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Heights of *Cb* clouds over India during the southwest monsoon season

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ABSTRACT. Thunderclouds constitute one of the worst hazards of flying. Over India, Cumulonimbus (*Cb*) clouds develop to very great heights during the southwest monsoon season, June to September. These are often embedded in other cloud layers and pose a serious problem to aviators. All available data regarding *Cb* clouds obtained by the meteorological reconnaissance flights and scheduled civil flights by jet aircraft across India during the last six monsoon seasons have been analysed. The mean heights of tops of *Cb* clouds and their diurnal and regional variations have been studied. Heights of bases of *Cb* clouds and weather phenomena in their vicinity are briefly discussed. Three typical synoptic situations illustrative of thunder activity in the monsoon season are also described.

1. Introduction

1.1. Instability weather phenomena present serious hazards to aviation in the tropics. *Cb* clouds, which are manifestations of great instability in the atmosphere, deserve special attention as they are often accompanied by severe turbulence, squalls, blinding rain, hailstones and lightning. Updrafts and downdrafts (which may exceed 5000 ft per minute) and violent gusts, sometimes encountered in *Cb* clouds, may lead to loss of control and great structural damage. The severity of turbulence experienced and the airframe stress induced by gusts are directly proportional to the airspeed. Studies in the U. S. A. have shown that the operational life of a DC-3 aircraft can be 10 times longer if the airspeed is reduced in turbulent areas by 30 miles per hour below normal. In addition to greater hazards due to increased turbulence and structural damage on account of their higher speeds, modern jet-aircraft face the danger of flame-outs of engines in *Cb* clouds.

The problem, which already constitutes one of the worst hazards of aviation, is likely to assume still greater importance in the next 5–10 years when supersonic aircraft (speed Mach II or higher) are put in commercial operation.

1.2. Considerable data regarding *Cb* clouds and thunderstorms have been gathered in Europe and America. In the *Thunderstorm Project* covering Florida and Ohio in the U. S. A., valuable and exhaustive data have been obtained by Byers and Braham (1949). However, till recently very little information in respect of *Cb* clouds in the tropics was available. Climatological Tables and Cloud Atlas in use in India showed cumulonimbus bases at 1500—5000 ft and tops varying between 30,000 and 40,000 ft. With the advent of jet aircraft in commercial operation across India, considerable post-flight data regarding *Cb* clouds became available. Ramamurthi (1955) and Rao (1955) analysed B.O.A.C. Comet debriefing reports of *Cb* clouds during 1952 and 1953 for routes across India and south Asia respectively. All available debriefing reports from civil jet aircraft and Meteorological reconnaissance flights organised by the Indian Air Force were analysed by the author in 1961. Recently Kulshrestha (1962) studied thunderstorm-echo data obtained by a high-power storm detecting radar set located at New Delhi.

1.3. These studies indicate that cumulonimbus clouds of great vertical extent develop over India during the southwest monsoon season (June—September). This is partly due to the pulsatory character of the monsoon and as stated by Rao (1955), due to the entrainment of relatively warmer environmental air in this season. Further in this season, *Cb* clouds are often embedded in thick nimbostratus, altostratus and cirrostratus clouds, the latter three clouds sometimes forming a solid cloud mass from 500 ft a.g.l. to 45,000 ft. In such cases it becomes difficult for a pilot to distinguish *Cb* clouds in flight, unlike in the summer season when *Cb* cells can generally be spotted in advance. Hence development of *Cb* clouds over India during the southwest monsoon season deserves a special study.

1.4. While it is possible with a radar set to follow each storm through its entire life history and determine the maximum height reached by *Cb* tops, the method suffers from a few limitations. In the first instance, echoes observed are over a restricted area, within about 150—200 miles radius of the storm-detecting radar set. Unless there is a close net-work of radar stations, it may not be appropriate to draw general conclusions for the country. It is also found that the heights of *Cb* tops obtained by radar study are generally lower than the heights visually observed; Byers (1949) noted that in many cases the error was over 2400 ft. Further, errors due to the curvature of the earth, the finite width of the radar beam, effects of rain and range attenuation on the radar response cannot be fully evaluated. Observations from high level aircraft flying in the vicinity of *Cb* cells are more useful as they provide supplementary data regarding turbulence, wind and temperature fields, icing etc in addition to the *Cb* heights. Meteorological reconnaissance flight reports are particularly valuable as they cover wide areas at different times, unlike the civil aircraft which fly along fixed routes at fixed times.

2. Data used for the present study

2.1. Visual observations from aircraft which offer more accurate information about *Cb* clouds have been used for the present study. In view of the fact that aircrews flying at lower altitudes find it difficult to estimate *Cb* tops, the study is confined to reports from jet aircraft whose operational altitude was higher than 33,000 ft (10 km). All available post-flight reports from civil jet aircraft, mainly Air India and B.O.A.C., and the meteorological reconnaissance flights of the I.A.F. for the last six southwest monsoon seasons (June to September, 1957–1962) were scrutinised and data regarding *Cb* clouds extracted. The reports obtained by the aircrews of the met reconnaissance flights were naturally more detailed and useful as they referred to areas and times not covered by scheduled flights and the aircrews could deviate to observe *Cb* clouds at close quarters. The present analysis is based on a total of 322 reports of *Cb* clouds actually observed during the six SW monsoon seasons 1957-62. Out of these a large majority, *viz.*, 66 per cent, were by reconnaissance flights. A map indicating the locations of *Cb* clouds observed is shown in Fig. 1. The observations are spread over most of India, although there is a large concentration of reports from the areas between Lat. 20° and 30°N. This is of great practical use as the principal air-routes across India lie in this region.

3. Analysis of data

3.1. *Heights of Cb tops*

3.1.1. The reporting jet aircraft generally operated at altitudes between 35,000 and 45,000 ft and in a few cases even at 50,000—55,000 ft. Flight levels, in most cases, were within 2000 ft of reported tops of *Cb* clouds. In some cases, aircraft actually skimmed the *Cb* anvils. Hence the height estimates may be regarded as fairly accurate.

3.1.2. Table 1 shows the frequency of height-levels of *Cb* tops over India during the SW monsoon, monthwise as well as for the season. The percentage frequencies of the different levels for the season are shown graphically in Fig. 2.

3.1.3. A few salient features of Table 1 are indicated below—

(*a*) Though the observed heights of *Cb* tops cover a wide range from 25,000 to 60,000 ft, over 70 per cent of the reports (*i.e.*, 229 of 322) for the

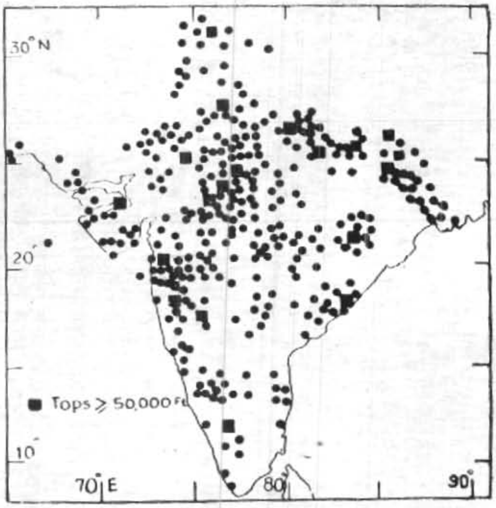

Fig. 1. Locations of *Cb* clouds observed (June—September, 1957—1962)

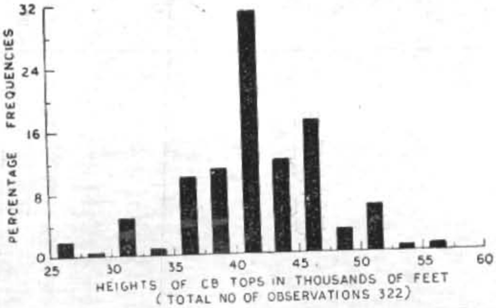

Fig. 2. Percentage frequencies of heights of *Cb* tops over India—June to September

TABLE 1

Frequencies of heights of *Cb* tops over India (June to September, 1957—1962)

Heights (in thousands of feet)	No. of reports					Percentage frequencies (season) Jun–Sep
	June	July	August	September	Total	
Below 25	0	0	0	0	0	0
25·0—27·4	1	2	3	1	7	2
27·5—29·9	0	0	1	0	1	0·3
30·0—32·4	8	0	2	7	17	5
32·5—34·9	0	1	2	0	3	1
35·0—37·4	7	8	5	12	32	10
37·5—39·9	8	5	10	13	36	11
40·0—42·4	26	12	23	38	99	31
42·5—44·9	7	14	8	9	38	12
45·0—47·4	11	17	10	18	56	17
47·5—49·9	3	5	1	2	11	3
50·0—52·4	7	1	6	5	19	6
52·5—54·9	0	0	0	1	1	0·3
Above 55	0	0	1	1	2	0·6
Total	78	65	72	107		

Total No. of reports 322 Highest top 60,000 ft Lowest top 25,000 ft Mean height 42,000 ft

TABLE 2

Comparative results—percentage frequency distribution of heights of *Cb* tops during June–September

	1952-53 Aircraft reports (South Asia) %	Radar study 1958–59 (North India) %	1957–62 Aircraft reports (India) %
Below 30,000 ft	0	3	3
30,000–34,900 ft	12 }	28	6
35,000–39,900 ft	22 }		21
40,000–44,900 ft	34 }	50	43
45,000–49,900 ft	17 }		20
Above 50,000 ft	5	15	7
Total No. of reports	112	238	322

TABLE 4

Percentage frequency distribution of *Cb* heights—Region-wise

Height-levels (thousands of feet)	Southern India (South of 20°N)	Central parts (between 20° and 25°N)	Northern India (North of 25°N)
Below 30	0	3	3
30—34·9	6	7	5
35—39·9	29	18	17
40—44·9	45	41	39
45—49·9	14	25	25
50—54·9	6	6	9
55 and above	..	..	2
Total No. of reports	86	138	98

TABLE 3

Frequency distribution of *Cb* tops at different periods of day

Height-level (thousands of feet)	Morning (00—06Z)	%	Afternoon (06—12Z)	%	Evening (12—18Z)	%	Night (18—24Z)	%
Less than 30	6	4	..	..	1	1	1	5
30—34·9	9	6	3	5	6	6	2	10
35—39·9	23	16	5	8	30	31	10	50
40—44·9	65	45	30	49	37	39	5	25
45—49·9	28	19	18	30	19	20	2	10
50—54·9	13	9	5	8	2	2	..	..
55 and above	1	1	..	..	1	1	..	..
Total No. of reports	145		61		96		20	

season are in the range 37,500 to 47,400 ft. This is also true in respect of each of the months, June to September.

(*b*) For the season as a whole, the maximum number of reports for any individual level is 99 (*i.e.*, 31 per cent) for the level 40,000–42,400 ft. The next frequent level is 45,000–47,400 ft, which accounts for 56 reports (17 per cent). These two levels also claim maximum number of reports in that order for June, August and September while for July, the maximum reports are for the level 45,000–47,400 ft.

(*c*) Total number of reports for *Cb* tops lower than 30,000 ft is only 8, that is, less than 3 per cent. On 22 occasions (*i.e.*, 7 per cent) *Cb* clouds developed to 50,000 ft or higher.

(*d*) The highest top of *Cb* clouds reported was 60,000 ft near Patna at 0325 GMT on 21 August 1961.

3.1.4. Table 2 shows comparative results of heights of *Cb* tops obtained by Rao (1955) for south Asia and by Kulshrestha (1962) by radar study for north India for the SW monsoon season, along with the results of the present analysis.

It will be observed that the present study yields higher value of *Cb* heights as compared to previous estimates. *Cb* tops were 40,000 ft or higher in 56 per cent cases in Rao's analysis and in 65 per cent cases by the radar study while in the present analysis the frequency is as high as 70 per cent. The range 40,000—50,000 ft accounts for half or more of the reports in all the three analysis, being 51 per cent in Rao's study, 50 per cent by radar study and 63 per cent in the present analysis.

3.2. *Diurnal and regional variations*

3.2.1. *Diurnal variation*—As the development of cumulonimbus clouds has a large diurnal variation, an analysis of *Cb* heights in relation to the time of the day was carried out. For this purpose the day was divided into four equal parts, morning (00—06 GMT), afternoon (06—12 GMT), evening (12—18 GMT) and night (18—24 GMT). An analysis of heights of *Cb* clouds reached at different periods of the day is given in Table 3.

3.2.1.1. There were only 20 reports at night. This is partly due to few flights at night. It is also due to the difficulty in estimating *Cb* heights while flying at high altitudes at night. However, the few reports of *Cb* heights at night indicate that *Cb* clouds at night are lower than at other periods of day.

3.2.1.2. The percentage frequencies of *Cb* tops being 40,000 ft or higher were 87 for afternoons, 74 for morning observations and 62 for evenings. The percentage frequencies of *Cb* tops being lower than 35,000 ft were 5 in the afternoons, 10 in mornings and 7 in evenings.

3.2.1.3. The preferred periods of attainment of maximum and minimum heights by *Cb* clouds, therefore, appear to be afternoons (06—12 GMT) and nights (18—24 GMT) respectively. However, instances of *Cb* clouds extending up to the highest level observed have been reported even in the mornings and evenings during the monsoon season. Kulshrestha (1962) similarly found that during the SW monsoon season, the most preferred period for maximum *Cb* heights was 0630—1030 GMT and the least preferred period 1830—2230 GMT over north India. The results of the present analysis covering whole of India are in fair agreement with the radar study.

3.2.2. *Regional variation*—According to the climatological charts for June to September, thunderstorms occur on about 40 per cent days of the monsoon season over Bengal, Bihar, Orissa and east Madhya Pradesh. These occur mainly in association with the monsoon 'lows' or depressions which form at the head of the Bay of Bengal and move westnorthwestwards. The frequency of thunderstorm days decreases westwards becoming less than 10 per cent west of longitude 75°E. To find out whether there is any regional variation in the heights of *Cb* tops, India was divided into three broad regions, *viz.*, southern India (south of Lat. 20°N), central parts (between Lat. 20°N and 25°N) and northern India (north of Lat. 25°N). As will be seen from Fig. 1, *Cb* cloud reports obtained provide a good coverage for most of the country. There were 86 reports from southern India, 138 from the central parts and 78 from northern India. It is remarkable that percentage frequencies for the three regions for each height level are within 10 per cent of each other in almost all cases. For instance, the percentage frequencies of *Cb* tops being 40,000 ft or more were 65 for the southern, 72 for the central and 75 for the northern regions. Similarly the frequencies for the observed heights of *Cb* clouds being less than 35,000 ft were 6, 10 and 8 per cent respectively. From Fig. 1, it will also be seen that the places where *Cb* tops had risen to 50,000 ft or higher are fairly distributed amongst the three broad regions. Allowing for variations due to times of observation, it seems that there is no large regional variation in the heights attained by *Cb* clouds over India during the SW monsoon season.

TABLE 5

Percentage frequency of heights of base of *Cb* clouds (June to September)

Region	Period	Height of base above surface (in thousands of ft)										
		1 to 1·9	2 to 2·9	3 to 3·9	4 to 4·9	5 to 5·9	6 to 6·9	7 to 7·9	8 to 8·9	9 to 9·9	10 to 10·9	Above 10·9
India	1957—62	3	4	20	7	13	20	4	20	1	8	0
South Asia	1952—53	5	26	25	14	15	3	5	1	2	3	1
Total reports :	108 (India) and 100 (South Asia)											

3.3. *Heights of base of Cb clouds*

3.3.1. It was observed that in many of the post-flight reports, heights of the bases of *Cb* clouds were not indicated. This may partly be due to the presence of intervening cloud layers and partly due to the difficulty in judging the base-height correctly while flying at an altitude of 40,000 ft or more. However, 108 reports regarding *Cb* bases were available. These are indicated in Table 5. Comparative figures of heights of bases of towering *Cu* and *Cb* clouds obtained by Rao (1955) are also included in the table.

3.3.2. It will be seen that less than 10 per cent reports were for bases lower than 3000 ft or higher than 9000 ft. The lowest and highest bases observed were 1000 ft and 10,000 ft respectively. The levels from 3000 to 7000 ft account for 60 per cent of the reports. However, no great accuracy can be claimed for the heights of bases.

3·4. *Weather phenomena near Cb tops*

3.4.1. *Turbulence*—There were 31 reports of turbulence encountered by aircraft in the vicinity of *Cb* clouds. In 7 cases the turbulence was slight, moderate in 18 cases while in 6 cases it was severe. In one case severe turbulence was encountered when the aircraft was flying at 48,000 ft just on the top of *Cb* clouds while in some other cases severe turbulence was experienced as far as 30 miles away and 5000 ft below the top of an anvil. There were, however, some instances when aircraft while flying close to or through the *Cb* tops felt moderate or even slight turbulence. More observations are essential for a detailed study of this phenomenon.

3.4.2. *Upper winds* — Available wind observations indicate that there were no sudden changes in wind in the vicinity of *Cb* clouds. Over the central parts of the country, winds near 40,000-ft level were generally ENE to ESE, with an average speed of 30-40 knots. The maximum wind speed reported was 90 knots in an easterly direction at 36,000 ft near Gaya on 14 August 1961.

3.4.3. *Temperatures*—Only 3 reports of temperatures in *Cb* tops were available. Hence no comparative study of in-cloud and environmental temperatures can be made. Environment temperatures indicate that at the average level of *Cb* tops (42,000—45,000 ft), the free air temperatures were generally between —55°C to —62°C. These are in fair agreement with the normal upper air temperatures at 150-mb level. The lowest temperature reported near a *Cb* top was —75°C at an altitude of 48,000 ft.

3.4.4. *Icing*—There were only two instances of slight icing. In one case, slight icing occurred as an aircraft flew through the top of a *Cb* cloud at 42,000 ft with the free air temperature at —56°C.

4. Typical synoptic situations

4.1. *22 June 1961*—On the morning of 22 June 1961, a depression lay over the north-east Arabian Sea with its centre about 100 miles south of Dwarka. A low pressure area had formed over the north Andaman Sea (Fig. 3). In association with these conditions, there was extensive thunder activity over the country. Stations which reported *Cb* clouds or thunderstorms on 22 June (00 to 18 GMT) are also indicated in Fig. 3. It will be noticed that over a wide area, exceeding 70,000 square miles, in central and northern India, there was thunder activity during the day. An aircraft on met. reconnaissance flight encountered *Cb* cells with tops upto 42,000—46,000 ft and moderate turbulence over Gujarat and west Rajasthan in the morning. Over the Punjab and east Rajasthan, *Cb* cloud tops were higher, with a huge *Cb* cell towering to 50,000 ft near Delhi. This is a good example of how widespread thunder activity can be in a monsoon month.

4.2. *24 August 1961*—An upper air trough over northwest India was becoming unimportant. A low pressure area extended from the north Bay of Bengal to Madhya Pradesh. Widespread *Cb* development was observed over northern and central India. 80 miles east of Jamnagar a wall of *Cb* clouds, with lightning flashes all along, was observed. *Cb* tops were well above 45,000 ft and the pilot could not find any soft spot to penetrate the clouds. Scattered *Cb* cells with tops upto 45,000 ft and heavy rain were encountered near Gwalior. There was a line of *Cb* clouds, 100 miles long running north and south of Bhopal with tops upto 42,000 ft. Over Bhopal itself *Cb* cells were embedded in thick altostratus clouds and there was a solid cloud layer from 2000 ft a.g.l. to 42,000 ft. The aircraft was subjected to an updraft of 1000 feet per minute. Over the track Kanpur to Calcutta there were *Cb* cells all along with tops upto 48,000 feet and an aircraft flying at 44,000 feet experienced a moderate turbulence throughout.

4.3. *8 September 1961*—A deep depression lay over east Madhya Pradesh, with its centre about 50 miles west of Jabalpur. In the evening, an aircraft encountered a line of *Cb* cells, 20—30 miles on either side of the track Ambala—Jodhpur. *Cb* tops were well over 45,000—50,000 ft with one large *Cb* build-up upto 55,000 ft near Bikaner. The captain of the aircraft, an experienced pilot, stated that he had never seen such severe and widespread lightning, almost like fireworks. He had to climb to 52,000 ft and zigzag all the way, just on the top of *Cb* cells. Moderate turbulence and heavy static were encountered throughout. Even over north Gujarat, *Cb* tops were at 40,000—47,000 ft. This flight indicates that severe thunderstorms are possible as far as 400 miles away from a monsoon depression.

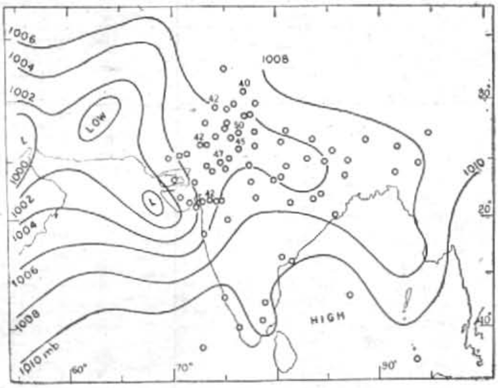

Fig. 3. Stations reporting *Cb* clouds on 22.6.1961

5. Conclusion

5.1. From the available data, it appears that the prevalent estimates of heights of *Cb* clouds during the southwest monsoon months, June to September, over India are underestimates.

5.2. Only 8 per cent of the observed heights of *Cb* clouds were below 35,000 ft while as many as 71 per cent reports were for the height level 38,000—47,000 ft. On 22 occasions, *Cb* tops extended beyond 50,000 ft; on two occasions, *Cb* clouds even towered to 60,000 ft, that is well within the stratosphere.

5.3. Some of the aircraft reports were recorded at times when perhaps the *Cb* cells had not matured fully. Also in some cases at least it is possible that the *Cb* heights recorded were with reference to the indicated height (which is much lower than the true height in this season) of the aircraft. In view of these possibilities, the mean height of *Cb* tops in the SW monsoon season appears to be about 45,000 ft.

5.4. The preferred periods of day for the attainment of maximum and minimum heights by *Cb* clouds are afternoons (0600—1200 GMT) and nights (1800—2400 GMT) respectively. *Cb* cells can develop to very great heights in the mornings and evenings also. There is no large variation in the heights of *Cb* tops with latitude over the Indian region.

5.5. The present analysis based on 6 years' data may be taken as fairly representative of normal cumulonimbus development over India during the southwest monsoon season. However, in view of the greater hazards to supersonic aircraft caused by turbulence and icing, it seems desirable to obtain additional information regarding weather phenomena encountered in and near *Cb* clouds through the co-operation of aircrews. Wherever possible radar studies of thunderstorms may be correlated with visual observations from high-level flying aircraft.

6. Acknowledgement

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