Heights of base and top and thickness of Tropical Clouds

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ABSTRACT. The heights of base and top of all genera of high and medium clouds and of thunderclouds from 1215 reports by Comet Jet Airliners over India and neighbourhood during the years 1952 and 1953 have been analysed. The mean heights and extremes are given and their seasonal variation discussed. High clouds have their bases most frequently between 30,000 to 45,000 ft with a mean height of 36,000 ft much higher than 24,000 ft, a value computed by earlier workers from pilot balloon data. The tops of high clouds may extend up to 50,000 ft but most of the high clouds are only 2000 ft or less in thickness. Medium clouds occur in three separate and distinct layers with bases at 12,000, 20,000 and 25,000 ft. The thickness of these layers decreased with increasing height of base. The tops of medium clouds never extended above 30,000 ft without transformation of the cloud into the cirriform type. The tops of medium clouds are thus much higher than the mean upper level of 20,000 ft, which is given in Cloud Atlases. The mean vertical height of thunderclouds is 40,000 ft which compares with a similar value of 37,000 ft for U. S. A. Thunderclouds go up to 50 to 55 thousand feet and are much higher than the presumed 30 to 40 thousand feet. The larger height of monsoon thunderclouds is attributable to entrainment of air, which is warmer in monsoon than in other seasons. One out of every ten thunderstorms appears to have a multicellular structure, which is ascribable to frictional drag and horizontal diffusion of momentum.

1. Introduction

With the advent of jet aircraft, the importance of accurate forecasts of the upper tropospheric weather has become paramount. Apart from winds and temperatures, the heights of base and thickness of medium and high clouds and the vertical extent of cumuliform clouds constitute the most important elements on which the jet pilot demands information. The factual information of mid-tropospheric clouding, on which such forecasts can be based, is however, meagre. In regard to the Indian theatre, Harwood (1924) was the first to discuss the mean heights of high, medium and low clouds over some stations, as determined by the heights at which pilot balloons were lost in clouds. Later, Narayanan and Manna (1931) computed such data in respect of a number of stations in India and neighbourhood. Alexander (1946) worked out the frequencies of heights of base of medium clouds from a large volume of observations made by reconnaissance aircraft based at Madras during May 1944 to January 1945 over the Bay of Bengal. The Cloud Atlas in use in the India Meteorological Department (1945) gives the mean upper and lower levels of high clouds as 35,000 and 25,000 ft and of medium clouds as 20,000 and 10,000 ft for tropical latitudes, which are in accord with the results of the above investigators. The mean upper level for cumulonimbus clouds is given as 30,000 to 40,000 ft. The London Meteorological Office gives much lower limits for such clouds for temperate latitudes in its recent publication entitled "Cloud Forms" (1949). The height limits given in Cloud Atlases and arrived at by the earlier workers fo medium and high clouds are too low when compared with those experienced by pilots of Comet Jet Airliners of the British Overseas Airways Corporation during their flights across India. On the basis of such experience, Majendie (1952) has indeed remarked that "the most notable deficiency, which we have uncovered in the meteorologist's knowledge of the upper air, is his belief in the general absence of cloud above about 30,000 ft. It has for long now been the practice of those of us in the Comet Fleet to add a minimum of 10,000 ft to all estimates forecast for the tops of high cloud, and this figure is often insufficient in practice". No observational data are available for South Asia on the heights of tops of thunderstorm clouds. A large volume of data of heights of base and tops of medium, high and cumuliform clouds is now available from the Comet pilots in the form of post-flight and debriefing reports. As such data are felt to be of great value in providing the tropical meteorologist with useful information, an analysis of all available reports tendered by the Comet pilots at the various meteorological offices in India and neighbourhood is attempted in this paper. The results are discussed with reference to cloud types and seasons.

2. Data analysed

The post-flight and debriefing reports utilised in this study are in respect of all Comet flights, which were available during the years 1952 and 1953 between the following stations—Karachi, Bombay, Delhi, Calcutta, Rangoon, Colombo, Singapore and Bangkok. A majority of them relates to flights across the Indian continent. In the first 200 miles of its flight from one airfield to the next, the Comet airliner generally climbs to the cruise-level. The middle section of the flight represents the cruise at an altitude which gradually increases from about 35 to 40 thousand feet. In the last 200 miles the descent of the aircraft takes place to the ground level. Whenever possible, the actual post-flight reports returned by the pilots for the route just covered were used. These reports depict pictorially the actual altitude, thickness and horizontal extent of the clouds encountered. In addition, the debriefing reports transmitted by wireless to Indian stations by the neighbouring foreign meteorological services were scrutinised. The heights of base, top and thickness of incipient and mature cumulonimbus and of high and medium clouds were tabulated with the dates on which and areas where these were encountered during flights. The data of bases of cumulonimbus and of medium clouds relate mainly to those met with during climb or descent, when the pilots' estimates of their bases and tops can be regarded as most reliable. Similarly, the data of bases and tops of high and medium clouds and of tops of cumulonimbus clouds analysed in this paper deal with those clouds, which occurred at or near the cruising level. In view of the very high cruising altitude, the pilots regard 500 feet as the outside limit of error in estimation.

3. Results and discussion

The results of this study are discussed with reference to the seasons of the year and the type of clouds in the following pages. A preliminary scrutiny of the data revealed that there was no variation of the heights or thickness of these clouds with latitude or the location of the point of observation on the surface. Therefore, no analysis with reference to latitude or longitude has been attempted. The year has been broadly divided into the following seasons for the purpose of computing the seasonal frequencies—

(*a*) December—February : Winter

(*b*) March—May : Pre-monsoon

(*c*) June—September : Monsoon

(*d*) October—November : Retreating Monsoon

Although this broad classification is not rigidly valid for all the regions covered by the Comet air routes in South Asia, it has been adopted for the sake of simplicity as it is generally applicable to a major portion of it and as it provides a convenient and reasonable working basis. The distribution of the observations in the four seasons is more or less uniform.

1. *Family A—High clouds*

(*a*) *Heights of base of high clouds*

There were 334 reports of heights of base of cirrus, cirrocumulus and cirrostratus clouds during the years 1952 and 1953. Of these 109 reports related to cirrus, 204 to cirrostratus and 21 to cirrocumulus clouds. The former two types of clouds are thus most frequent amongst the family of high clouds in South Asia. The genus cirrocumulus is comparatively rare. Real cirrocumulus is uncommon both in the tropics and in the higher latitudes (1935). It must show definite connection with or form integral part of cirrus or cirrostratus, of which it represents a degraded state. All the 21 cases of cirrocumulus discussed in this paper were picked up only from the pictorial post-flight reports received from Comet flights and all cases of doubtful identification were completely rejected. It is seen that real cirrocumulus forms only about 0·6 per cent of the frequency of occurrence of the other genera of the high cloud family—an index of their relative rarity of occurrence.

The distribution of the number of occasions of the heights of base of the three genera of high clouds during the different seasons in layers of air 5000 ft in thickness from 20,000 to 55,000 ft is reproduced in Table 1.

193 out of 334 cases of high clouds occurred during the monsoon period; 50 to 60 cases during the pre-monsoon and retreating monsoon months; and only 30 cases during the winter period in the two years under study. Taking the year as a whole, 37 per cent of the cirrus clouds had a base between 35-40 thousand feet. The majority of these clouds (63 per cent) had a base, which lay in the layer from 35-45 thousand feet.

The genera cirrostratus and cirrocumulus have a maximum frequency of 40-43 per cent in a lower layer of 30-35 thousand feet taking the year as a whole. About 70 per cent of these have a base of between 30-40 thousand feet. It may, therefore, be inferred that cirrostratus and cirrocumulus have generally a base, which is lower than that of cirrus clouds by 5000 feet. Taking all genera of high clouds together, it is seen that cirriform clouds generally have a base lying between 30,000 and 45,000 feet the frequency of such bases being 80-85 per cent of all occasions of their occurrence.

The seasonal distribution of the bases of high clouds shows some interesting features. There are few or no cases of cirrus and cirrostratus with a base above 45,000 ft during the winter and summer periods while an increasingly larger percentage of them occurs between 45 and 55 thousand feet during the monsoon and retreating monsoon seasons. As convective activity, which is predominant in the tropics, attains its maximum during the latter period, the formation of cirrus and cirrostratus with such high bases must be attributable to the great heights attained by thunderstorms in this part of the year*. During the summer months, when thunderstorm activity is in the process of gradual increase, thunderclouds should, in the light of this argument, spread out into the cirriform-anvil even in the lower levels, with a consequent higher frequency of lower bases in summer than in any other part of the year. This is borne out by the fact that 16 to 20 per cent of cirrus clouds have bases lying between 20,000 and 30,000 feet during the hot weather period. 45 per cent of all cases of cirrostratus bases occur in all seasons in the layer from 35 to 40 thousand feet.

It is interesting to find that the cirrocumulus base is mostly confined to the layer between 30,000 and 45,000 feet, not a single occasion of its occurrence with a base of more than 45,000 feet being on record. In the monsoon and winter seasons, however, a lower base is met with on a few occasions.

The heights of base of high clouds are thus appreciably greater than supposed. Narayanan and Manna found that the mean base of cirrus and cirrostratus in the tropics is 24,000 feet while for cirrocumulus they give the base as even so low as 18,000 feet. The maximum, minimum and mean heights of base of all genera of cirriform clouds found by the author are shown together with the corresponding values for Calcutta given by Narayanan and Manna in Table 2. *n* in this table represents the number of observations

*The question of the heights attained by thunderstorms during the different seasons is dealt with later in the paper

TABLE 1

Percentage frequency of heights of base of high clouds

Season	Heights in thousands of feet: 20 to 24·9	25 to 29·9	30 to 34·9	35 to 39·9	40 to 44·9	45 to 49·9	50 to 54·9	Total No. of obser-vations
				(a) *Cirrus*				
Winter	0	0	21	43	29	7	0	14
Pre-monsoon	8	8	39	30	15	0	0	13
Monsoon	4	6	17	36	29	6	2	52
Retreating monsoon	7	0	20	37	26	7	3	30
Year	5	4	21	37	26	5	2	109
				(b) *Cirrostratus*				
Winter	8	8	50	17	17	0	0	12
Pre-monsoon	6	14	30	30	17	3	0	36
Monsoon	7	5	40	27	19	2	0	130
Retreating monsoon	0	0	46	19	23	8	4	26
Year	5	6	40	26	19	3	1	204
				(c) *Cirrocumulus*				
Winter	0	25	50	25	0	0	0	4
Pre-monsoon	0	0	0	50	50	0	0	2
Monsoon	0	9	46	27	18	0	0	11
Retreating monsoon	0	0	50	25	25	0	0	4
Year	0	9	43	29	19	0	0	21

TABLE 2

Maximum, minimum and mean heights (in thousands of feet) of base of high clouds

Season	Cirrus					Cirrostratus					Cirrocumulus				
	X	*N*	*M*	*n*	Cal-cutta*	*X*	*N*	*M*	*n*	Cal-cutta*	*X*	*N*	*M*	*n*	Cal-cutta*
Winter	46	30	37	14	(20) 21	40	20	32	12	(11) 23	35	28	31	4	..
Pre-monsoon	41	23	34	13	(12) 24	46	22	34	36	(6) 21	42	39	41	2	..
Monsoon	50	25	36	52	(20) 27	46	20	34	130	(17) 25	42	27	34	11	(2) 18
Retreating monsoon	50	20	37	30	..	50	30	36	26	..	33	40	36	4	..
Year	50	20	38	109	(52) 24	50	20	34	204	(34) 24	42	27	34	21	(2) 18

X : Maximum height *M* : Mean height

N : Minimum height *n* : No. of observation

*Values given by Manna and Narayanan

TABLE 3

Percentage frequency of heights of tops of high clouds

Season	(Height of tops in thousands of feet) 20 to 24·9	25 to 29·9	30 to 34·9	35 to 39·9	40 to 44·9	45 to 49·9	50 to 55	Total No. of Observations
				(*a*) *Cirrus*				
Winter	0	0	0	28	43	29	0	7
Pre-monsoon	11	0	11	33	45	0	0	9
Monsoon	0	0	14	23	50	9	4	22
Retreating monsoon	0	0	10	40	40	0	10	10
Year	2	0	11	29	46	8	4	48
				(*b*) *Cirrostratus and Cirrocumulus*				
Winter	0	67	0	33	0	0	0	3
Pre-monsoon	4	24	41	17	10	4	0	29
Monsoon	0	18	35	36	11	0	0	77
Retreating monsoon	0	7	26	57	0	0	0	14
Year	1	18	36	35	9	1	0	123

on which the author's results are based. The corresponding figures for Narayanan and Manna's results are shown in brackets. These investigators suffixed October to the monsoon months and prefixed November to the winter period in all the computations they made in the course of their paper. Hence no comparative data for the post-monsoon season are available from their paper.

It is seen from Table 2 that the base of *Ci* and *Cs* can be as low as 20,000 feet and as high as 50,000 feet in extreme cases. The mean base for both types of clouds is, however, of the same order, being 34,000 to 38,000 feet. Narayanan and Manna's value of 24,000 feet for both these types of clouds appears to be too low. The limits given in the Cloud Atlas in use in the Indian observatories are nearer the author's results, being 25,000 to 30,000 feet for the mean lower and upper levels. As the values utilised in the present study are based on actual observations of aircraft flying near the cirrus levels, these are much more reliable than those based on the computation of the altitude of disappearance of pilot balloons. As Narayanan and Manna point out, "with increasing height of cirrus cloud, the chances of reaching it by pilot balloons get progressively smaller and the mean values given in the tables will therefore err on the side of underestimation." The author's results emphasise the desirability of the revision of the accepted limits for heights of high clouds.

Cirrocumulus cloud occurs at about the same mean height with the difference that its maximum limit is lower and minimum limit higher than in the case of other clouds. The mean value of 18,000 feet given by Narayanan and Manna appears to be too low. Their data are based on the reports of different pilot balloon observers, who, in view of the great liability for confusing between cirrocumulus and high altocumulus, may have mistakenly identified many clouds of the latter family as cirrocumulus.

(*b*) *Heights of tops of high clouds*

Table 3 shows the percentage frequency of occasions of occurrence of high cloud tops in different layers of the atmosphere from 20,000 to 55,000 feet at intervals of 5000 feet. The genera cirrocumulus and cirrostratus have been clubbed together in this table as an analysis of each separately shows about the same type of distribution.

TABLE 4

Frequency of thickness of all types of high clouds

Thickness (ft)	(Height of base in thousands of feet) 20 to 24·9	25 to 29·9	30 to 34·9	35 to 39·9	40 to 44·9	45 to 49·9	50 to 54·9	Total No. of obser-vations
500 or less	0	0	0	3	1	0	2	6
1000	0	1	5	7	5	1	0	19
2000	1	1	13	19	8	3	0	45
3000	0	0	4	9	3	0	0	16
4000	0	1	9	2	1	0	0	13
5000	0	0	7	5	1	0	0	13
6000	1	1	6	0	0	0	0	8
7000	2	2	0	3	2	0	0	9
8000	0	0	6	2	0	0	0	8
9000	0	1	1	0	0	1	0	3
10,000	0	1	9	0	1	0	0	11
11,000	0	0	1	0	0	0	0	1
12,000	0	2	2	0	0	0	0	4
13,000	0	0	2	0	0	0	0	2
14,000	0	0	0	0	0	0	0	0
15,000	1	0	1	2	0	0	0	4
16,000	0	0	0	0	0	0	0	0
17,000	0	0	0	0	0	0	0	0
18,000	1	0	0	0	0	0	0	1
19,000	1	0	0	0	0	0	0	1

It will be seen from Table 3 that the vast majority (71 to 80 per cent) of cases of cirrus tops lie between 35,000 to 45,000 feet, the exceptions being a few cases in the summer periods, when the lowest cirrus top is limited to 30,000 feet. In the summer months, cloud tops occur at all levels from 20,000 to 45,000 feet with increasing frequency but none were reported above that altitude during the period under study. This summer cirrus appears to be derived mostly from the tops of cumulus clouds of large vertical growth. In the winter months when such cumuliform growth is rare, there was no occasion of cirrus tops below 35,000 feet or above 50,000 feet.

Cirrostratus and cirrocumulus tops, on the other hand, rarely extend above 45,000 feet and almost all of them occur between 25,000 to 40,000 feet.

The above inferences suggest that the denser the high cloud, the lower its top. *Cc* and *Cs* form by the growth of ice crystals into thick snow flakes, which descend into the lower levels as they increase in weight. One should therefore expect their tops to be lower than those of cirrus clouds, as the results in Table 3 show. These results, however, are reproduced without reference to the thickness of high clouds and do not permit of any inference being drawn from them regarding the thickness of high clouds, because, although a particular cloud may have a top of 55,000 feet its base may not be lower than 50,000 feet. The frequencies of high cloud thickness have, therefore, been worked out and are shown in Table 4. All the high clouds have been treated as one class for the purpose. The frequencies of thickness of clouds in steps of 1000 ft are indicated for heights of base lying in layers of the atmosphere from 20,000 feet upwards up to 55,000 feet at intervals of 5000 feet.

It is atonce seen from Table 4 that the higher the base of the high cloud, the smaller

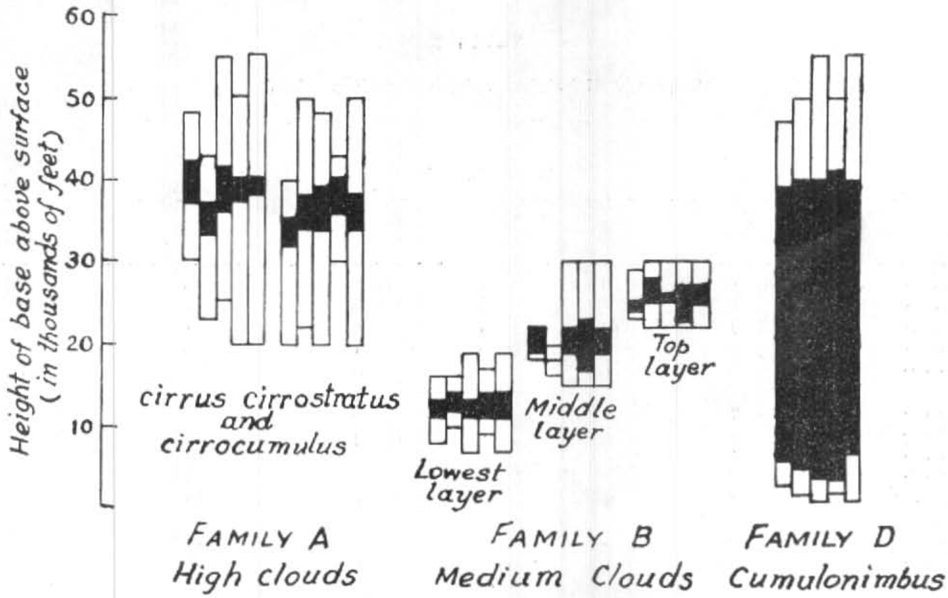

Fig. 1. Extreme and mean heights of base and top of tropical clouds

its thickness. The bulk of the high clouds are only 1000 to 2000 ft thick. The frequency of occasions of high clouds having a thickness of between 2000 and 5000 ft works out to be about 75 per cent, 4 out of 5 clouds which form with a base of 45,000 ft are less than 2000 ft thick. Instances of high clouds having a thickness of 15,000 to 20,000 ft are exceptional. Equally rare are cases of high clouds which are less than 1000 ft in thickness, such cases being confined entirely to levels above 35,000 ft.

It may, therefore, be inferred with justification that the tops of cirrus clouds lie generally betweeen 35,000 and 45,000 ft. Cirrocumulus and cirrostratus clouds have a top lying between 25,000 to 40,000 ft. Generally speaking, the higher the base of the clouds the smaller its thickness.

The extreme and mean values of the heights of base and tops of various types of high clouds are shown pictorially in Fig. 1 and dealt with later.

2. *Family B—Medium clouds*

(*a*) *Heights of base*

There were altogether 252 reports on the heights of bases of medium clouds during the period under study of which 99 were of genus altocumulus and the rest 153 of genus altostratus. These cases were dispersed separately against the height of base during the various seasons, with a view to discover whether there is any distinct difference in the heights favoured most by each genus of the medium cloud family. Such analysis failed to reveal any significant result. Both the genera of medium clouds were, therefore, treated as belonging to the same class and grouped together. The frequency of their bases at different heights is shown in Table 5.

A scrutiny of the results in Table 5 reveals that there are three distinct and separate heights in the atmosphere, which are favoured most by medium cloud bases. These occur in the layers (*i*) 10,000-13,000 ft (*ii*) 18,000-21,000 ft and (*iii*) 25,000-27,000 ft. The frequencies attain three distinct maxima in the region where medium clouds occur. This aspect is best brought out by the histogram shown in Fig. 2, where the ordinates show the heights and the abscissa the total number of cases during the period under study. It is clearly seen from Fig. 2 that there are three distinct maxima at 12,000, 20,000 and 25,000 ft. The intervening cases must be

TABLE 5

Frequency of heights of base of medium clouds

Heights of base (thousands of ft)	All medium clouds					Altostratus only
	Winter	Pre-monsoon	Monsoon	Retreating monsoon	All seasons	Monsoon
6- 6·9	0	0	0	0	0	0
7- 7·9	0	0	1	0	1	1
8- 8·9	1	0	7	0	8	5
9- 9·9	0	0	3	1	4	1
10-10·9	0	1	18	3	22	9
11-11·9	2	2	5	0	9	2
12-12·9	1	7	16	4	28	6
13-13·9	1	2	6	3	12	3
14-14·9	0	0	7	0	7	2
15-15·9	0	0	5	6	11	4
16-16·9	0	3	5	4	12	2
17-17·9	0	1	7	0	8	7
18-18·9	2	5	11	3	21	7
19-19·9	0	0	6	0	6	5
20-20·9	1	3	32	5	41	19
21-21·9	0	2	1	0	3	1
22-22·9	0	3	9	5	17	4
23-23·9	1	0	3	0	4	2
24-24·9	0	3	4	2	9	3
25-25·9	1	4	5	4	14	3
26-26·9	0	3	5	0	8	5
27-27·9	0	0	0	0	0	0
28-28·9	0	2	1	0	3	0
29-29·9	0	0	1	0	1	1
30-30·9	0	3	0	0	3	0
Total No. of observations	10	44	158	40	252	92

those of clouds belonging to one or other of these layers, which occur on a fewer number of occasions at slightly higher or lower level on either side.

The maximum contribution to the data is during the monsoon season when 158 cases are reported out of a total of 252. Of these, 92 cases were of altostratus. If layered formation of medium clouds is genuine, these monsoon altostratus clouds must also show three distinct peaks on frequency histograms. The frequencies of heights of base of monsoon altostratus are also shown in Table 5 and the corresponding histogram in Fig. 3. This histogram shows three distinct maxima at 10,000, 20,000 and 26,000 ft.

Indian pilots flying during the monsoon months between 10,000 to 15,000 ft of altitude have often reported the occurrence of altostratus in two separate layers, leaving a clear flying gap in between. Occasional reports are also received of three layers of medium clouds having been encountered one above the other with good horizontal visibility in between. A scrutiny of the percentage frequencies of heights of base of medium clouds in the Bay of Bengal computed by Alexander (1946), based on reconnaissance aircraft reports during the period May 1944 to January 1945 also reveals similar large frequencies of occurrence at 8000-11,000 ft and 15,000-16,000 ft.

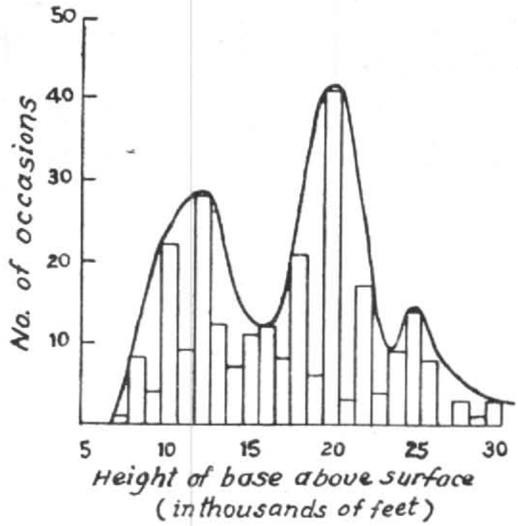

Fig. 2. Frequency distribution of heights of base of medium clouds

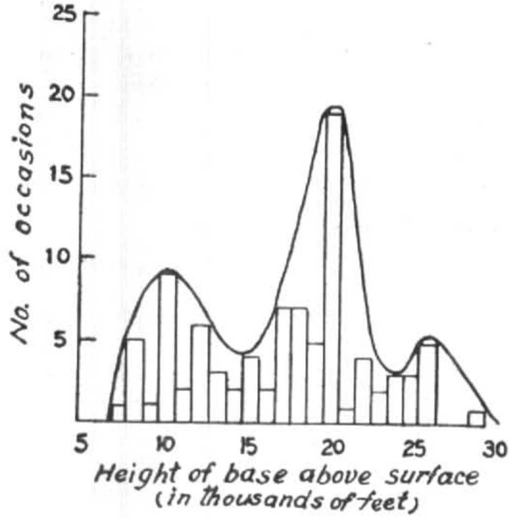

Fig. 3. Frequency distribution of heights of base of altostratus clouds during monsoon period

It may, therefore, be concluded that medium clouds occur in three distinct layers, the lowest of them corresponding to high stratocumulus. They appear to have a lower base over the sea than over land, as the author's results, which mainly relate to the clouds over land, suggest on comparison with those of Alexander. The height of the highest layer of medium clouds over the sea is not available from Alexander's results as the reconnaissance aeroplane flights rarely exceeded an altitude of 20,000 ft. The highest altitude at which medium clouds can occur is 30,000 ft over land and presumably of the same order over the sea also. The largest number of cases of medium clouds form with a base of as much as 20,000 ft. Secondary maxima of frequencies occur at about 10,000 and 24,000 ft in decreasing order of importance.

(*b*) *Thickness of medium clouds*

A layered formation of medium clouds would lead one to expect a certain maximum of thickness of cloud for each of these layers, so long as they exist separately. It follows that with increasing height of base, the thickness should show a gradual decrease for each layer. The frequencies of thickness of medium clouds associated with varying cloud bases are shown in Table 6. Heights of base and thickness are shown in this table in steps of 1000 ft. It may be mentioned in this connection that the heights of tops of medium clouds were not always available in the case of every medium cloud, the base of which was reported by the Comet pilots. There were also cases of data of cloud tops alone being available without those of the heights of bases. As a result there were only 131 reports of medium cloud tops available during the period examined, as against 252 cases of cloud base.

The data in Table 6 are seen to arrange themselves into 3 distinct groups corresponding to the three layers of medium clouds at 11,000, 18,000 and 25,000 ft. The thickness of each of these layers of clouds shows a progressive decline with increasing height of base. It is interesting to note that the maximum possible upper level for the lowest layer is 25,000 ft and for the intermediate and upper layers 30,000 ft. There were only three cases of medium clouds reported with a base of 30,000 ft. The cloud was stratiform and transformed into cirrostratus aloft in every one

TABLE 6

Height of base of cloud (ft)	*Ac* and *As* thickness (thousands of feet)																								
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	Total
500								1												2						3
1000				1				4	1				3	4	1		1	1	2	1		1			1	21
2000					1	4	1	6		1		6	1	5		6		1	2	3	1	6		1		45
3000								1	1		1	1	1			2					1					8
4000				2				2		1		2		2	1	1		2			1					14
5000	2					5	1	2					1			2					3					16
6000				3												1										4
7000	1									1		1		2												5
8000								2										1								3
9000								1																		1
10,000																4										4
11,000							2	1							1											4
12,000														1												1
13,000								1																		1
14,000							1																			1
15,000																										0

of these cases, without any demarcation in between. Again, the instances of extreme thickness of the lowest layer of the medium cloud have been found mostly to be the consequence of active monsoon conditions. The inference, therefore, seems justifiable that medium clouds form in separate layers when the monsoon is weak, the maximum number of cases of occurrence being at the partition between the monsoon air and the continental air which occurs at about 20,000 ft. When the monsoon is strong however, the cloud layers thicken and merge into one solid mass which may extend from 5000 ft to above 30,000 ft.

The frequencies in Table 5 were grouped together for each season into separate compartments, taking the heights of transition from one layer to another as those at which the frequency distribution curve reached the maximum values. The maximum, minimum and mean heights of base were then computed for each layer of cloud in each season. The results are reproduced in Table 11 together with the number of observations in each class. The mean heights of base of the three layers of the medium clouds appear from this table to be in the ranges shown below—

(*i*) Lowest layer—11,000-12,000 ft

(*ii*) Middle layer—17,000-19,000 ft

(*iii*) Topmost layer—23,000-25,000 ft

The origin of the three separate frequency maxima may be traceable to the varied causes leading to the formation of medium clouds. Those clouds which form as a result of the vertical transport of air from the surface must have the lowest mean base of 11,000 ft. The intermediate layer presumably marks the region of transition on the interface between air masses of continental and maritime origin. The topmost layers appear to form as a consequence of the descent of thick cirriform clouds to the lower levels. Although this explanation is not based on the analysis and scrutiny of individual observations, it is tentatively offered as an acceptable postulate in an effort to understand the triple-layer formation of medium clouds. The maximum possible thickness of medium clouds of different heights of base is shown in Table 7 for each of the three layers of medium clouds, on the basis of the results in Table 6.

The maximum thickness of medium cloud decreases from the lowest to the topmost layer from 14,000 to 5000 ft. The maximum possible heights for the tops of these three layers are respectively 25,000, 30,000 and 30,000 ft from the lowest layer upwards. It is of interest to find that the maximum possible thickness progressively decreases at the same rate as the cloud base increases in height. The highest top of any layer of medium clouds never exceeds 30,000 ft and occurs on most occasions below that level. This level therefore seems to represent the highest altitude that could be reached by medium clouds without transformation into the cirriform family.

(c) Comparison with earlier results

The mean lower and upper levels of medium clouds are given in the Cloud Atlas (1945) as 10,000 and 20,000 ft and in 'Cloud Forms' (1949) as 20,000 ft. In the light of the author's results, the upper limit appears to be too low. Narayanan and Manna computed the maximum, minimum and mean heights of base of medium clouds from pilot balloon data. For comparison with these results, the author has also worked out these limiting and mean values from the Comet debriefing reports. The results are shown in Table 8 together with those of Narayanan and Manna for Calcutta (Diamond Harbour). As already mentioned, these authors split the year into only 3 periods by adding October to the monsoon months and prefixing November to the winter period.

As the results of Narayanan and Manna are based on the heights of disappearance into clouds of pilot balloons, the maximum cloud base obtained by them would have varied from one observation to another through large ranges, depending on which of the three layers of medium cloud was present in the sky at the time of observation. The large variability of the maximum base vindicates the postulate of the existence of different favoured heights of formation of medium clouds. The maximum base represents the highest altitude where the top layer of medium cloud can form. This lies between 24 to 30 thousand feet with the exception of altocumulus in winter, which seems to form only at the lowest favoured level. Apart from this, the maximum base for medium clouds treated as a unitary layer appears to be devoid of any other significance.

What is more comparable is the minimum base of cloud, which invariably refers to the lowest layer. It is seen that the results of the author are in very close agreement with those of Narayanan and Manna in this regard.

The mean base of medium clouds, computed with data that do not always pertain to the same layer of the medium cloud would depend on the number of occasions of each class that enter into the computation. It is therefore of no physical import whatsoever in the case of medium clouds.

3. *Family D—Clouds with vertical development*

(a) Heights of tops of thunderclouds

As a considerable amount of published data is already available in regard to the heights of base and thickness of stratus, stratocumulus and cumulus clouds, the present study has been restricted in regard to low clouds to cumulus congestus and cumulonimbus. Little information is available on

TABLE 7

Maximum possible thickness (in thousands of ft) of medium clouds of varying heights of base

Lowest layer		Intermediate layer		Topmost layer	
Height	Thickness	Height	Thickness	Height	Thickness
11	14	18	12	25	5
12	13	19	11	28	2
		20	10	29	1
		22	8		

TABLE 8

Maximum, minimum and mean heights (in thousands of feet) of base of medium clouds

Season	Altocumulus								Altostratus							
	Author's results				Results of Narayanan and Manna				Author's result				Results of Narayanan and Manna			
	n	X	N	M	n	X	N	M	n	X	N	M	n	X	N	M
Winter	3	13	8	11	47	18	8	12	7	25	11	18	3	13	8	10
Pre-monsoon	21	28	10	19	44	18	9	13	24	30	11	21	1	..	..	15
Monsoon	66	28	8	16	84	22	8	13	92	29	5	17	24	21	7	12
Retreating monsoon	9	24	10	15	..	..	..	..	31	25	9	18	..	..	..	..
Year	99	28	8	16	175	22	8	13	154	30	5	18	28	21	7	12

TABLE 9

Percentage frequency distribution of vertical heights of thunderclouds in South Asia and U.S.A.

Period and Region	Heights of tops of thunderclouds (in thousands of feet)							No. of storms	Mean heights
	25-29·9	30-34·9	35-39·9	40-44·9	45-49·9	50-54·9	55-55·9		
South Asia									
Winter	0	22	22	34	22	0	0	9	39
Pre-monsoon	0	9	29	40	16	6	0	32	40
Monsoon	0	13	24	38	19	5	1	112	40
Retreating monsoon	0	15	12	35	26	12	0	34	41
Year	0	13	22	37	21	6	1	187	40
U.S.A.	19	24	17	15	13	10	2	114	37

the heights of tops of the latter cloud in the tropical latitudes, where it constitutes the most serious hazard to aviation. Reconnaissance flight data have a ceiling of 25,000 ft or less. The intensive work with a close network of radar sets on thunderstorms in U.S.A. over Florida and Ohio (1949) in a concerted thunderstorm project yielded an absolute maximum of 56,000 ft and a mean of between 37,000 to 38,000 ft for the heights of thunderclouds. It cannot be gainsaid in the light of these results that the forecaster is apt greatly to underestimate the thickness of thunderstorm cells.

There were 187 cases of thunderstorms, reliable data on the tops of which became available through the reports of jetliners during the years 1952 and 1953. The percentage frequencies of the heights of tops of these thunderstorms in the different seasons in South Asia are shown in Table 9. Corresponding frequencies in the case of 114 occasions of air mass thunderstorms in U. S. A. are also shown in this table for comparison. These cases were of thunderstorms which developed in areas where there were no frontal or pre-frontal influences.

Byres and Braham (1949) conclude from the results of the Thunderstorm Project operations in Florida and Ohio in 1946-47 that thunderclouds reached their greatest heights at the end of the mature stage, when the up-drafts completely disappeared. During this stage, the height of the thunderstorm clouds reaches upto 40,000 ft although individual cells may extend much higher or may complete their life cycle without growing higher than 30,000 ft. Table 9 fails to reveal even a single case of thundercloud maturing and dissipating below a height of 30,000 ft in South Asia. About 80 per cent of these had a top of between 35 to 50 thousand feet. Half the total number of occasions were of clouds with a top of 40 to 45 thousand feet. Only 13 per cent of the cases attained maturity below 35,000 ft. 7 per cent of them extended into the layer between 50,000 and 55,000 ft. There was only one instance of a thunderstorm which extended up to 55,000 ft during the whole period.

Byers and Braham (1949) find that a fifth of all thunderclouds studied by them were of cells which matured even below 30,000 ft. The general tendency shown by their results is for a larger number of thunderstorms maturing in the lower levels, contrary to the tendency shown by the author's results for South Asia. The mean vertical height of top of thunderstorm in the tropics is 40,000 ft as against 37,000 ft found by Byers and Braham. They however, caution that the heights obtained by them are not of visual, but of radar clouds and that the actual height would have extended somewhat higher in all cases. With this difference in approach in mind, it may be safely concluded that the average heights of tops of thunderstorms in the tropics are of the same order of magnitude both in the tropics and in the temperate latitudes, the mean height in both the cases being about 40,000 ft. The presumption that the mean upper level of the clouds with vertical development "may go up to 30,000-40,000 ft above ground in cumulonimbus" made in the Cloud Atlas in use in India appears to be too conservative and may lead a forecaster to underestimate the vertical height of tropical thunderstorms.

The winter thunderclouds in South Asia were never reported as extending above 50,000 ft, while in the pre-monsoon and monsoon periods the storms attained heights of 50,000 to 55,000 ft on 6 per cent of occasions. In the post-monsoon months 12 per cent of all cases of thunderstorms have tops extending into the layer from 50,000 to 55,000 ft, over 60 per cent of them reaching 40,000 to 50,000 ft. Over 70 per cent of all retreating monsoon thunderclouds thus have a lower limit for the top of 40.000 and an upper limit of 55,000 ft. The mean height of top is lowest in winter being 39,000 ft and highest in summer, being 41,000 ft.

It is of interest to find that the frequency of thunderstorm tops extending above 40,000 ft or more is as high as 62 per cent of all occasions both in the monsoon as well as the pre-monsoon months. The highest top of 55,000 ft for thunderclouds is also met with in the monsoon season. More than 70 per cent of the retreating monsoon thunderstorms also attain heights exceeding 40,000 ft. The question naturally arises how the monsoon thunderclouds attain heights as great as and sometimes greater than those in the hot-weather period, notwithstanding a much smaller environmental lapse rate in the monsoon and the retreating monsoon than in the preceding months. If the forces of buoyancy alone were the cause of the vertical growth of thunderclouds, the monsoon clouds should mature and dissipate at much lower levels than those occurring in the summer season.

Stommel (1947) showed that the lapse rates in trade wind cumuli were less than moist-adiabatic. Subsequently, Byers and Hull (1949), Ray Chaudhury (1952) and others discussed the question of the entrainment of environmental air in cumulus clouds in great detail. It is now accepted that entrainment in ascending parcels of air is a factor to reckon with in assessing thermodynamic diagram for thunderstorm liability. The degree to which the updraft lapse rate is made steeper than the moist-adiabatic depends on the temperature lapse rate and moisture content of the environmental atmosphere as well as the rate of entraining. The drier the environment and the more the entrainment, the steeper will be the resulting lapse rate. In the monsoon and retreating monsoon periods, the environment is warmer and more moist than in the pre-monsoon and winter months up to great heights. The atmospheric conditions are therefore favourable for greater vertical growth of thunderstorms in the monsoon and retreating monsoon than in the preceding months. The author's results follow as a necessary consequence of entrainment in updrafts of environmental air and emphasise the necessity of taking entrainment into account in analysing and utilising thermodynamic diagrams.

(b) Heights of base of cumulus congestus and cumulonimbus

Byers and Braham showed from graphs drawn to study the growth of thunderclouds with the maximum cloud echo at any time plotted against time that the thunderstorm top ascended in a series of steps in most cases. Between these steps was a short period during which the top of each echo remained essentially the same. They interpret these steps as manifestation of growth of additional cells in close proximity to an already existing one. Schmidt proposed an explanation for the development of new cloud towers in close proximity to an already existing one, taking into account the friction drag. As a result of the friction drag and horizontal diffusion of vertical momentum, there is ascending air outside the actual cloud. Schmidt postulates that if this ascending air has realised its conditional instability, another cloud tower may develop. Such ascentional motion is likely to give rise to clouds with very high heights of base. Comet pilots have often reported thunderclouds with a very high base above the surface. The percentage frequency of heights of base of thunderclouds during the different seasons during the years 1952 and 1953 is shown in Table 10.

The mean lower level of cumuliform clouds is given in the Cloud Atlas (1945) as 3000 ft and in Cloud Forms (1949) as 1600 ft. It is seen from Table 10 that the formation of cumulus congestus or cumulonimbus with a base of less than 2000 ft is a very rare event, the few exceptions being confined totally to the monsoon period. The greatest number of such clouds occur in all seasons below a height of 6000 ft. Alexander, however, found only two cases out of 2475 reconnaissance aircraft observations when the base was 5000-6000 ft and none with a higher base.

In the winter period cumuliform cloud bases never appear above 9000 ft. In the rest of the months, they form even at as high as 11,000 ft on occasions. A solitary instance was found of a thundercloud in the monsoon period, which had a base of 12,000 ft.

TABLE 10

Percentage frequency of different heights of base of towering *Cu* and *Cb* clouds

Season	(Height of base above surface in thousands of feet) 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	11 to 11·9	12 to 12·9	Total No. of observations
Winter	0	0	20	0	30	20	10	20	0	0	0	0	10
Pre-monsoon	0	16	16	26	16	0	0	4	11	11	0	0	19
Monsoon	5	26	25	14	15	3	5	1	2	3	0	1	100
Post monsoon	0	31	27	13	20	5	0	0	2	2	0	0	45
Year	2	25	25	14	17	4	3	2	3	4	0	1	174

A distinctly higher frequency of cloud base is found through all the seasons between 8000 and 11,000 ft. This must be attributed to the development of multicellular thunderclouds with secondary turrets based at the higher level, owing to frictional drag and horizontal diffusion of momentum.

It is thus seen that thunderclouds form on a large number of occasions with a base of 2000 to 4000 ft and on a smaller number of occasions with as high a base as 10,000 to 12,000 ft. As the latter occasions form about 5 per cent as against 50 per cent of cases with a lower base of 2000 to 4000 ft which should refer to single turret thunderstorms, it may be inferred that one out of every ten tropical thunderstorm has apparently a multicellular structure with a very high base on account of frictional drag.

4. Variation of height of base with latitude, amount of cloud and thickness of cloud

Narayanan and Manna report that they found no systematic variation of height of high and medium clouds with latitude. The author has also failed to find any such effect. The available data in respect of all types of clouds were analysed with a view to discover whether the height of cloud base varied with its amount or thickness. It was found in every case that the base was independent of these factors. The results of this study are thus valid for any place in South Asia, irrespective of whether a particular cloud is present in traces or heavy amounts and what its thickness is.

5. Summary of the results and suggested re-classification

In Table 11 is presented a summary of the results of this investigation. The maximum and minimum values of the heights of base and tops of all genera of high and medium clouds and of cumulonimbus clouds together with the number of observations on which each set of values is based are reproduced here.

The extreme and mean values of all the clouds studied are shown in Table 11. Cirrostratus and cirrocumulus clouds have been grouped together as the processes leading to their formation are more or less similar and also as the number of available reports on the tops of cirrocumulus clouds in each category was inadequate for working out the seasonal peculiarities. The data of medium clouds have been split into three sets corresponding to the three layers in which these clouds tend to form. The largest number of these observations relates to the middle layer of medium clouds and reflects the relatively higher frequency of occurrence of medium clouds in the intermediate levels. Although there were three occasions of the top of middle layer of medium cloud on record in winter, data of the tops in two of these cases were lacking and hence the blank against minimum

TABLE 11

Maximum, minimum and mean heights of base and tops of tropical clouds

(All heights in thousands of feet above surface)

Height	High clouds				Medium clouds (*Ac As*)						Cumiliform clouds	
	Cirrus		Cirrostratus and cirrocumulus		Lowest layer		Middle layer		Top layer		Cumulonimbus	
	Top	Base	Top	Base	Top	Base	Top	Base	Top	Base	Top	Base
Winter												
Maximum	48	46	40	40	16	14	22	21	29	26	47	8
Minimum	38	30	32	20	14	8		18	23	23	32	3
Mean	42	37	35	32	15	11	22	19	25	24	39	6
No. of observations	7	14	3	12	2	5	1	3	4	2	9	10
Pre-monsoon												
Maximum	43	41	50	46	16	14	20	21	30	30	50	10
Minimum	20	23	29	22	13	10	18	16	26	22	32	2
Mean	37	33	38	34	14	12	18	18	28	25	40	5
No. of observations	9	13	29	36	2	12	8	13	5	19	32	19
Monsoon												
Maximum	55	50	48	46	19	15	30	23	30	29	55	12
Minimum	32	25	30	20	9	7	18	15	22	22	30	1
Mean	41	36	39	34	13	11	22	19	26	25	40	4
No. of observations	22	52	77	130	28	66	33	73	23	19	112	100
Retreating monsoon												
Maximum	50	50	43	50	17	14	30	22	30	26	50	10
Minimum	32	20	34	30	12	9	19	15	25	22	30	2
Mean	40	37	40	36	14	11	23	17	27	23	41	4
No. of observations	10	30	14	26	4	11	6	18	2	11	34	45
Year												
Maximum	55	50	50	50	19	15	30	23	30	30	55	12
Minimum	20	20	29	20	9	7	18	15	22	22	30	1
Mean	40	38	38	34	14	11	22	19	27	25	40	7
No. of observations	48	109	123	204	36	91	48	110	34	51	187	174

height for this layer. Except in the case of cumulonimbus clouds, data of the heights of tops were less than those of heights of base in all cases. The larger number of reports in the case of tops of cumulonimbus clouds is due to the fact that the Comet airliners fly at very high altitudes for the most part of each route and chance upon the bases of these clouds on less number of occasions during the limited mileage of the climb and descent portions of the route.

It is of interest to note that the extreme values of the tops and bases of all genera of all the families of clouds studied occur almost entirely during the monsoon period. This is particularly so in regard to all types of medium clouds.

In order to provide at a glance the gist of the results of this investigation, histograms of the extreme and mean heights of base and top of all types of clouds in all the four seasons and during the whole period under

TABLE 12

Classification into families and Genera : mean upper and lower levels of clouds

Family	Form	Genus	Mean upper level		Mean lower level	
			Existing	Proposed	Existing	Proposed
A (High Clouds)	b1	Cirrus	35,000 ft (10 km)	50,000 ft (15 km)	25,000 ft (7·5 km)	25,000 ft (7·5 km)
	b2	Cirrocumulus	35,000 ft (10 km)	45,000 ft (13·5 km)	25,000 ft (7·5 km)	35,000 ft (10·5 km)
	b 3	Cirrostratus	35,000 ft (10 km)	45,000 ft (13·5 km)	25,000 ft (7·5 km)	25,000 ft (7·5 km)
B (Middle Clouds)	a4 b4 and c5	Altocumulus and Altostratus	20,000 ft (6 km)	30,000 ft (9 km)	10,000 ft (3 km)	8000 ft (2·5 km)
D (Clouds with vertical development)	a9 and a10	Cumulus and cumulonimbus	30,000 to 40,000 ft (9-12 km)	50,000 ft (15 km)	3000 ft (1 km)	2000 ft (0·5 km)

study are reproduced in Fig. 1. In this figure, the observed lowest and highest top of each type of cloud in each season is shown by the base and top of each rectangle. The mean base and top are shown by the upper and lower limits of the solid portion of each such rectangle. The successive rectangles of each histogram for each type of cloud represent the limits in the different seasons in the year and in the whole period of study in the following order—

1. Winter season (December-February)
2. Pre-monsoon season (March-May)
3. Monsoon season (June-September)
4. Post-monsoon season (October-November)
5. During the whole period of study

In the light of the results of this study, the existing limits of mean heights of base and top of the various genera of the high (A) and medium (B) cloud families and of the clouds with vertical development (family D) in the tropics, will require to be recast. A suggested modified scheme for this purpose on the lines of the International Cloud Atlas is shown in Table 12 for adoption in India and South Asia. The figures have been rounded off to the nearest 5000 ft in the case of all altitudes above 10,000 ft for convenience consistent with acceptability. In the cases of the lower heights they are rounded off to the nearest thousand feet or half km. The existing limiting values as given in the Cloud Atlas at present in use in India are also shown in Table 12 for comparison.

6. Conclusions

(*a*) *High clouds*

(1) Of all genera of high clouds, cirrocumulus is the rarest. Of the rest cirrostratus is more frequent than cirrus, 2 out of every three other clouds being of cirrostratus.

(2) The majority of cirrus clouds occur in the layer 35 to 45 thousand feet. Cirrostratus and cirrocumulus are confined within 30 to 40 thousand feet.

(3) There is a higher frequency of lower heights of base between 20 and 30 thousand feet during the summer months. There are no cases of high clouds with a base of 45,000 ft or more in winter, coincident with absence of or smallness of thunderstorm activity during this season.

(4) The mean height of base of high clouds is 36,000 ft, which is much higher than the value given by

earlier workers of 24,000 ft based on pilot balloon observations.

(5) Cirrus tops extend up to 50,000 ft and cirrocumulus and cirrostratus clouds up to 45,000 ft in the year as a whole. The higher the base of the cloud, the smaller is its thickness.

(b) *Medium clouds*

(1) Three out of every five cases of medium clouds are of altostratus.

(2) Medium clouds occur in three distinct and separate layers with bases at 12, 20 and 25 thousand feet.

(3) The thickness of each of these layers decreases with increasing height of base. The maximum possible top is, however, 30,000 ft, above which medium clouds transform into cirriform ones.

(4) Medium clouds extend up to 30,000 ft, which is much more than the level of 20,000 ft assumed at present to define the mean upper level of these clouds.

(5) In active monsoon conditions, all the layers of medium clouds unify into one single mass of cloud with a base often below 8000 ft, transforming into nimbostratus below and cirrostratus aloft.

(c) *Thunderclouds*

(1) The mean vertical height of the visual tops of cumulonimbus clouds is 40,000 ft, which is comparable with that of 37,000 ft for radar thundercloud tops in U.S.A.

(2) Cumulonimbus tops are invariably below 50,000 ft in winter but go up to 55,000 ft in the other seasons. The assumption that the clouds with vertical development "may go up to 30,000-40,000 ft in cumulonimbus" clouds is an underestimate.

(3) The larger heights attained by the tops of thunderclouds in the monsoon season compared with those in the pre-monsoon months are attributable to the entrainment of relatively warmer environmental air in the monsoon season.

(4) One out of every ten tropical thunderstorms appears to possess a multicellular structure, ascribable to frictional drag and horizontal diffusion of momentum.

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