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A radar study on thunderstorms and convective clouds around New Delhi during southwest monsoon season

B. P. GHOSH

Meteorological Office, New Delhi

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ABSTRACT. Data collected during the monsoon season of 1959 with an AN/CPS-9 radar located at New Delhi have been used to study and distinguish the echoes from thunderstorms with that from convective clouds. It is shown that for an echo whose top is colder than—25·5°C there is 85 per cent probability that it is or will shortly become a thunderstorm. Convective echoes which do not grow above this level are less likely to produce thunderstorms. It is also shown that from the knowledge of the height of the echo tops and the height of the 0°C isotherm from radar and radiosonde observation, one can ascertain with 85 per cent probability whether the clouds still remain convective or have culminated into thunderstorm. From the point of view of aviation weather warning, this simple method would be of considerable practical utility.

1. Introduction

1.1. It is well known that thunderstorm is a serious weather hazard to aviation. The hazards manifest themselves in the form of heavy turbulence, hail, lightning and the squalls associated with them. In its method of development, it builds up from small detached cumulii into the towering and awe inspiring cumulonimbus which finally culminate in a full fledged thunderstorm. A precise knowledge of its development and occurrence is therefore considered most essential specially for aviation.

Radar has been used extensively for the study of thunderstorms. The type of echo received from it exhibits clearly defined edges of high echo intensity and well-defined vertical structure. It may be emphasised, that unless thunder is heard or lightning echoes are seen there is no obvious way of distinguishing between an echo from a thunderstorm and that from a strongly developing convective cloud. Although in specially favourable conditions, transient echoes from the ionised path due to lightning strokes have been observed but such detections are infrequent due to the very nature of the lightning phenomenon. Furthermore, lighting echoes, specially those which occur between a cloud and the ground, are often obscure by the accompanying precipitation. Therefore, as a relible method of detecting the existence of a thunderstorm, such echoes can be discounted.

In middle and high latitudes intensive study of thunderstorms has been made for a number of years and the general conclusion is that "if the echo is of exceptional intensity or if the top of the echo extends to great heights (*e.g.*, heights at which the temperature is probably below—40°C) the probability is great that the echo is from a thunderstorm" (W.M.O. Tech. Note 27, 1959).

1.2. As far as India is concerned, not enough is known in this regard; although in recent years several studies have been made but no precise information could be collected because of lack or sufficient observational data. Based on radar observations of precipitation echoes from convective clouds and thunderstorms during the monsoon months (June to September) of 1959 with an AN/CPS-9 radar at New Delhi, an attempt has been made in this paper to make a statistical estimate of the critical height of supercooled layer above the 0°C isotherm and the critical temperature of the echo top which may act as a guide to determine when a convective echo will be considered to fall into the category of a thunderstorm. A total of 160 echoes are evaluated for this study.

2. Data used

2.1. The primary data for this study were obtained from 35 mm pictures of PPI and RHI scopes radar weather observations with an AN/CPS-9 radar at New Delhi. The AN/CPS-9 radar is an X-band radar with the following characteristics: Peak power 250 KW, Pulse width 0·5 and 5·0 miscroseconds, PRF 931 and 186 pps, Beam-width 1 degree conical, and a maximum range of 400 statute miles.

2.2. The present study covers a period of four months (June to September) during the monsoon season of 1959 when precipitation echoes from convective clouds and thunderstorms were observed on the radar. This particular year is selected as during that period the performance of the radar was known to have been particularly uniform without having any breakdown. From the data read off, finally those occasions when it was thought probable that the echo viewed came from a thunderstorm were separated from the occasions when it was almost certain that no thunderstorm was present.

TABLE 1

Details of radar echoes from thunderstorms at New Delhi during the monsoon season of 1959

Date	Time (IST)	Range (miles)	Azimuth (°N)	Max. ht. of echo (m.a.s.l.)	Min. temp. of echo (°C)	Ht. of 0°C isotherm (m.a.s.l.)
13 Jun	1631	27	230	10046	—25·3	5420
15 Jun	0044	10	348	7442	—11·3	4780
24 Jun	0255	50	270	12549	—45·5	4760
	0340	38	265	11769	—40·3	4760
	0343	30	205	10379	—30·7	4760
26 Jun	1309	25	225	10298	—27·5	5510
	1533	10	020	13948	—54·2	5510
	1538	10	220	13948	—54·2	5510
	1540	10	130	13948	—54·2	5510
	1758	62	170	12642	—45·7	5510
27 Jun	0142	63	325	12379	—49·4	4700
	0241	50	360	9503	—27·5	4700
	0250	38	360	10218	—32·5	4700
	0352	60	301	9834	—29·6	4700
	0452	40	275	10298	—33·0	4700
	0552	60	271	11969	—46·3	4700
	0915	8	360	8766	—21·5	4700
28 Jun	0050	80	340	9627	—23·7	5210
2 Jul	0240	90	152	15467	—65·2	6200
	0244	75	165	17065	—75·5	6200
	0438	75	190	16456	—71·0	6200
	0550	38	195	12659	—44·5	6200
4 Jul	1153	30	165	8842	—19·3	5790
	1243	80	197	15723	—69·8	5680
	1356	50	245	13160	—50·2	5680
	1605	35	200	14679	—62·3	5680
	1736	45	235	12969	—48·7	5680
	1745	25	315	12431	—44·5	5680
	1750	75	180	17065	—73·5	5680
	1751	25	285	12431	—44·5	5680
5 Jul	1305	38	300	12687	—45·5	5610
6 Jul	0605	13	080	8760	—18·7	5560
	0608	10	050	10289	—28·5	5560
	1102	35	230	14079	—57·3	5560
	1106	62	095	11999	—41·3	5560
	1254	12	262	11814	—36·3	6050
	1403	40	270	15814	—70·3	6050
	1407	35	245	15589	—68·5	6050
	2019	20	190	14862	—62·3	6050
7 Jul	1144	30	290	14649	—57·3	5550
	1148	20	110	14557	—56·7	5550
22 Jul	1141	7	186	9376	—20·5	5870
	1205	20	280	14557	—61·5	6240
	1845	25	065	12431	—40·8	6240
24 Jul	1508	13	085	15472	—67·7	6040
	1510	70	055	15380	—67·0	6040
31 Jul	1444	85	250	17399	—74·7	6120
	1645	38	330	15125	—62·5	6120
	2240	40	370	15815	—67·3	6120
	2322	63	215	16654	—72·7	6120
7 Aug	0554	88	066	14472	—57·5	6080
	0640	85	075	15905	—67·3	6080
10 Aug	0348	15	075	9376	—20·3	5610
13 Aug	0048	50	145	13160	—49·5	5490
	0050	75	160	16456	—71·0	5490
	0255	25	155	12431	—44·8	5490
22 Aug	1218	40	345	14291	—55·9	5700
	1345	20	120	10900	—31·5	5700
3 Sep	1510	18	280	13338	—55·0	5450
7 Sep	1528	10	020	10900	—32·7	5490
	1615	13	045	12424	—44·5	5490
	1920	18	225	13948	—54·2	5490
	2044	25	029	13955	—54·3	5490

2·3. *Method of classifying echoes as convective clouds or thunderstorms*

For the above classification due consideration was given to the facts that (1) the precipitation echoes from convective clouds and thunderstorms are, in general, characterised on the PPI scope by their tendency towards oval shapes, sharp gradients of intensity and high echo intensity and on the RHI by their large vertical extent and fairly uniform high intensity through a relatively narrow vertical column without showing 'bright band' except sometimes in the decay stage of the cells; and (2) echoes from thunderstorms are relatively tall and of large sizes having clearly defined edges and well defined vertical structures exhibiting sometimes, but not always, anvil shape as compared to simple convective types which are relatively small and narrow and at times exhibiting decreased echo intensity towards the top of the echoes. It may be emphasised that each echo was followed through its entire life cycle and the height was recorded when it showed its maximum development. Other pertinent information like synoptic situation and current weather were also taken into account. The above two occurrences are listed in Tables 1 and 2. The corrected heights of the echo tops, the minimum temperatures of echo tops corresponding to the maximum heights of the echoes, and the heights of the 0°C isotherm are given in the last three columns of the tables. The temperature of the echo tops and the height of the 0°C isotherm have been taken from the radiosonde ascents. In this connection, it may be mentioned that two radiosonde ascents at 0530 and 1730 IST are taken daily at New Delhi as a matter of routine. Out of these two ascents whichever was close to the time of occurrence of the weather echoes was utilised for the determination of temperature of echo tops and heights of the 0°C isotherm.

2.4. *Height correction* — The height correction due to finite beam width has not been applied in this case as the AN/CPS-9 radar has a very small beam width of 1° only.

The correction due to the earth's curvature and atmospheric refraction was, however, applied as follows.

TABLE 2

Details of radar echoes from convective clouds at New Delhi during the monsoon season (1959)

Date	Time (IST)	Range (miles)	Azimuth (°N)	Max. ht. of echo (m.a.s.l.)	Min. temp. of echo top (°C)	Ht. of 0°C isotherm (m.a.s.l.)
13 Jun	1640	37	203	7417	—15·0	4600
	1848	20	265	7242	—8·8	5420
	1849	50	142	6824	—6·7	5420
	1943	20	241	6937	—7·0	5420
14 Jun	2241	30	281	6999	—8·8	5130
	2359	13	310	6326	—4·7	5130
15 Jun	0002	90	277	8426	—17·3	4780
16 Jun	1640	25	221	7251	—8·3	5030
	1755	35	275	8584	—15·0	5030
	1855	12·5	347	7242	—8·2	5030
	2000	35	280	7364	—8·7	5030
24 Jun	0255	25	270	8471	—18·3	4760
	0340	13	265	8766	—20·5	4760
	0343	10	205	6937	—10·2	4760
	1045	30	195	9467	—25·3	4760
	1203	13	150	9467	—25·3	4820
	1205	13	180	9467	—25·3	4820
25 Jun	1541	80	226	9982	—28·7	5560
	1638	90	284	9036	—22·2	5560
26 Jun	1140	85	310	8564	—21·7	4770
	1309	40	225	8991	—19·5	5510
	1313	20	345	10289	—27·5	5510
	1855	75	260	9535	—22·7	5510
27 Jun	0142	63	325	7102	—9·5	4700
	0452	10	275	7242	—10·3	4700
	0552	50	271	7434	—11·2	4700
	1045	18	280	7242	—10·3	4700
28 Jun	0050	62	340	3409	+10·2	5210
29 Jun	1330	60	144	10684	—29·3	5780
	1452	25	084	5421	+2·3	5780
2 Jul	0148	100	150	8151	—11·3	6200
	0150	85	160	6918	—3·7	6200
	0152	80	170	8305	—12·4	6200
	0244	88	165	7756	—8·8	6200
	0438	50	190	8348	—12·5	6200
	0550	30	195	7303	—6·2	6200
4 Jul	1148	50	310	11396	—37·5	5790
	1153	20	165	4804	+4·0	5790
	1243	60	197	8534	—16·2	5680
	1356	25	245	7119	—7·7	5680
	1454	63	195	11674	—38·5	5680
	1457	50	275	11396	—36·9	5680
	1607	25	200	7882	—11·9	5680
	1750	50	180	6809	—6·2	5680
5 Jul	1353	38	295	8974	—18·3	5610
	1915	75	293	9840	—23·5	5610
	2338	90	285	10453	—28·3	5610
6 Jul	0446	25	115	6663	—6·3	5560
	1102	8	230	5566	—0·2	5560
	1254	20	262	5718	+1·8	6050
	1359	75	090	7401	—7·5	6050
	1403	50	270	8348	—12·7	6050
	1407	8	245	11814	—36·2	6050
	2019	35	190	12603	—42·5	6050
7 Jul	1144	50	290	8348	—14·5	5550
	1148	38	110	5926	—1·8	5550
9 Jul	1805	25	045	6968	—4·8	5200
	1807	60	110	10837	—30·2	5200
	2225	50	090	8043	—9·7	5200
	2317	50	350	9110	—17·5	5200
15 Jul	1850	88	222	8671	—17·7	5870
16 Jul	1711	65	210	6503	—0·3	6410
	1713	70	170	5766	+3·3	6410
	1725	70	312	5766	+3·3	6410
	1749	70	205	7080	—4·3	6410
	2338	10	145	5718	+3·5	6410
19 Jul	1641	35	145	5840	+2·3	6330
	2150	40	320	6551	—1·5	6330
	2155	20	295	8752	—9·0	6330
	2255	13	285	7242	—5·3	6330
	2300	12·5	270	5718	+2·5	6330
20 Jul	1256	38	275	9584	—21·3	5980
	1558	8	305	7852	—11·0	5980
21 Jul	0244	62	122	8011	—11·0	6130
22 Jul	1104	20	158	8461	—15·3	5870
	1141	22	186	3280	+12·7	5870
	1205	12	280	11509	—34·3	6240
	1752	30	355	6389	—0·5	6240
24 Jul	1510	38	055	5743	+1·7	6040
25 Jul	0547	18	200	5413	+0·2	5420
	1310	62	250	8591	—14·5	5900
31 Jul	1444	62	250	8591	—14·3	6120
	2215	60	310	10684	—28·3	6120
	2322	38	215	4979	+5·2	6120
7 Aug	0554	68	066	4781	+7·2	6080
	0640	65	075	5025	+5·7	6080
12 Aug	2248	50	100	6824	—4·3	6010
13 Aug	0253	30	110	10989	—32·5	5490
	0255	63	155	5578	—0·5	5490
22 Aug	1215	30	320	8522	—16·5	5700
	1550	40	360	10513	—27·8	5700
	1554	60	098	5501	+1·2	5700
	1665	70	360	6681	—5·3	5700
	1704	45	098	5940	—0·8	5700
26 Aug	0337	12	050	6328	—5·2	5350
3 Sep	1246	40	035	3503	+10·5	5450
	1510	30	280	6390	—6·2	5450

TABLE 3

Frequency distribution of supercooled layer $H—H_0$

A. Thunderstorm echoes			B. Convective echoes		
S.No.	Height interval $H—H_0$ (km)	No. of cases (n)	S. No.	Height interval $H—H_0$ (km)	No. of cases (n)
1	2·0 to 2·5	1	1	—3·0 to —2·5	1
2	2·5 to 3·0	0	2	—2·5 to —2·0	0
3	3·0 to 3·5	2	3	—2·0 to —1·5	2
4	3·5 to 4·0	2	4	—1·5 to —1·0	3
5	4·0 to 4·5	2	5	—1·0 to —0·5	5
6	4·5 to 5·0	4	6	—0·5 to 0	6
7	5·0 to 5·5	3	7	0 to 0·5	7
8	5·5 to 6·0	4	8	0·5 to 1·0	7
9	6·0 to 6·5	3	9	1·0 to 1·5	7
10	6·5 to 7·0	4	10	1·5 to 2·0	9
11	7·0 to 7·5	6	11	2·0 to 2·5	10
12	7·5 to 8·0	4	12	2·5 to 3·0	11
13	8·0 to 8·5	7	13	3·0 to 3·5	3
14	8·5 to 9·0	4	14	3·5 to 4·0	6
15	9·0 to 9·5	6	15	4·0 to 4·5	4
16	9·5 to 10·0	4	16	4·5 to 5·0	8
17	10·0 to 10·5	2	17	5·0 to 5·5	2
18	10·5 to 11·0	3	18	5·5 to 6·0	5
19	11·0 to 11·5	2	19	6·0 to 6·5	0
			20	6·5 to 7·0	1
	Total	63		Total	97

TABLE 4

Frequency distribution of temperature of echo tops

A. Thunderstorm echoes			B. Convective echoes		
S. No.	Temp. interval (°C)	No. of cases (n)	S. No.	Temp. interval (°C)	No. of cases (n)
1	—10 to —12	1	1	14 to 12	1
2	—12 to —14	0	2	12 to 10	2
3	—14 to —16	0	3	10 to 8	0
4	—16 to —18	0	4	8 to 6	1
5	—18 to —20	2	5	6 to 4	2
6	—20 to —22	3	6	4 to 2	7
7	—22 to —24	1	7	2 to 0	4
8	—24 to —26	1	8	0 to — 2	7
9	—26 to —28	2	9	— 2 to — 4	1
10	—28 to —30	2	10	— 4 to — 6	7
11	—30 to —32	2	11	— 6 to — 8	8
12	—32 to —34	3	12	— 8 to —10	9
13	—34 to —36	0	13	—10 to —12	8
14	—36 to —38	1	14	—12 to —14	3
15	—38 to —40	0	15	—14 to —16	6
16	—40 to —42	3	16	—16 to —18	5
17	—42 to —44	0	17	—18 to —20	3
18	—44 to —46	8	18	—20 to —22	3
19	—46 to —48	1	19	—22 to —24	3
20	—48 to —50	3	20	—24 to —26	3
21	—50 to —52	1	21	—26 to —28	2
22	—52 to —54	0	22	—28 to —30	4
23	—54 to —56	7	23	—30 to —32	1
24	—56 to —58	4	24	—32 to —34	1
25	—58 to —60	0	25	—34 to —36	1
26	—60 to —62	1	26	—36 to —38	3
27	—62 to —64	3	27	—38 to —40	1
28	—64 to —66	1	28	—40 to —42	0
29	—66 to —68	4	29	—42 to —44	1
30	—68 to —70	2			
31	—70 to —72	3			
32	—72 to —74	2			
33	—74 to —76	2			
	Total	63		Total	97

The correction factor H on this account is given by —

$$H = 5280\, R \sin \alpha + (R^2/2) \cos^2\alpha$$

where, H = height in ft of the beam axis

R = range in statute miles

α = angle of elevation of antenna in degrees

This correction factor is available in the form of a nomogram in the India met. Dep. Weather Radar Manual (1965).

3. Discussions

3.1. From Tables 1 and 2, it is seen that the minimum temperature reached by the echo tops over New Delhi vary from —11°C to —74°C, with a mean value of about —48°C in thunderstorms; and from —38°C to +13°C with a mean of about —11°C in convective clouds. Out of 97 cases of convective echoes studied, there was only one isolated case when an echo reached a height of about 13 km and its top was —42°C.

3.2. The mean maximum height reached by the echoes in thunderstorms is about 13 km, the maximum height recorded being 17 km. For convective echoes the mean maximum height is about 7 km and the maximum height recorded is 12 km. In this connection, it may be of interest to note that over 60 per cent of the thunderstorms investigated by the Thunderstorm Project in U.S.A. (Byers and Braham 1949) gave radar echoes extending over 11 km, the mean value being nearly 12 km and the maximum height recorded, 17 km. The actual cloud probably extended somewhat higher in all cases. In England, thunderstorm echoes extending beyond 12 km have been recorded. In India, from the studies based on debriefing reports from high flying jet aircraft and on observations from a limited number of meteorological reconnaissance flights (Deshpande 1964) and also from radar studies (Kulshrestha 1962) in recent years, it is known that during monsoon season over north India, the mean maximum height of thunderstorms is about 13 km; which is found to be in agreement with the observations of this study.

3.3. The frequency distribution of the supercooled layer $H—H_0$ (where H is the height of the echo top and H_0 the height of the 0°C isotherm) in thunderstorms and convective clouds are illustrated in Fig. 1 and Table 3. The clouds which

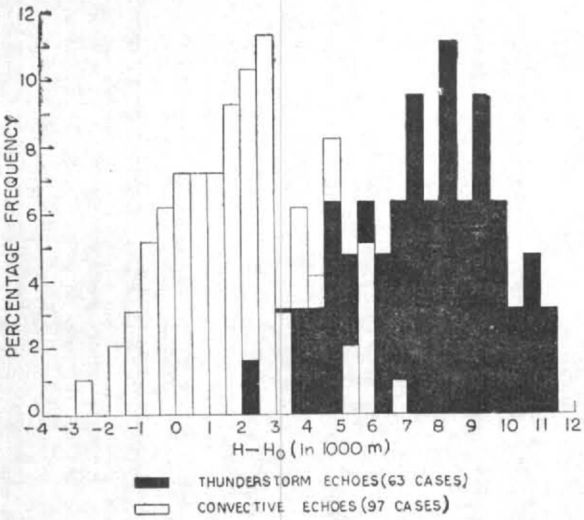

Fig. 1. Frequency distribution of the supercooled layer

do not extend to °C isotherm are explained by the negative values of $H—H_0$.

3.4. The frequency distribution of temperature of echo tops for the two types of clouds are illustrated in Fig. 2 and Table 4.

3.5. The accumulated frequencies in which the echo tops appear above the 0°C isotherm and the accumulated frequencies of temperature of echo tops for the two categories of clouds are shown in Figs. 3 and 4 respectively where the illustrations for thunderstorm and convective type of echoes are shown as reverse to each other. The point of intersection of the two curves determines the "critical" value which appears to determine whether a particular echo is from a convective cloud or a thunderstorm.

3·6.1. Most of the convective clouds formed around Delhi during the monsoon season are about 2·5 km higher than the 0°C isotherm while for thunderstorms this value is about 8 km. The average value of $(H\text{–}H_0)/H_0$ is equal to 0·37 for convective clouds and 1·32 for thunderstorms. The echo tops are thus seen to reach the height of 1·37 H_0 for convective clouds and 2·32 H_0 for thunderstorms. Therefore, knowing the height of tops of radar echoes and the height of 0°C isotherm from radiosonde ascents, one can judge whether the clouds are still of convective type or have culminated into thunderstorm.

3.6.2. Most of the echo tops of convective clouds are found to be around —8°C and those of thunderstorms around —44°C. From Fig. 3 it will be seen that when the height difference between echo top and the height of 0°C isotherm exceeds 4·5 km, the transition from convective echo to thunderstorm takes place. The larger is the height difference, the greater is the chance of the echo

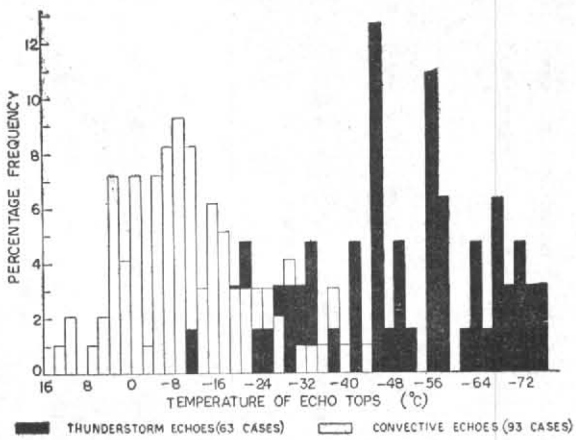

Fig. 2. Frequency distribution of temperature of echo tops

being from thunderstorm. This height difference may, therefore, be taken to denote a critical parameter which if attained, there is 85 per cent probability that the echo will shortly become a thunderstorm.

3.6.3. Similarly from Fig. 4, the critical temperature T_c of echo tops, at which the transition for convective type of thunderstorm appears to take place, is found to be —25·5°C. When the echoes have tops extended above the level of —25·5°C, the clouds are considered to be of thunderstorm type with 85 per cent probability, otherwise they belong to simple convective type. In New Delhi, during the monsoon season the height of —25·5°C isotherm is generally found between 9·3 and 10·5 km with a mean of about 10 km.

3.7. It is well known that although in some cases cumulonimbus clouds consist of ice crystals above the freezing level, yet in the majority of cases they consist of supercooled water drops. Although by thermodynamic analysis it is difficult to indicate precisely where in the vertical the water drops will become all ice and vapour, yet on the basis of Kohler's results one may infer (Mull and Rao 1950) that the region of supercooled water drops will not extend beyond the level of —10°C or —20°C. In nature, however, the transition may be more gradual or may even take place at a lower temperature. It is also very likely that all the water in the supercooled layer does not freeze at once but gradually. This temperature which exists at the interface between the supercooled layer and the ice layer aloft may be called the "Critical Temperature."

It will be seen from the above discussion that the value of the critical temperature (—25·5°C) as brought out from this radar study is fairly in agreement with the conclusions of Mull and Rao (1950).

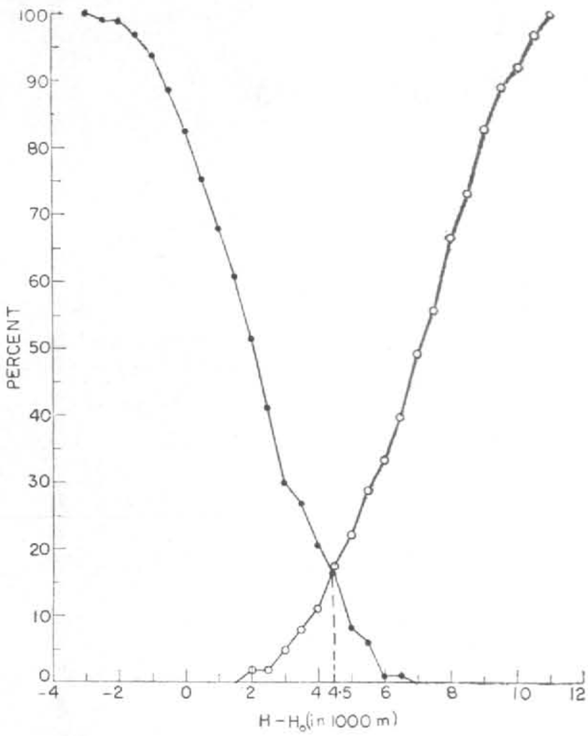

Fig. 3. Accumulated frequencies of echo tops above 0°C isotherm

Curve joining the filled circles indicates convective echoes and that joining the open circles represents thunderstorm echoes

3.8. It may be emphasised that in a developing thunderstorm cell, the in-cloud temperature will be higher than that of the surrounding air and that the heights given are of radar echoes and not of the cloud tops, which will naturally be higher. In order to obtain a really conclusive information about the formation, and development of thunderstorms, the radar observation should be closely coordinated with measurements on visual clouds from the high-flying aircraft.

4. Conclusions

4.1. Thunderstorms which form around Delhi during the monsoon season generally extend to about 8 km above the 0°C isotherm and the minimum temperature reached by the echo tops is about —44°C.

4.2. A developing convective cloud whose echo top is colder than —25·5°C, has an 85 per cent probability that it is or will shortly become thunderstorm. Echoes which do not grow beyond

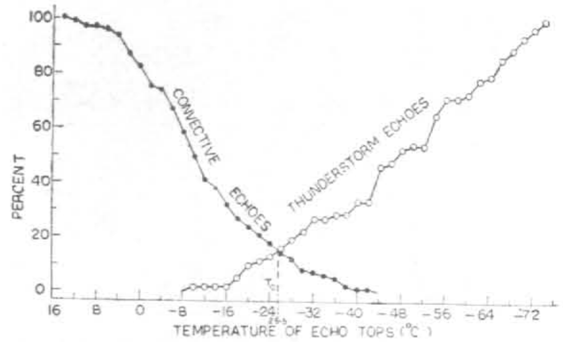

Fig. 4. Accumulated frequencies of temperature of echo tops

this level do not produce thunderstorms with the same factor of probability.

4.3. The heights of the top of the echoes above the 0°C isotherm also appear to be good indicator in determining whether the clouds still remain convective or have culminated into thunderstorm. The present study has shown that as soon as the height of the echo top exceeds 4·5 km above the 0°C isotherm, there is 85 per cent probability that the observed echo belongs to the thunderstorm type. From the point of view of aviation, this simple method may be of considerable practical value.

4.4. Having regard to the small observational sample and possible improper classification of some of the radar echoes and also the well known limitations of radar (India met. Dep. Weather Radar Manual 1965) in the measurement of cloud height (to which the cloud top temperature will be intimately related), it is possible that the temperature as determined may not be exact; however the values are indicative of the magnitude which might be expected for the development and occurrence of thunderstorms around Delhi. Further observations and critical study are therefore needed to permit any firm generalisation in this regard.

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