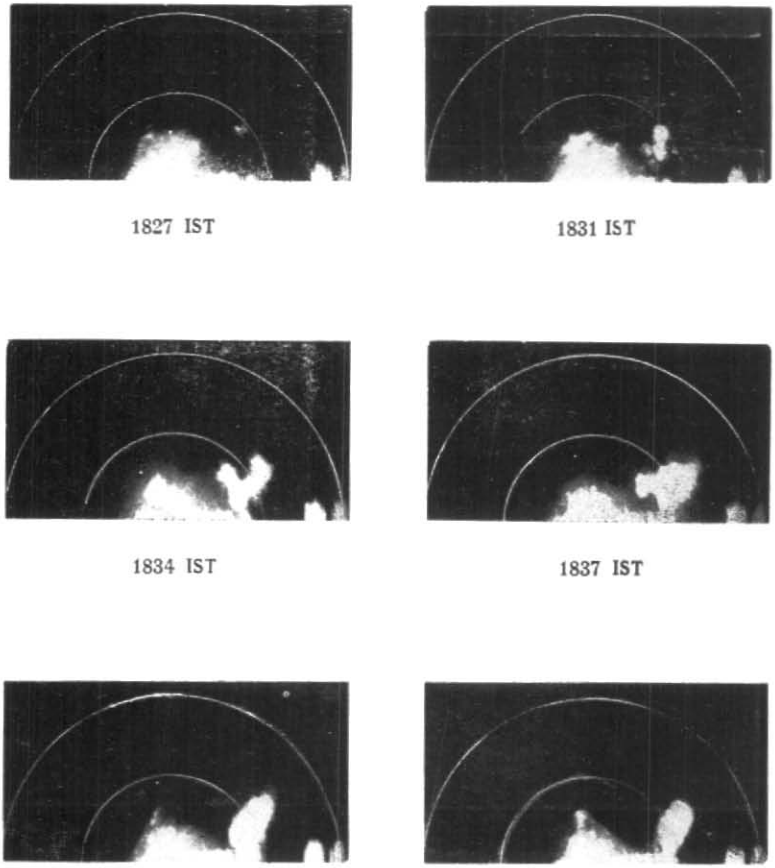


1805 IST 1811 IST

1827·30 IST 1841 30 IST

Fig. 1(b). Thunderstorm on 16 March 1954

Range markers are for 5 nautical miles



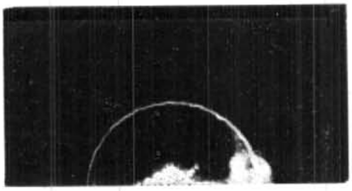
1827 IST   1831 IST

1834 IST   1837 IST

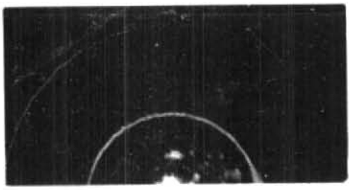
1844 IST   1847 IST

Fig. 2. Thunderstorm on 16 March 1954

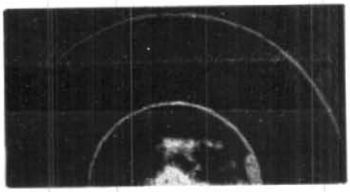
Range markers are for 5 nautical miles



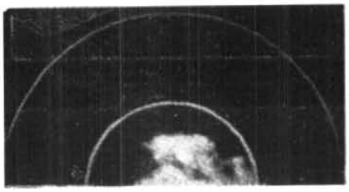
1817 IST



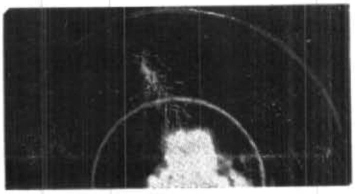
1825 IST



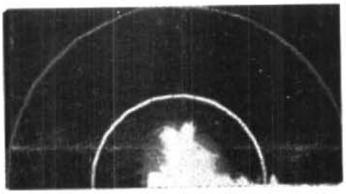
1827 IST



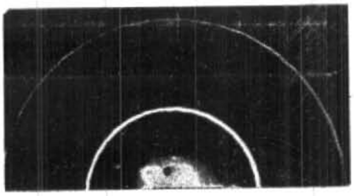
1829 IST



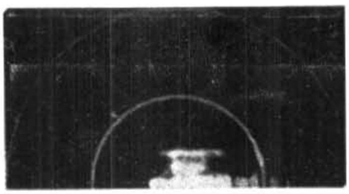
1833 IST



1839 IST



1849 IST



1918 IST

Fig. 3. Thunderstorm on 21 April 1954

Range markers are for 5 nautical miles

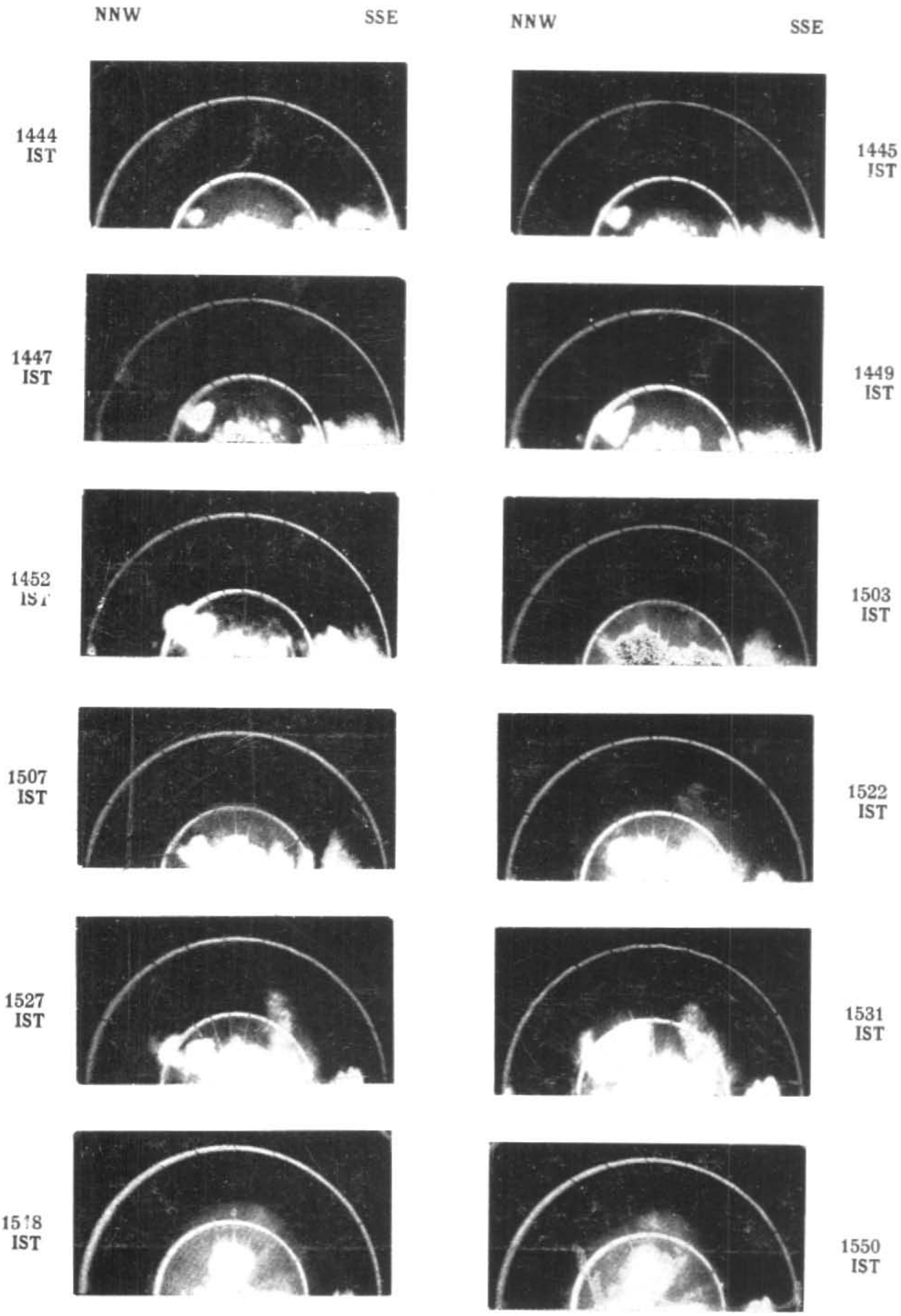


Fig. 4. Thunderstorm on 26 May 1958

Range markers are for 5 nautical miles

each season and the level above 0°C to which water is lifted. It must be remembered that the air temperature inside a developing thunderstorm will be higher than that of the surrounding air and that the heights given are of the radar echoes and not of the cloud tops, which will naturally be higher.

5. The growth and decay of radar echoes in thunderstorms, with special reference to the initial release of precipitation in clouds

In Figs. 2, 3 and 4 (pp. 64-66) are reproduced three series of photographs illustrating the growth and decay of thunderstorms as seen on the VHI. These give a complete history of the echo from the moment of its first appearance on the scope.

5·1. *Thunderstorm on 16 March 1954*— On this day, the first radar echo made its appearance at 5·5 km, and was relatively shallow in extent, being less than 1-km thick. It grew rapidly both upwards and downwards, the rate of growth of the radar echo being of the order of 3 and 10 m/sec up and down respectively. It developed two turrets reaching 7·6 km, which later merged and descended to lower levels.

5·2. *Thunderstorm on 21 April 1954*— On this day, a number of cumulus cells developed over and around the station giving rise to heavy rain. The first radar echo of the sequence appeared at 1817 IST at a height of 6 km. It did not grow appreciably upwards, the top of the echo remaining at 6·3 km even at the time of its maximum growth. The first echo was sharp and shallow, being only 0·5-km thick. By 1825 IST, it had brightened and had a thickness of 1 km. A number of similar cells appeared to the southeast at the same level and merged into one relatively shallow mass at 1827 IST. These intensified and rapidly grew downwards reaching the ground at 1833 IST and dissipated slowly afterwards. A bright band made its appearance at 1835 IST at a height of 4 km. By 1845 IST only echoes below the band remained. By 1900 IST even the band had disappeared, but reappeared at the same level at 1905 IST, persisted till 2011 IST, when it finally disappeared from the radar scope.

5·3. *Thunderstorm on 26 May 1958* — On this day, the radar echo associated with rain, lightning and thunder over the station made its first appearance at 1444 IST at a height of about 4 km a.s.l., 7 km to the NNW of the station. The echo was about 2-km deep, with its top at about 3°C; it grew rapidly in all directions, the top reached a height of about 7 km and the base approached the ground by 1452 IST. The rate of ascent of the echo was about 5 m/sec and of descent 12 m/sec. After attaining its maximum height, the top of the echo descended at about 8 m/sec.

By 1507 IST, the pattern of echoes had changed appreciably, there appearing as many as six individual cells in a row, each being about 3 km wide and 6 km in vertical extent separated by about 1 km. From 1501 to 1510 IST, 11 flashes of lightning were recorded on a local lightning flash counter and 25 mm of rain fell 6 km to the north of the observatory.

The different cells merged into one conglomerate mass by 1514 IST; by 1522 echoes were visible even at heights of 10-16 km. The echoes at these high levels result from a combination of two factors, *viz.*, the upward transport of detectable hydrometeors in the updraught and the growth of particles at progressively higher levels towards detectable size. Both these factors were apparently present in this case.

A new faint echo made its appearance towards the NNW at 1522 IST at about 5-6 km, developed rapidly and merged with the main body of the echo on the left, till by 1530 IST there were two main echo masses, extending horizontally about 16 m with the tops at about 10-12 km a.s.l. Lightning flashes were recorded from 1528-1540 IST and rain fell to the north of Poona.

Only one echo remained by 1548 IST. Its top had grown from about 5-6 km a.s.l. at 1541 IST to 8 km by 1550 IST, with a feeble echo above it extending to 12 km a.s.l. The development of this cell was associated with a third spell of lightning and thunder and heavy rain from 1545-1630 IST.

TABLE 2

Details of initial radar echoes from convective clouds

Date	Time (IST)	Ht. of 0°C level (km a.s.l.)	Ht. of base of initial echo (km a.s.l.)	Temp. of base of initial echo (°C)	Ht. of top of initial echo (km a.s.l.)	Temp. of top of initial echo (°C)	Max. ht. of echo (km a.s.l.)	Temp. of max. hr. of echo (°C)	Rate of growth of echo (m/sec) Up	Down
6 Oct 1953	1522	5·2	4·6	1·5	6·8	—11·4	9·6	—32·5	..	10
	1525	5·2	7·6	—16·5	9·6	—32·5			..	..
	1547	5·2	6·1	—7·4	7·1	—14·0	7·6	—16·5	..	..
8 Oct 1953	1413	4·1	4·1	0	4·6	—3·0	5·6	—8·0	5	10
	1414	4·1	3·6	2·7	4·6	—3·0	5·6	—8·0	3	7
16 Mar 1954	1827	4·3	5·1	—7·0	6·1	—14·6	7·6	—18·0	3	10
	1841	4·3	4·6	—2·0	5·1	—7·0	5·6	—11·6	2	5
21 Apr 1954	1817	4·9	5·8	—4·9	6·3	—8·0	6·3	—8·0	..	9
22 Apr 1954	1509	5·3	4·8	4·0	5·9	—3·5	5·9	—3·5	..	14
	1525	5·3	4·3	8·2	4·9	3·3	5·9	—3·5	..	..
	1743	5·3	3·8	12·0	5·9	—3·5	6·5	2·5	..	..
	1808	5·3	2 2	20·6	4·9	3·3	4·9	3·3	..	..
5 Jun 1954	1453	5·9	2·8	15·0	6·2	—1·8	7·4	—7·5	..	4
	1453	5·9	1·7	22·4	7·4	—7·5	7·4	—7·5	..	..
	1530	5·9	5·1	5·0	7·4	—7·5	9·7	—21·0	8	4
19 Oct 1954	1452	5·2	3·6	6·5	6·1	—5·2	6·1	—5·2	..	..
	1743	5·2	3·3	8·2	5·6	—3·5	5·6	—3·5	..	..
16 Mar 1955	1745	4·9	3·8	7·5	6·0	—5·0	6·0	—5·0	..	..
22 Mar 1955	1611	4·6	2·8	11·0	6·3	—7·0	9·7	—21·0	18	13
	1611	4·6	1·7	15·2	6·1	—1·9	6·3	—7·0	9	9
	1615	4·6	2·8	11·0	3·7	5·2	6·8	—15·6	5	6
	1742	4·6	3·3	8·5	4·4	0·5	4·9	—3·5	2	5
	1748	4·6	2·7	12·0	5·1	—1·9	5·1	—4·4	..	3
23 Mar 1955	1546	4·1	3·6	4·5	9·2	—28·6	9·2	—28·6	7	7
	1646	4·1	5·1	—4·4	9·7	—31·0	11·9	—42·0	4	4
23 Apr 1955	1627	4·7	5·1	0	8·5	—20·0	9·7	—26·0	5	7
27 Sep 1955	1654	5·0	4·3	6·6	5·9	—1·5	7·6	—13·3	7	..
17 Apr 1956	1600	4·5	5·5	—2·5	6·8	—16·0			3	..
18 Apr 1957	1549	4·7	3·4	10·5	8·7	—23·0	9·7	—34·0	8	..
	1607	4·7	6·5	—10·2	8·1	—19·8	11·8	—45·0	11	..
	1615	4·7	3·4	10·5	6·5	—10·2	9·7	—34·0	21	..
	1621	4·7	5·5	—4·2	10·7	—30·2	10·7	—40·0	..	..
	1631	4·7	4·5	2 2	8·1	—19·8	9·7	—34·0	13	..
23 May 1957	1631	5·9	5·5	2·0	9·7	—23·0	10·7	—37·0	6	..
	1644	5·9	6·0	—1·5	8·1	—13·5	12·8	—44·0	22	..
	1659	5·9	6·0	—1·5	9·7	—23·0	10·7	—37·0	14	..
26 May 1958	1444	5·4	3·3	10·0	4·8	2·0	7·3	—13·0	6	12
	1447	5·4	2·4	16·0	3·9	7·0	4·8	2·0	5	5
	1522	5·4	6·6	—8·0	8·5	—20·0	8·5	—20·0	..	10

It is seen that—

(1) The first echo always makes its appearance suddenly, suggesting a sudden release of considerable quantities of large water drops.

(2) Numerous small echoes appear around an active thunderstorm cell. A cluster of cells come into existence almost simultaneously with the initial or parental cell, as indicated by the radar echoes.

(3) The maximum horizontal and vertical extents of a convective echo are generally of the same order of magnitude.

(4) The rates of ascent and descent of the echo are also generally of the same order.

(5) The duration of the individual radar cell is small, of the order of 20 minutes—except when it stratifies and forms the band when it may persist for hours.

(6) Hail is most likely to occur when the thunderstorm echo is tallest and most intense.

(7) The frequency of the lightning discharges and intensity of rain are associated with the growth and development of radar echoes. The occurrence of heavy rain and lightning is associated with a decrease in the growth of the radar echo, suggesting a decrease in the intensity of updraughts.

6. Results of observations

Table 2 summarises the characteristics of initial echoes from a number of convective clouds over Poona. The heights and temperatures of both the base and the top of the initial echo, the heights of the 0°C isotherm obtained from radiosonde ascents, the rates of growth of the echo with the maximum heights reached by the echoes are also given.

In 25 of the 39 cases studied, the base of the initial echo was below the 0°C isotherm and on the remaining 14 occasions, at or above it. On 6 occasions, both the base and top of the initial radar echo were at temperatures above 0°C. Only in 7 cases was the bright band observed in the dissipating stages.

The vertical depths of the first detectable echoes ranged from 500—3500 m, with a mean vertical thickness of about 2 km. Byers and Braham (1949) found the horizontal dimensions of the initial echoes to be as small as 500 m. Both these authors and Kuettner (1950) report the existence of sub-cells in a thunderstorm cell about one-tenth of the size of the cell itself, *viz.*, 100—1000 m.

The rates of ascent of the radar echo varied from 2-22 m/sec and of descent from 4-14 m/sec. The rates of ascent and descent were generally of the same order. Byers and Braham (1949) in the Thunderstorm Project and Workman and Reynolds (1949) in their studies in New Mexico, report similar rates of ascent, of the order of 2-8 m/sec and of descent, about 4 m/sec after the top of the echo had reached the —30°C level.

The mean maximum height reached by the radar echoes is about 8 km, the maximum height recorded being 13 km. The maximum height of radar echoes recorded of thunderstorms over England is 12 km (Jones 1950), in the U.S.A. 17 km (Byers and Hall 1955) and in Canada 11·5 km (Douglas and Hitschfeld 1958).

The minimum temperatures reached by the echoes vary from +3° to —45°C, with a mean value of about —18°C. Byers and Braham (1949) found it to be about —20°C and Workman and Reynolds (1949) about —30°C.

7. Discussion

A radar cloud usually indicates the presence of elements larger than 10 μg (about 270μ diameter) in certain concentration, so that its first appearance can be taken as a sign that the release of precipitation has begun (Browne *et al.* 1954). From measurements of the height at which the first radar echo from a thunder cloud appears, several workers have tried to analyse the processes involved in the initial release of precipitation.

Workman and Reynolds (1949) and Byers and Braham (1949) found the initial radar echo to be always near the —10°C isotherm. Battan (1953) from an analysis of the ground radar records during the Thunderstorm Project in Ohio concluded that the initial echo frequently appears below the freezing level. Although the tops of the visual clouds invariably reached the —20°C level and often higher, he found that in 60 per cent of the 123 cases studied, the whole of the first echo was located at temperatures above 0°C. The mean temperature of the initial echo was 0.4°C and its base 10°C. There was a definite tendency for the colder echoes to be associated with lower freezing levels so that the cloud thickness appeared to be a more important parameter than the temperature difference in determining the onset of precipitation.

Wexler (1953) criticised Battan's conclusion that raindrops were formed by coalescence without an ice phase, since under certain conditions the echoes may be too weak to be detected. On the other hand, as Browne, Palmer and Wormell (1954) point out, initial echoes near —10°C does not necessarily imply the presence of ice. In a cloud of liquid water content 1 gm/m^3 and updraughts of 3 m/sec, droplets growing by coalescence would give an appreciable radar echo only after they had been carried 3 km above the cloud base, which might well be near the —10°C isotherm.

Australian workers Styles and Campbell (1953) and Day (1953) conclude that rain over Australia form wholly by coalescence. Feteris and Mason (1956) in England also give radar evidence of production of showers by coalescence.

Koteswaram and De (1959) studying post-monsoon clouds over Calcutta reported the first radar echoes to be below 0°C in most cases. In 7 complete life cycles studied, the initial echo was below the freezing level in five, in one near it and one well above it.

Radar observations are not conclusive, unless simultaneous visual and aircraft observations are also taken. It is generally accepted, however, that in tropical regions, precipitation is almost always initiated in the parts of the clouds warmer than freezing (Byers and Hall 1955) and in extra-tropical regions the condensation-coalescence process plays an important role in initiating precipitation in growing cumuli in warm, humid air (Battan 1959).

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