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Vertical growth and decay of convective cloud cells and associated precipitation rates at different levels

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ABSTRACT. Study, using radar, has been made of history of growth and decay, in the vertical, of convective rain cells around Delhi, and of associated variations in liquid water concentration or rate of precipitation release at different heights as judged from echo intensity measurements. Data relating to three such situations, typifying respectively rain from (a) warm, (b) moderately cold and (c) very tall and highly supercooled (as in a severe thunderstorm) convective cloud are presented in the paper. One common feature noticed, namely, that the rise or fall in precipitation rate at each level, follows closely a similar trend in variation of height of radar cloud top, needs to be given detailed consideration on the basis of suitable model of distribution of vertical currents within such a cell. Some tentative considerations have been given to this aspect of the problem.

1. Introduction

Based on use of a centimetric radar, much valuable data have been collected in recent years (Langille and Gunn 1948, Byers and Braham 1949, Workman and Reynolds 1949 and Jones 1950) on the genesis and progressive development of thunderstorms and some of their important associated characteristics, such as the first level of appearance of radar echo, its subsequent extension in the vertical as well as horizontal, nature and intensity of vertical currents, echo intensity gradients marking relative severity of turbulence within the cloud etc. Available data are, however, rather scanty regarding one important aspect of study in this field, namely, how precipitation rates at various heights are related to the rates of rise or fall of radar echo top at different phases of development or decay of the storm. Some limited studies made in this regard recently by the Rain and Cloud Physics Research Centre of the National Physical Laboratory are presented in the paper.

2. Equipment used and observations made

The radar employed is a 3·2 cm equipment described by Roy (1959). Use has been made of all the three indicators provided, namely, the PPI, RHI and A-Scope, for making each complete set of observation in connection with the study. The PPI is utilised for keeping track of the highest level of radar echo at any given instant. For this, the tilt of the antenna is varied slowly and in regular steps, and by noting the azimuth at which the echo just disappears while scanning at the highest elevation, the antenna is fixed immediately at that position. The RHI is then used for determining the depth of echo at the corresponding azimuth, and also for directing the beam towards appropriate levels at which echo intensity measurements are desired to be made. Lastly, echo intensity estimate is made on basis of indications on the A-Scope, calibrated previously with reference to the position of sensitivity control of radar receiver at which the amplitude of echo return reaches a certain predetermined value. The details of the calibration method used are given in a paper, under publication.

Data presented are based on observations made at Delhi during the southwest monsoon season, 1959, relating to three rain cells of columnar type of different vertical extent and showing different scales of convective activity during their life cycle. The first cell observed on 30 July 1959 typifies warm convective rain, though lasting for an unusually long time, while the two other cases studied on 1 and 3 September 1959 represent respectively a moderately cold convective cloud, and a highly supercooled very tall *Cb* cell as in a severe thunderstorm. In each of

TABLE 1

Time (IST)	Range of echo (km)	Vertical extent of echo (km)	Rate of change of echo top (m/s)
(a) 30 July 1959 (Warm convective rain)			
1450	20	0—3·7	
1455	19	0—3·3	—1·3
1506	17	0—3·3	..
1512	17	0—3·3	..
1517	17	0—3·3	..
1532	17	0—4·8	+1·7
1536	18	0—4·8	..
1541	17	0—4·8	..
1545	21	0—4·2	—2·5
1549	21	0—3·8	—1·7
1552	21	0—3·8	..
1556	22	0—3·6	—0·8
1558	23	0—3·3	—2·5
1600	23	0·5—3·0	—2·5
1603	23	1·0—2·6	—2·2
(b) 1 September 1959 (Moderately cold convective cloud)			
1101	70	0—4·6	..
1108	70	0—5·8	+3
1115	72	0—6·3	+1
1134	75	0—5·0	—1
1137	78	0—5·7	+4
1140	78	0—6·0	+1·5
1144	78	0—5·3	+3
1147	78	0—5·0	—1·5
1152	78	0—5·4	+1·3
1200	78	0—5·7	+0·6
1202	78	0—6·1	+3·3
1205	78	0—6·6	+2·8
1209	78	0—7·5	+4·0
1215	78	0—6·6	—2·5
1220	80	0—6·2	—1·3
(b) 1 September 1959 (Moderately cold convective coud)—*contd*			
1227	80	0—5·4	—2·0
1239	80	0—6·7	+5·4
1247	80	0—7·5	+1·7
1255	80	0—6·6	—1·9
1258	80	0—5·6	—5·6
1305	80	0—4·9	—1·7
1308	80	0—4·0	—5·0
1310	80	0·2—3·2	—6·7
1312	80	1—2·8	—3·3
(c) 3 September 1959 (Very tall and highly supercooled convective cloud)			
1113	55	0— 6·4	..
1118	55	0— 8·5	+ 7·0
1121	55	0—10·2	+ 9·4
1129	52	0— 8·5	— 3·5
1140	50	0— 8·0	— 0·8
1145	48	0— 8·5	+ 1·7
1151	48	0—11·3	+ 7·8
1155	48	0—11·8	+ 2·1
1157	48	0—13·0	+10·0
1200	48	0—15·2	+12·2
1206	48	0—18·0	+ 8·0
1215	45	0—17·9	— 0·2
1219	43	0—16·4	— 6·0
1222	43	0—15·2	— 7·0
1231	40	0—14·3	— 1·7
1236	40	0—13·7	— 2·0
1240	38	0—12·5	— 5·0
1249	35	0—10·9	— 3·0
1259	33	0— 6·4	— 9·0
1312	33	0— 5·4	— 1·3
1317	32	0— 4·7	— 2·3

the three instances the cell examined was well separated from others in the neighbourhood, permitting a categorical study being made of its growth and decay and associated precipitation characteristics at various levels. No melting band was detectable in either of the two cold convective rain cells studied.

3. Discussion of data collected

Table 1 [(a) to (c)] presents data giving rates of rise or fall of radar echo top in the three cases under study, while Figs. 1(a) to 1(c) show progressive variations with time in echo intensity at various heights. The height-time pattern of echo top is also represented graphically by the top most curve in each figure. Besides the three instances discussed in detail in the paper, certain limited observations had been made during the season in a number of other convective cells of a similar type. Using all such observations, Table 2 gives the highest level reached by echo, steepest rate of rise or fall of echo top, and maximum precipitation rate observed near ground in each instance. For estimating rainfall rates on the basis of echo intensity determinations, use has been made of an empirical relation, connecting radar reflectivity Z and rain intensity R found earlier for Delhi monsoon rains based on measurements of rain drop sizes (Ramana Murty and Gupta 1959).

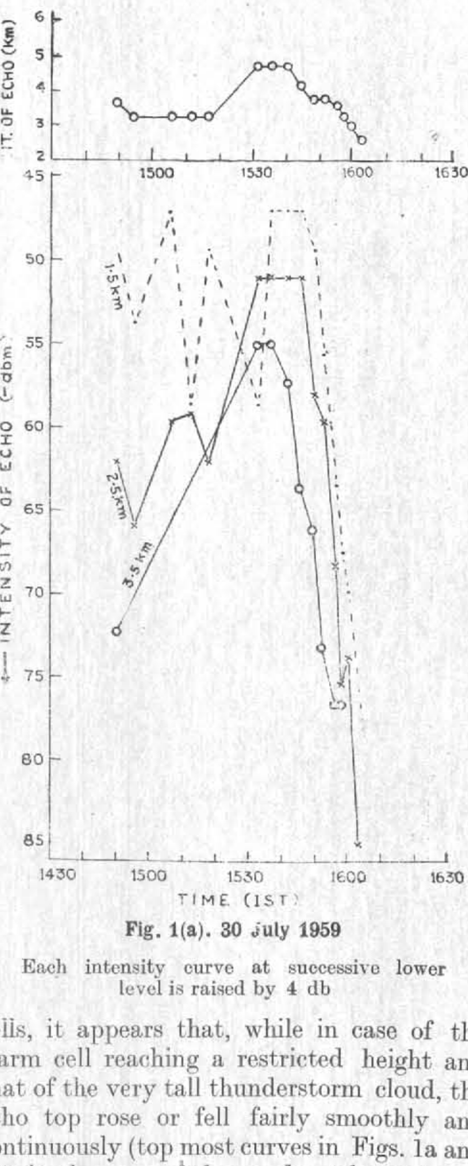

Fig. 1(a). 30 July 1959

Each intensity curve at successive lower level is raised by 4 db

(*i*) *Height changes of echo top*—From observations made in the warm rain cell on 30 July 1959 it is seen [(a) of Table 1] that the maximum rate of descent of echo top in this case was 2·5 m/s. Available observations during the season in three other similar rain cells have shown the maximum rate of rise of echo top in such a cell to range from 1·0 to 2·6 m/s. Comparing these with the rates observed in the two cold rain cells, it is seen [(b) and (c) of Table 1] that the highest rates of fall and rise of radar echo top in the moderately cold convective cloud on 1 September 1959 are 6·7 and 5·4 m/s, and those in the full-fledged thunderstorm cell of 3 September 1959 are 9·0 and 12·2 m/s respectively. The rates observed are of the same order of magnitude as found by other investigators, for example, —12 ft/sec and +18 ft/sec observed by Byers and Braham (1949), and —13 ft/sec and +13 ft/sec by Workman and Reynolds (1949). The values observed in the three instances, that a convective cell growing vigorously to a great height is liable also to suffer a similar rapid collapse. Again, from an examination generally of the phases of growth and decay of the three cells, it appears that, while in case of the warm cell reaching a restricted height and that of the very tall thunderstorm cloud, the echo top rose or fell fairly smoothly and continuously (top most curves in Figs. 1a and 1c), in the case of the moderately cold convective cloud of 1 September 1959 there was a distinct tendency of a series of steps of rising echo top being separated by intervals of marked subsidence, at times by several thousand feet (topmost curve in Fig. 1b). The distinguishing features observed in these instances can not be taken to be really typical of growth processes in convective cells of the three kinds mentioned unless

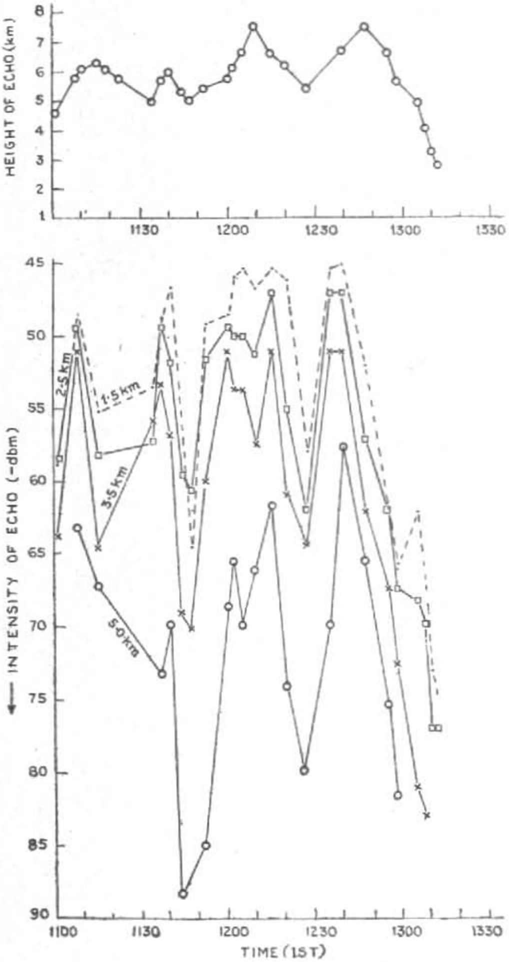

Fig 1(b). 1 September 1959

Each intensity curve at successive lower level is raised by 4 db

these are confirmed by more observations in other cells.

In any attempt to estimate vertical currents in a convective cloud based on radar measurements, we have to note that, while progressive changes in the height of echo top gives us a general idea of nature and intensity of vertical currents at the highest level of precipitation detection, factors like continuous growth to detectable size of precipitation elements at any given heights, and fall velocities of growing droplets, are liable to affect our judgments in this regard. Also observations such as these do not give us a dependable clue to the nature of vertical currents within the body of the rain cell.

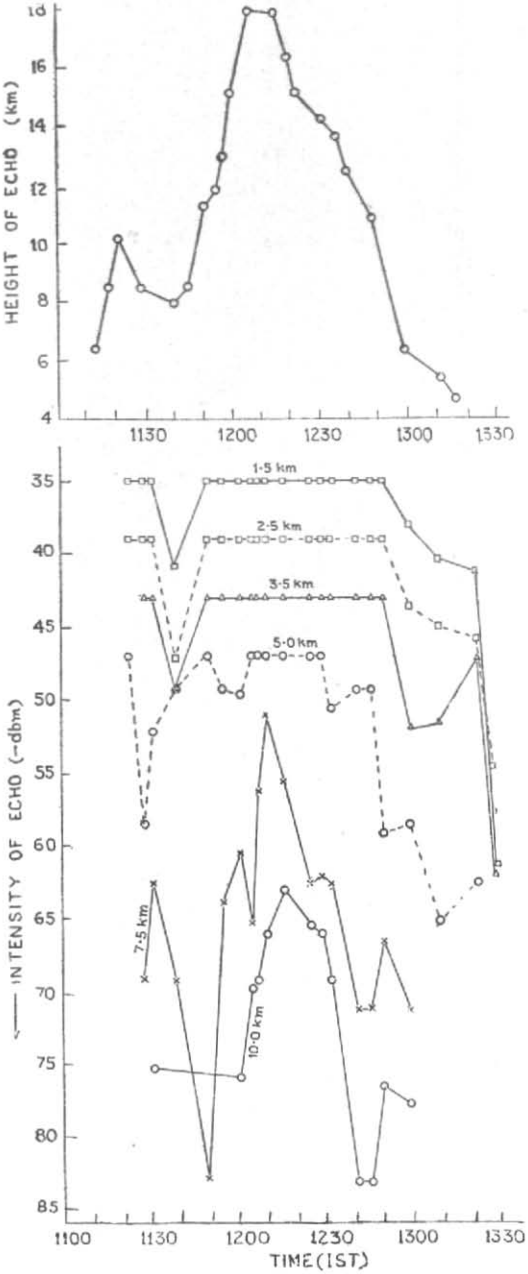

Fig. 1(c). 3 September 1959

Each intensity curve at sucessive lower level is raised by 4 db

TABLE 2

Date	Range of echo (km)	Max. ht. of echo (km)	Max. rate of rise (m/s)	Max. rate of fall (m/s)	Max. rain intensity observed (mm/hr)
30-7-59	18	4·8	+ 1·7	—2·5	>2
1-9-59	80	7·5	+ 5·4	—6·7	>14
3-9-59	48	18·5	+12·2	—9·0	>>7·5
2-7-59	72	4·2	+ 1·0	—1·1	10
3-7-59	42	7·5	..	—2·2	>5·3
24-7-59	90	10·0	+ 5	..	>16·7
24-7-59	98	8·5	+ 3	—2·0	7·0
27-7-59	30	14·0	+ 5	..	7·5
28-7-59	32	6·0	+ 2·7	—2·0	7·5
7-8-59	65	7·0	+ 7·0	—7·5	>>10·0
11-8-59	42	4·4	+ 1·1	—1·7	5·3
17-8-59	25	6·1	+ 5·0	—5·0	>>4·5
22-8-59	85	7·5	+ 7·5	—4·2	>16·7
21-12-59	20	4·0	+ 2·6	—3·3	>>2·0
18-4-59	35	6·5	+ 1·1	..	1·0

(*ii*) *Echo intensities in the vertical and their variations with time*—From the curves as in Figs. 1(a) to 1(c) it appears that there is a good parallelism in the general trend of variations with time in echo intensity at each level in all the three cells studied ,and that this further bears a nearly one to one correspondence with the height-time pattern of the radar echo top. Thus with the rise of echo level, there is nearly simultaneous increase of precipitation rates at all heights and with its descent a fall in rainfall rate occurs. The features observed in relation particularly to intensity variations near ground seemed rather doubtful at first, being at variance with our common expectations on the basis of general considerations, namely, that shower intensity in a convective cloud would be at its maximum only some time after the phase of peak updraft in the cloud. However, on reference later to a paper by Donaldson (1958), relating to his studies using radar in a number of thunderstorm situations, it was found that the findings as in the present studies were largely in agreement with what was observed by Donaldson, namely, that the radar reflectivity factor near ground level tends to swing in the same direction as the radar echo top. In any case, the features brought out by these studies are rather intriguing, and would require detailed and careful consideration of an appropriate model distribution of vertical currents within a convective cloud cell, for their satisfactory explanation.

The important point revealed by the study, namely, that precipitation rates at all levels rise or fall more or less simultaneously would need to be found a plausible explanation. In considering the phase of falling precipitation rates with subsiding echo top, it would be reasonable to expect that the sinking of the cloud top is an indication that not only there has been a distinct falling off of up currents through the body of the cumulus cloud but that downdraft had actually set in, and that the rain that is still observed to fall is the result of supply of moisture during the earlier phases of updraft. However, consideration such as these would not satisfactorily account for the observed fall and then rise in echo intensity, coinciding with fall and rise later of echo top, as in example relating to 1 September 1959.

In discussing the mechanisms of updraft in a growing convective cell, we have to remember that a rising parcel of air has to overcome, besides its body and form drag due to movement through the environmental air, also the drag due to water droplets contained within the cell, this being taken as equivalent to total weight of the droplets. As shown by Byers and Braham (1949), liquid water content of 1 gm/m^3 at 400-mb level produces a drag on an updraft, that is, a downdraft equivalent to a loss of buoyancy force, caused by a fall of temperature by 0·5°C within the cloud. At 900 mb this will be equivalent to a temperature fall by 0·25°C. Thus, it appears that with the removal of more and more liquid water from lower levels during the phase of rising radar echo intensity the buoyancy of the cloud in its upper layers would tend to increase. Considerations such as these might help to provide some tentative explanation of ascending echo top being associated with rising echo intensity at various levels. However, the general question as to how far water droplets affect vertical current within a cumulus cloud is not yet free from controversy.

Yet another way of looking at the problem is on the basis of consideration of effects of entrainment into cloud of environmental air. As a result of this, a certain amount of liquid water present in the top layers of cloud would get evaporated, and consequent cooling would cause the upper part of the cloud to lose its buoyancy. But, as precipitation starts and continues at a growing rate more and more water falls out from lower levels and the net amount available in the top layers of cloud to suffer evaporation as a result of entrainment becomes less and less. With the buoyancy loss decreasing the cloud top tends to rise further. A mechanism such as this has been suggested by some of the workers in their consideration of potentialities of rain augmentation by seeding of convective clouds, by arguing that with seeding treatment helping to accelerate the process of precipitation growth in such clouds, the entrainment effect discussed above would tend to decrease, allowing the cumulus cloud to grow further in height and gain in its rain giving capacity.

One limitation to systematic measurements, with the help of radar, of growing precipitation rates, particularly at lower levels, in connection with the above study has been that as the rain intensity reaches a certain maximum limit depending upon the distance of the rain cell, the radar scope gets saturated and it is no longer possible to determine what the absolute intensity values are. For example, in the case of thunderstorm cell studied on 3 September 1959 it was not possible to determine how the actual precipitation rates varied during the one hour period commencing from 1150 IST (Fig. 1c). It has since been possible to overcome to a large extent, this limitation as above by effecting suitable changes in the circuitry which has increased considerably the upper limit of estimate of rainfall by radar.

4. Conclusion

While it is difficult to offer a satisfactory explanation for the observed features of rising echo top being associated with increasing precipitation rates at all levels, and *vice versa*, the findings are of interest and these, if confirmed by further observations, may be of help in contributing further to our knowledge of the dynamics of raindrop growth in convective clouds.

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