

## The effect of vertical wind structure on some aspects of convective activity at Bombay

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**ABSTRACT.** The convective activity along the west coast of India in the southwest monsoon season has some characteristic features, the reasons for which could not be given earlier. The observed features of convective weather over Bombay in this season show that they do not fall into the general pattern found in other areas of the tropics. A study of the thermodynamic conditions reveal that these features cannot be explained in terms of the observed instability. On the other hand, these features could be explained in terms of the environmental wind field.

### 1. Introduction

Classical approaches to convective development were based on thermodynamic instability of the airmass in which these clouds grow (Bjerknes 1938, Normand 1938). Later studies have brought into focus such factors such as entrainment (Stommel 1947), form drag (Schmidt 1947), and the effect of environmental wind field (Byers and Braham 1949, Malkus 1952, Malkus and Scorer 1955, Newton 1960, Browning and Ludlam 1962). By the 'Slice' method the heights of cloud tops work out to be lower than the height of the instability layer. But as Ludlam (1963) points out cloud tops often terminate below even the level given by the above methods. No satisfactory explanation for this was available so far. A partial explanation was provided by a recent study by the present authors (1967), who postulated a parameter called 'Relative top shear', which seem to account for the vertical extent of convective clouds on a large percentage of occasions. This parameter depends on the environmental wind conditions.

A spectacular example of growth of convective clouds terminating often below the level they ought to grow according to thermodynamic considerations occur in the southwest monsoon season along the west coast of India. Even though this aspect is known to the meteorologists, no satisfactory explanation for the same has been given so far. A study of the thermodynamic and environmental wind data of Bombay for the years 1955 to 1962 was made and results of this study are presented in this paper.

### 2. Observed features of convective activity at Bombay

Bombay experiences significant hydrometeors only in the summer half of the year. Fig. 1(a) gives the mean rainfall, the average number of rainy days and thunderstorm days at Bombay in different months of the year. The interesting feature shown by the figure is that in spite of the enormous increase of rainfall in the months of July and August, there is a sharp decrease in thunderstorm activity. That this is an unusual feature for the tropical latitudes is shown by the comparable data of some of the other stations in low latitudes given in Figs. 1(b) and 1(c).

Thunderstorm activity at Bombay is maximum in the transition periods before the onset of the southwest monsoon (from beginning of May to middle of June) and after the withdrawal of the monsoon (from middle of September to end of October). During this period the storms develop in the afternoons and evenings over the hills to the east of the station. They drift in the easterly winds and strike the station giving some precipitation. Some of them cause easterly squalls. A typical case of this type is shown in Fig. 2.

However, radar studies have shown that the convective clouds which develop over the hills during these periods move sluggishly or remain stationary at the place of their origin. They have also a tendency to dissipate rapidly as they move from the favourable terrain (Narayanan and Krishnamurthy 1966). So many of these storms which strike the station are in a dissipating

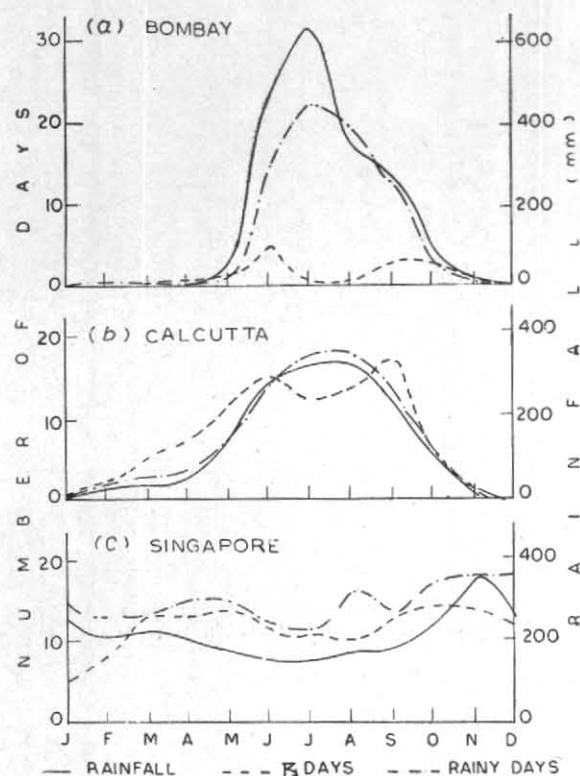


Fig. 1. Monthly mean data for some selected stations

The sudden fall of thunderstorm activity at Bombay occurs simultaneously with an enormous increase in rainfall

state, cause mild thunderstorm conditions and are not accompanied by any surface squalls.

During the southwest monsoon period a significant difference in the quantity and the quality of the convective activity at Bombay is observed. Vigorous convection occurs during this season and heavy rainfall is recorded at the station. The ground weather is controlled by the passage of innumerable convective cells. On days of active monsoon conditions, the surface winds are strong. A large number of gusts caused by the downdrafts of the eastward moving convective clouds are superimposed on the prevailing wind. Some of these gusts are of sufficient speed and duration to be termed as squalls. In Fig. 4 are shown the autographic charts for a typical day of active monsoon conditions at Bombay. As can be seen from these charts, squalls in this season are markedly different in character from the squalls of the non-monsoon period; which are of the type shown in Fig. 2. The rainfall is also marked by the rapid variation in its intensity. A typical intensity raingauge chart of the monsoon period is shown in Fig. 3. On the other hand, on a large percentage of days when thunderstorms do occur at the station, the surface winds are

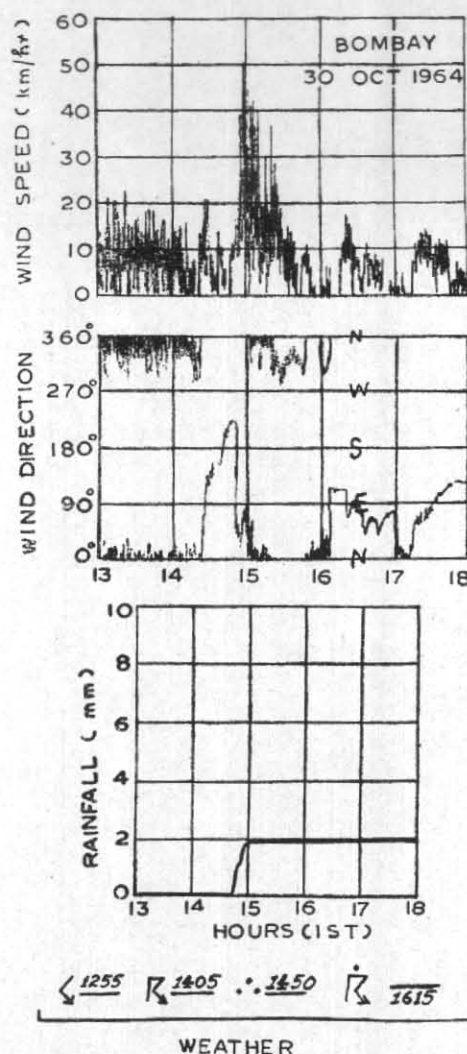


Fig. 2. Autographic charts showing the effect on the surface weather over Bombay caused by a typical post monsoon thunderstorm

generally light and squalls do not accompany the showers. This, rather interesting feature, is illustrated by autographic charts shown in Fig. 5.

For the purposes of this paper, we shall call the squalls unaccompanied by thunder as rainsqualls, and those accompanied by thunder as thundersqualls. The days of rainsqualls are used in this paper as measure of the days of active convection but not culminating in thunderstorm activity. The number of rainsqualls, thundersqualls and thunderstorms which occurred at Bombay during different months in the years 1955-1962 are shown in Fig. 6. It can be seen from the figure that even though the number of squalls are quite large, the number of thundersqualls are quite small. Actually the enormous

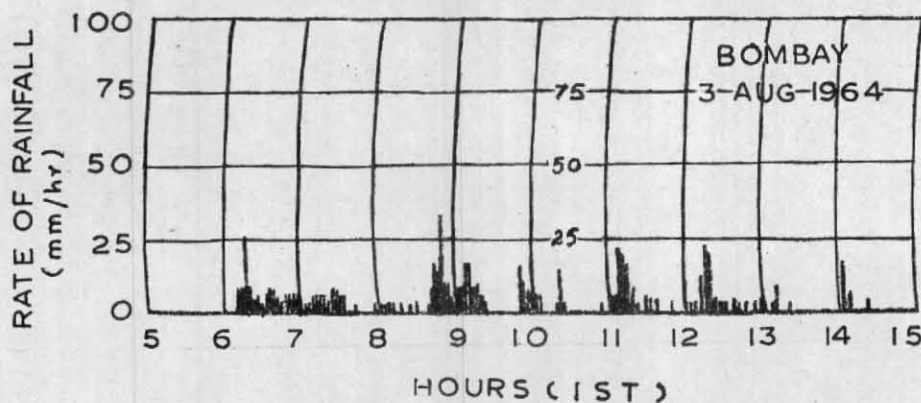


Fig. 3. The intensity rain gauge record shows the rapid variations in the rainfall on a rainy day at Bombay

increase in convection in July and August is not truly reflected by rainsquall numbers shown in Fig. 6. As Dekate and Baja] (1966) have pointed out for every downdraft gust which could be counted as a squall as per definition, there were at least four more gusts which just missed to attain the required speed to be termed as squalls. However, the data (Fig. 6) show that only on a small percentage of days of vigorous convection during July and August, the clouds grow to sufficiently great heights to give violent electrical manifestations.

Radar observations also confirm that the cloud tops at Bombay and neighbourhood generally extend only to about 5 km on most of the heavy rain days. The absence of significant electrification of clouds is indirectly confirmed by the absence of sferics in the medium wave radio reception, which is generally excellent on active monsoon days.

### 3. Thermodynamic Factors

It is apparent from the above discussions that some physical factors must be preventing the convective clouds on active monsoon days from growing to great heights to become thunderstorms. An attempt was made to correlate the thermodynamic parameters with the variations in the convective activity and the results are shown below.

Bombay takes radiosonde and rawin observations twice daily at 00 and 12 GMT. For this study the data from the radiosonde ascent of the hour nearest the occurrence of the phenomena are utilized.

(a) *Height of the environment of instability*—Thermodynamic considerations suggest that the vertical extent of convective clouds be closely related to the height to which the environment of instability extends. This height was calculated for all the days of thunderstorms and of rainsqualls. The data obtained are shown in Table 1. It can be

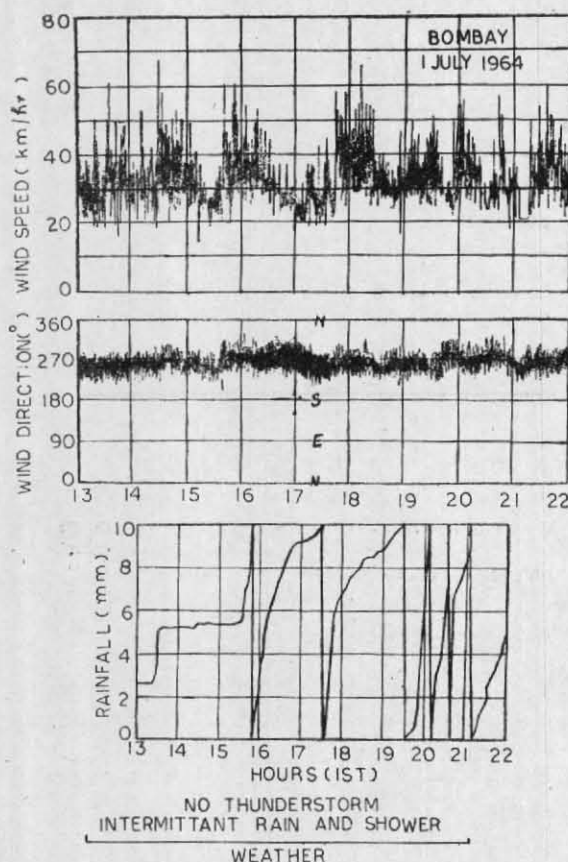


Fig. 4. Autographic charts of Bombay during a period of active monsoon condition

The short duration and smaller changes in the wind speed associated with the rain squalls as compared to the post monsoon squall shown in Fig. 2

seen from the table that this parameter is not able to discriminate between rainsquall days and thunderstorm days.

(b) *Showalter's Index*—Showalter's Index (1953) is another parameter which shows the degree of instability of the airmass. This parameter was also calculated for all the above days. The data

TABLE 1

Number of occurrences of thunderstorms and rainsqualls when the top of environment of instability ( $H_e$ ) was at different heights

(Data for 1955-1962)

Phenomena	$H_e$ in mb				No instability	Total
	600 to 500	500 to 400	400 to 300	>300		
<b>May and June</b>						
Thunderstorm	1	5	9	39	16	70
Rainsquall	—	2	3	7	3	15
<b>July and August</b>						
Thunderstorm	1	2	3	19	5	30
Rainsquall	2	10	8	27	7	54
<b>September and October</b>						
Thunderstorm	2	2	4	32	7	47
Rainsquall	—	—	—	9	3	12
Total	6	21	27	133	41	228

TABLE 2

Number of occurrences of thunderstorms and rainsqualls arranged according to different values of Showalter's Stability Index ( $S$ )

(Data for 1955-1962)

Phenomena	Showalter's Stability Index $S$															Total		
	>-8	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5		6	6
<b>May and June</b>																		
Thunderstorm	5	5	6	8	6	7	8	7	5	7	4	1	—	—	—	1	—	70
Rainsquall	—	1	—	—	3	2	3	1	1	2	2	—	—	—	—	—	—	15
<b>July and August</b>																		
Thunderstorm	—	—	2	1	1	7	5	5	1	4	1	1	1	—	—	1	—	30
Rainsquall	—	—	1	1	6	8	11	9	7	7	3	1	—	—	—	—	—	54
<b>September and October</b>																		
Thunderstorm	6	2	6	5	5	5	7	4	5	—	1	1	—	—	—	—	—	47
Rainsquall	—	1	—	—	3	—	1	3	1	—	2	1	—	—	—	—	—	12
Total	11	9	15	15	24	29	35	29	20	20	13	5	1	—	—	2	—	228

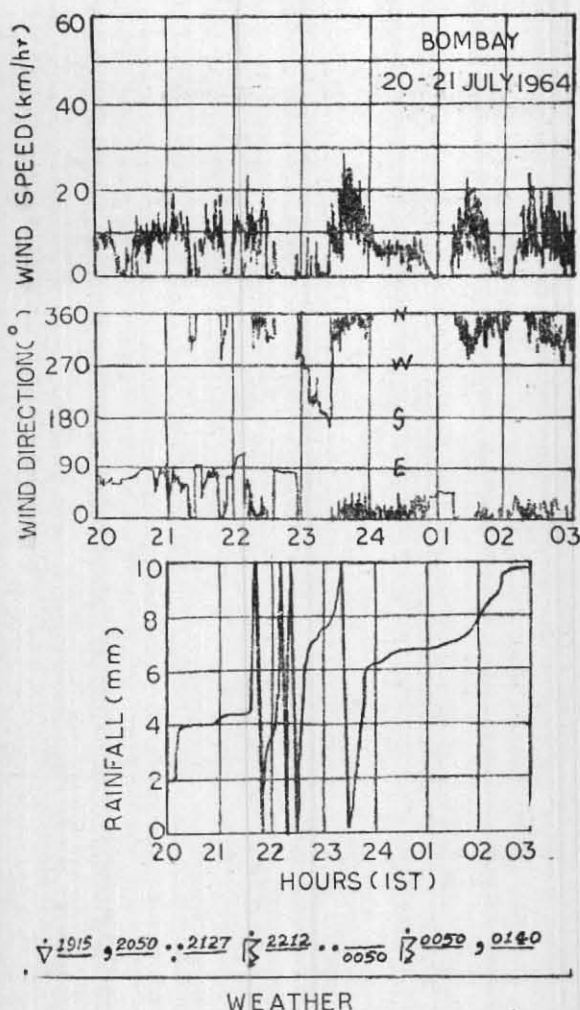


Fig. 5. The autographic charts during a monsoon thunderstorm at Bombay

The thunderstorm is accompanied by heavy showers, surface wind remained light and at times calm conditions prevailed

are shown in Table 2. The data show that the degree of instability is generally much lower in the monsoon season than in other seasons. But it is unable to discriminate between the days of rainsqualls and the days of thunderstorms.

(c) *Mid-tropospheric inversions*—A mid-tropospheric inversion or isothermal layer is sometimes found over Bombay during the monsoon months. This is usually present at or near the level of the wind reversal between the lower westerly current and easterly flow aloft. A typical example of the same is shown in Fig. 7. Some have held that this inversion acts as a cap preventing further growth of convective clouds. The heights of this inversion, whenever present, were tabulated for the above days. The results are shown in Table 3. It can be seen from the table that this inversion is present

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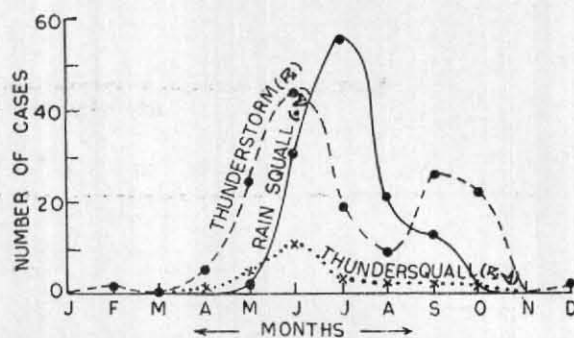


Fig. 6. The number of thunderstorms, rainsqualls and thundersqualls which occurred in different months during the period from 1955 to 1962

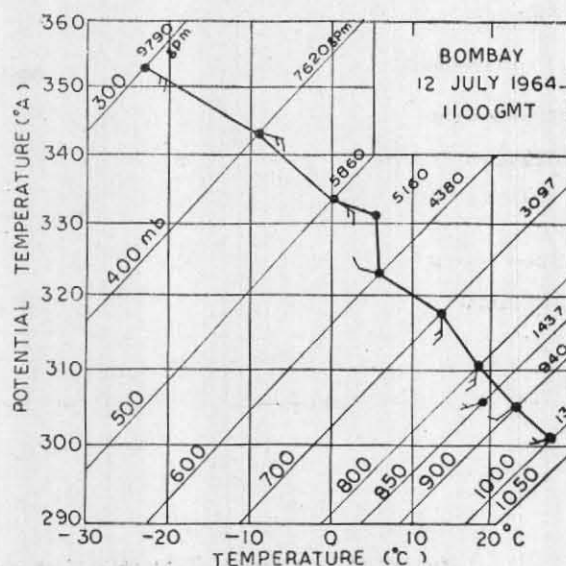


Fig. 7. An example of the mid-tropospheric isothermal layer is shown by the tephigram of Bombay (see text)

on only a small percentage of days of active convection but it is not able to discriminate between rainsquall days and thunderstorm days.

So, from the foregoing, the obvious conclusion that can be arrived at is that on a day of active convection in the monsoon season, whether the cloud tops will extend to sufficiently great heights to become thunderstorms or not is not governed by thermodynamic factors.

#### 4. Environmental Wind Field

Fig. 8 shows the monthly mean upper winds over Bombay. A comparison of Figs. 1 and 8 shows that thunderstorm activity is more in the transition months of May, June, September and October when the upper winds are generally weak at all levels. On the other hand, rainsqualls predominate

TABLE 3

Number of occurrences of thunderstorms and rainsqualls arranged according to height of the inversion/isothermal layer (*I*)  
(data for 1955-1962)

Phenomena	Height of the inversion/isothermal layer, <i>I</i>						No inversion or isothermal layer	Total
	1000-850	850-700	700-600	600-500	500-400	400-300		
May and June								
Thunderstorm	3	3	1	5	1	—	57	70
Rainsquall	—	—	—	—	—	—	15	15
July and August								
Thunderstorm	—	1	1	3	2	—	23	30
Rainsquall	—	8	3	1	1	1	40	54
September and October								
Thunderstorm	—	1	—	—	—	—	46	47
Rainsquall	—	1	—	—	—	—	11	12
Total	3	14	5	9	4	1	192	228

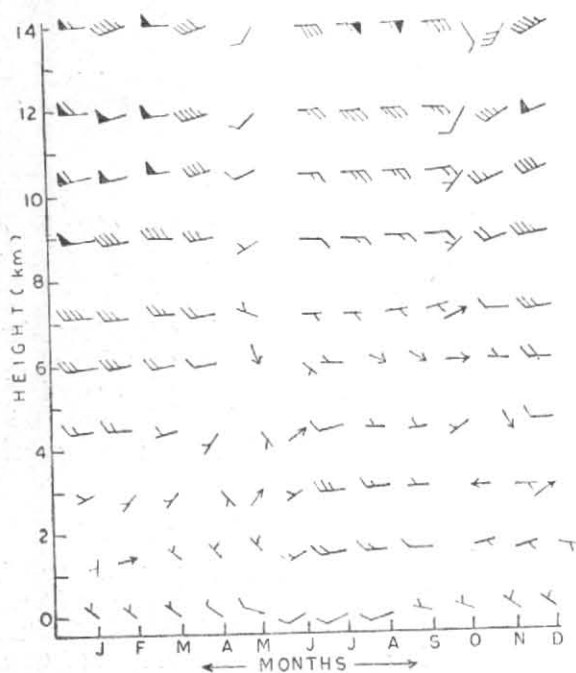


Fig. 8. Mean upper winds over Bombay

Note the mid-tropospheric wind reversal which occurs in the summer months

in those months (July and August) when the winds are strong both in the upper and lower troposphere but contrary to each other. Individual cases also show the same features. In Fig. 8 are shown the upper winds over Bombay on the three days for which the corresponding autographic charts are given in Figs. 2, 4 and 5. During pre-monsoon and post-monsoon days the winds in the lower and upper tropospheric levels are in phase (Fig. 9a). Clouds developing in this type of flow, move westward and generally grow to sufficient heights to become thunderclouds. On strong monsoon days (Fig. 9b) the lower tropospheric flow is westerly and is contrary to the easterly flow aloft. In such situations the clouds do not seem to penetrate much above the westerlies and so rarely become thunderclouds. But their movement is quite fast (Narayanan and Krishnamurthy 1966) and the associated downdrafts cause frequent gusts and squalls. When the lower westerlies are weak and shallow (Fig. 9c) clouds are found to grow to considerable heights and often become thunderclouds. But the mean wind in the convection layer works out to be quite small and as the cloud movement depends on the mean wind (Byers and Braham 1949, Venkataraman and Bhaskara Rao 1966), the downdrafts from such slow moving or stationary storms do not seem to cause any squalls.

Most of the convective activity at Bombay occurs when the upper tropospheric flow is easterly. So apparently the lower tropospheric flow to a large extent determines whether on a particular day thunderclouds develop or not. The mean winds in the layer between 1.5 and 6.0 km a.s.l. was calculated for all the days of the above mentioned phenomena when the flow in the upper troposphere was easterly. The number of thunderstorms, rainsqualls and thundersqualls which occurred under different ranges of the zonal component of the mean wind were worked out. The graphs are shown in Fig. 10. As can be seen from these graphs thunderstorm activity is mainly confined to those days when the mean zonal component is easterly or a light westerly. Secondly, the rainsquall frequency increased with the speed of the westerly component and 90 per cent of the squalls, which occurred when the mean wind and westerly component, were rainsqualls. Thirdly all the squalls, which occurred when the mean wind had an easterly component, were thundersqualls.

#### 5. Relative top shear as a parameter

The present authors (1967) in an earlier study on convective clouds, found that large vertical wind shears limit the growth of convective clouds. To take into consideration the movement of the clouds also, they defined a term called 'Relative top shear' (R. T. S.) as

$$R. T. S. = [V_{(Z_T-1)} - C_v] / \Delta Z$$

where,  $V_{(Z_T-1)}$  is the wind at the level  $(Z_T+1)$ ,  $C_v$  is the mean wind in the layer from level 1 to level  $Z_T$ , taken as the velocity of the cloud and  $\Delta Z$  is the height interval between  $Z_T$  and  $Z_T+1$ . On comparing the values of actual cloud height measured by weather radars with R. T. S. conditions in the vertical it was found that cloud heights generally terminated at or below the level when and where the R. T. S. value reached 10 kt/km. The value of 10 kt/km was termed as limiting R. T. S.

The height of the limiting R. T. S. was calculated for all the instances under study and the frequency of thunderstorms and rainstorms for different ranges of these heights were obtained. The graphs are shown in Fig. 11. The excellent resolution obtained between rainsqualls and thunderstorms can be seen from the graphs. The graphs show at once that it is the environmental wind conditions which seem to predominantly determine to what height the clouds would grow on a day of active convection. The graphs also bring out another significant feature. The graphs for thunderstorms and rainsqualls separate out near the 6-km height of limiting R. T. S. The freezing level for Bombay

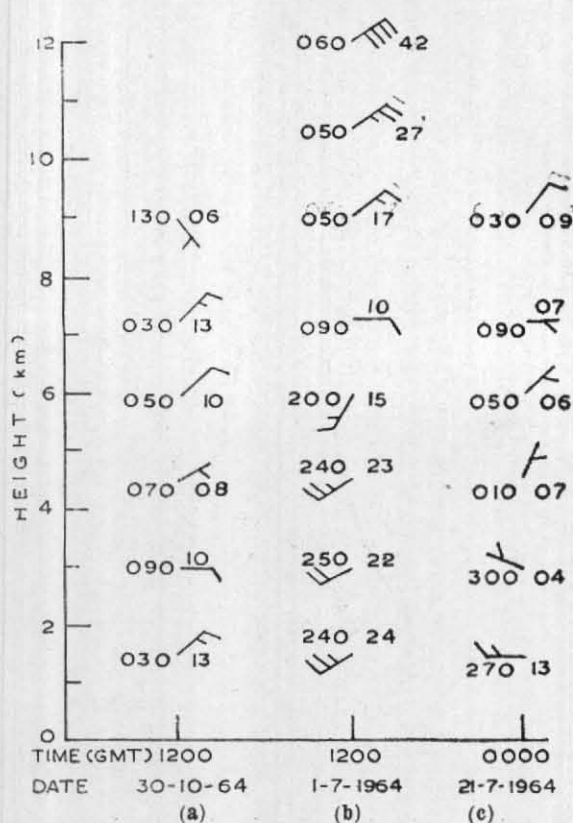


Fig. 9. Upper winds over Bombay on the three days for which the autographic charts have been shown in Figs. 2, 4 and 5

Note the strong shears at about 6 km on 1st July, a day of rainsqualls

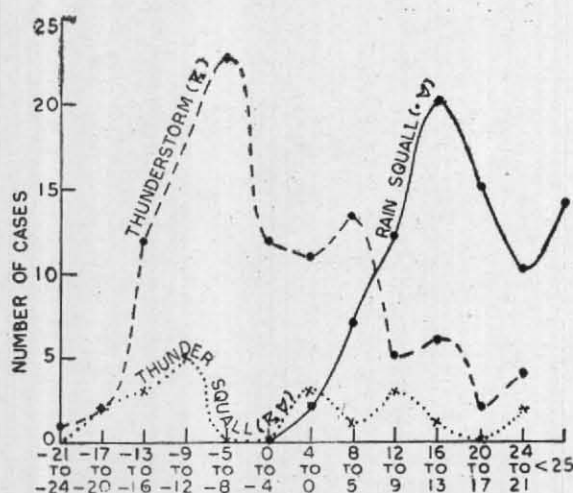


Fig. 10. Number of thunderstorms, rainsqualls and thundersqualls which occurred during the period 1955 to 1962 as a function of westerly component of mean wind in the lower troposphere (abscissa), when the upper troposphere flow is easterly

The number of thunderstorms decreased and the number of rainsqualls increased as the westerly component increased

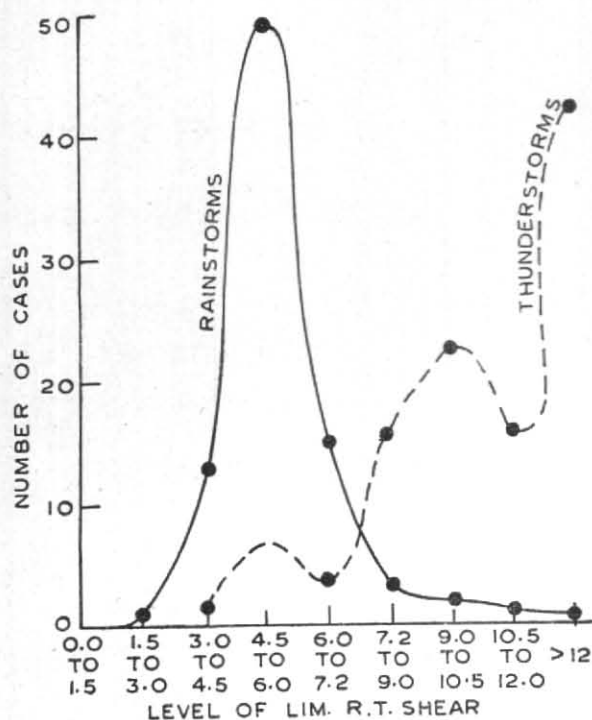


Fig. 11. The number of thunderstorms, rainsqualls & thunder-squalls which occurred during the period 1955 to 1962 as a function of the height of limiting R. T. S. (abscissa)

A sharp fall in rainsqualls and a sharp rise in thunderstorms occur as the height of the limiting R.T.S. increased above the 6-km level

is near 5.5 km on an average in the summer season. If the level of limiting R. T. S. is roughly taken as the height of the cloud tops, the graph shows that significant electrification of clouds does not occur unless the cloud tops reach above the freezing level.

## 6. Conclusions

The features of convective activity at Bombay can be summarised in terms of the environmental wind field as follows —

- (1) On days when lower tropospheric winds are easterly, (*i.e.*, in phase with the upper tropospheric easterlies) clouds tend to develop to great heights and become thunderclouds. They cause easterly squalls at the station. But, as many of them are in a dissipating stage by the time they reach the station, they cause only mild thunderstorm conditions.
- (2) On days, when the lower winds are weak westerlies, clouds grow to great heights and become thunderstorm clouds but their movement is sluggish and they do not cause squalls.
- (3) When the lower tropospheric winds are strong westerlies, the 'relative top shears' attain large values in the transition layer between the lower westerlies and higher easterlies. Hence the cloud tops terminate below the level of the limiting R. T. S. and do not become thunderclouds. But as the mean wind in the convection layer is quite high, clouds move fast and frequent squalls are caused by the drafts.

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## REFERENCES

- |   |      |  |
|---|------|--|
| Bhaskara Rao, N. S. and Dekate, M. V.       | 1967 | <i>Quart. J. R. met. Soc.</i> , <b>93</b> , pp. 363-367.   |
| Bjerknes, J.                                | 1938 | <i>Ibid.</i> , <b>64</b> , pp. 325-330.  |
| Browning, K. A. and Ludlam, F. H.           | 1962 | <i>Ibid.</i> , <b>88</b> , pp. 117-135.  |
| Byers, H. R. and Braham, R. R.              | 1949 | <i>The Thunderstorm</i> , U. S. Govt. Printing Office, Wash., pp. 101-114.   |
| Dekate, M. V. and Bajaj, K. K.              | 1966 | <i>Indian J. Met. Geophys.</i> , <b>17</b> , 2, pp. 217-224.   |
| Ludlam, F. H.                               | 1963 | <i>Met. Monogr. Amer. met. Soc.</i> , <b>5</b> , 27, pp. 1-28.   |
| Malkus, J. S.                               | 1952 | <i>Tellus</i> , <b>2</b> , pp. 71-78.  |
| Malkus, J. S. and Scorer, R. S.             | 1955 | <i>J. Met.</i> , <b>12</b> , pp. 43-57.  |
| Narayanan, V. and Krishnamurthy, G.         | 1966 | <i>Indian J. Met. Geophys.</i> , <b>17</b> , 2, pp. 237-244.   |
| Newton, C. W.                               | 1960 | <i>Cumulus Dynamics</i> , Proc. 1st Conf. on cumulus convective (Anderson Ed.), Oxford, Pergamon Press, pp. 135-144. |
| Normand, Sir Charles                        | 1938 | <i>Quart. J. R. met. Soc.</i> , <b>64</b> , pp. 47-49.   |
| Schmidt, F. H.                              | 1947 | <i>Meded. Verh. K. ned. met. Inst. B.</i> , <b>1</b> , 8, p. 54.   |
| Showalter, A. K.                            | 1953 | <i>Bull. Amer. met. Soc.</i> , <b>34</b> , 6, p. 250.  |
| Stommel, M.                                 | 1947 | <i>J. Met.</i> , <b>4</b> , pp. 91-94.   |
| Venkataraman, K. S. and Bhaskara Rao, N. S. | 1966 | <i>Indian J. Met. Geophys.</i> , <b>17</b> , 4, pp. 529-545.   |