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A forecasting aspect of thundersquall over Calcutta and its parameterisation during pre-monsoon season

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सार - भारत के उत्तरी-पूर्वी क्षेत्र में पूर्व-मानसून ऋतु के दौरान होने वाली झंझाओं के साथ साथ प्रचंड गर्जते तूफानों की घटनायें अत्याधिक संकटपूर्ण मौसम की परिघटना मानी जाती है। इस शोध पत्र में पूर्व मानसून ऋतु के दौरान कलकत्ता (हवाई अड्डा) में गर्जते झंझाओं के पूर्वानुमान का पता लगाने के लिए कुछ प्राचलों का अध्ययन करने का प्रयास किया गया है। इस शोध पत्र में कलकत्ता में गर्जते झंझाओं के दौरान सिनाप्टिक के सहयोग के साथ-साथ उष्मागतिकी घटकों के प्राचलीकरण पर विचार विमर्श किया गया है। रेडार प्रतिध्वनि स्थितियों मध्य सतह पवनों और संवहनी प्राप्य संभाव्य ऊर्जा (सी.ए.पी.ई.) के विषय में पूर्व मानसून ऋतु के दौरान कलकत्ता में गर्जते तूफान सेल की संचरण गति का पता लगाने के लिए पूर्वानुमान के पहलू की जाँच की गई है। कलकत्ता हवाई अड्डें में कुछ घंटों के अंतरालों में होने वाली बहुल गर्जते झंझाओं की घटनाओं पर विचार विमर्श किया गया तथा बेगालेख विश्लेषण, रेडार प्रेक्षणों और सिनाप्टिक स्थितियों के माध्यम से इनकी जाँच की गई है।

ABSTRACT. Severe thunderstorms accompanied by squalls are the most hazardous weather phenomena during pre-monsoon season in north-eastern region of India. An attempt has been made in this paper to study some parameters for forecasting thundersqualls over Calcutta (Airport) during pre-monsoon season. Parameterisation of thermodynamic components alongwith the synoptic support during thundersqualls over Calcutta has been discussed here. A forecasting aspect for propagation speed of thunderstorm cell at Calcutta in pre-monsoon season has been examined with respect to radar-echo positions, mid-level winds and convective available potential energy (CAPE). Occurrences of multiple thundersqualls over Calcutta Airport within a few hours' interval have been discussed and examined through hodograph analysis, radar observations and synoptic situations.

Key words – Thundersquall, Thermodynamic parameter, Radar-echo, Hodograph, CAPE.

1. Introduction

Pre-monsoon thunderstorms are known to be more hazardous than those occurring in other seasons of the year. The severe thunderstorms which occur over Gangetic West Bengal and neighbourhood in this season are often accompanied by squalls and locally known as 'Kal-Baishakhi' or 'Norwester'. The dynamic components of this destructive weather phenomenon like thundersqualls are of complex nature. These systems are intensive atmospheric vortices of small dimensions, associated with strong convective motions. To understand the nature and behaviour of squalls, a systematic study of the meso-scale disturbances alongwith the mechanism for formation of thunderstorm/thundersquall is required by considering both the aspects of synoptic as well as thermodynamics. In the meso-scale convective systems, convective storms are grouped into multi-cells which are spread over much larger area than an individual storm and these convective systems are associated with convergence in the lower troposphere and divergence aloft. Sometimes, this organisation of multi-cells in the meso-scale convective system results in a 'Squall-line'.

Several authors have attempted to explain the nature and behaviour of thundersqualls through synoptic factors and thermodynamic conditions by using surface and upper air data with their full support and justifications. Koteswaram and Srinivasan (1958) have examined the favourable conditions for formation of thunderstorms over Gangetic West Bengal in pre-monsoon season and related them to low level synoptic conditions as well as passage of high level perturbations like Jet-stream / trough of Jets over the area. Bhattacharya and Barma (1981) and

Chaudhury and Rakshik (1970) have analysed the squall over Calcutta and over Gangetic West Bengal respectively with reference to radar-echoes.

A dynamic model to simulate the characteristics of squall-lines as presented by Moncrieff and Miller (1976) and applied by Betts *et al*. (1976) over Venezuela is found to be very effective for predicting the propagation speed of squall-lines using buoyant energy (CAPE) of the thundersquall and the radar-echo positions. David (1998) has discussed a method for measuring vertically integrated buoyant energy distribution in the free convective layer for atmospheric instability, where a measure of convective available potential energy (CAPE) and convective inhibition (CIN) are calculated numerically. Many authors have also attempted to measure various stability indices and the latent instability favourable for the formation of thunderstorms/thundersqualls. Showalter (1953) and George (1960) have explained methods for calculating numerical values of Showalter Index (SI) and K-Index (KI) respectively to determine the stability of the atmospheric state between 850 hPa and 500 hPa for the purpose of forecasting thunderstorms.

Kevin and Gary (1997) in their study of heavy rain events for the Hawaiian situation, have offered a potential forecast guidance where all the stability indices are examined. They have established a relation between rainfall in one hand and the precipitable water in the mid-levels (750 – 450 hPa) and the K-Index on the other hand. The increase in mid-level moisture content and the presence of a synoptic-scale disturbance favour the formation of convective system, resulting in a thunderstorm.

In the present study, an attempt has been made to find out suitable parameters for forecasting thundersqualls that hit Calcutta in pre-monsoon seasons. The propagation speed of the squalls by considering the recorded radar-echo positions (or squall-lines) with time and space, has been co-related with the mid-levels (700–500 hPa) wind and buoyant energy of the atmospheric condition. To examine the instability in the atmosphere, change of equivalent potential temperature with height $\partial\theta_e$ **Error! Bookmark not defined.**/∂z for different layers of the atmosphere for each cases of squall has been calculated. The vertical shear of horizontal wind speed for different layers has also been computed to study the formation of squalls. Different stability indices like SI, KI and the humidity mixing ratios at different levels in the atmosphere have been examined for the squall conditions. Favourableness or unfavourableness of occurrence of thundersqualls for such conditions has also been discussed with the parameterisation of its thermodynamic components. A new non-dimensional parameter of the buoyant energy (CAPE) with reference to the convective inhibition (CIN) of the squall has been defined and examined the feasibility of its existence for the formation of such thundersquall.

2. Data used and processing

2.1. *Thermodynamic components*

Squalls occurred over Calcutta in the pre-monsoon season during 1997 and 1998 have been considered in this study. Data of radio-sonde observations of Dum Dum (Calcutta) for those squall dates are taken and plotted on T–ϕ grams for each of the cases. Further, the vertical shear of horizontal wind speed and the change in equivalent potential temperature with height for different layers of the atmosphere have been calculated by using computer programmes.

2.2. *Radar-echoes data*

The available radar-echo data of Calcutta Airport during 1997 and 1998 pre-monsoon season squalls are utilised here. Hourly radar-echo data are collected for a few hours prior to squalls' occurrence over Calcutta and examined their movement, intensification and nature of growth before those squalls hit the ground. The height of cumulonimbus clouds in their course of formation are also compared with the radar-echo positions and the computed height of the equilibrium levels from T–ϕ grams.

3. Methodology

3.1. *Stability indices of squalls*

Showalter (1953) stability index (SI) for thunderstorm forecasting gives a measure of latent instability between levels 850 hPa and 700 hPa in the atmosphere. For computation of SI, the parcel at 850 hPa is lifted dry adiabatically to saturation and then pseudo-adiabatically to 500 hPa and the lifted 500 hPa temperature is then subtracted from the observed 500 hPa temperature. When SI is positive, it indicates stability and when SI is negative, it indicates instability.

The static stability K–Index (KI) of 850–500 hPa, as considered by George (1960) for evaluating the probability of air-mass type thunderstorm which is given by equation

$$\mathrm{KI} = T_{850} - T_{500} + T_{d\,850} - (T_{700} - T_{d\,700})$$

where, T_{850} and $T_{\mathrm{d}\,850}$ are the dry bulb temperature and dew point temperature at 850 hPa respectively; T_{500} is the dry bulb temperature at 500 hPa and (T_{700}–$T_{d\,700}$) is the dew point depression at 700 hPa.

The relationship between the K-Index and precipitable water in the atmosphere has an important role in the development of convective systems, as examined by Kevin and Gary (1997) which indicates with an increase in mid-level moisture, the value of K-Index becomes higher. The lower value of dew-point depression ($T_{700} - T_{d\,700}$) at 700 hPa suggests that the mid-level moisture content is greater and consequently K-Index is greater.

3.2. *Precipitable water content and humidity mixing ratio*

The precipitable water (R) content in the vertical column of atmosphere is given by equation

$$R = \frac{1}{\rho_w\, g}\int w(P)\,\mathrm{d}P$$

where, ρ_w is the density of liquid water, $w(P)$ is the mixing ratio at the pressure level P and g is the acceleration due to gravity.

The above equation for estimation of precipitable water between two layers P_1 and P_2 may be reduced to

$$R = 0.0005\ (q_{P1} + q_{P2})\ \mathrm{d}P$$

where, q_{P1} and q_{P2} are the specific humidities at pressure levels P_1 and P_2 respectively ; dP is the difference of pressure between two layers; R is the precipitable water in cm.

3.3. *Buoyant energy and its kinetic parameter indices for squalls*

The latent instability of squall is understood by measures of cumulative buoyant energy in the free convective layer. Bluestein and Jain (1985) have suggested a method to measure of the vertically integrated buoyant energy for formation of meso-scale squall lines in Oklahoma during the spring season. The vertically integrated buoyant energy gives the convective available potential energy (CAPE) and is given by

$$\mathrm{CAPE} = g\int_{Z_1}^{Z_2}\left(\frac{\theta_p - \theta_{ev}}{\theta_{ev}}\right)\mathrm{d}z$$

where, θ_p and θ_{ev} are the potential temperature of air parcel and the environment respectively; 'g' is the acceleration due to gravity; the integration is carried over for the buoyant energy between levels Z_1 (Z_1=Z_{LFC}) and Z_2.

The other important energy required is to lift a parcel through a layer that is warmer than the parcel and allow the parcel to reach the free convective level (LFC) from the surface. This is a measure of convective inhibition (CIN) which is defined similar to CAPE but with negative energy barrier and is required to overcome by the parcel to ascend for forming convective cloud. The smaller value of this energy is favourable for formation of convective cloud, fulfilling with synoptic as well as thermodynamic conditions.

Thus, the CIN is given by the equation

$$\mathrm{CIN} = -g\int_{Z_{SFC}}^{Z_{LFC}}\left(\frac{\theta_p - \theta_{ev}}{\theta_{ev}}\right)\mathrm{d}z$$

where, the integration is carried out from the surface to the level of free convection (LFC).

A new non-dimensional kinetic parameter (L) is defined relative to thermodynamic energies CAPE and CIN to understand the squall strength and is given by

$$L = \frac{(\mathrm{CAPE} - \mathrm{CIN})}{\mathrm{CIN}}$$

When the value of CAPE is large and that of CIN is small, the parameter L will be large. Atmospheric state is more favourable for formation of thunderstorm/ thundersquall when the value of L is greater and sufficient moisture is available upto a considerable depth in the atmosphere.

3.4. *Propagation speed of the squall*

The propagation speed of a thundersquall relative to the mid-level wind is a function of the convective available potential energy (CAPE). Moncrieff and Miller (1976) have suggested a relation between the propagation speed C of a thundersquall/squall-line, the mid-level wind and the CAPE which is given by

$$C = r\sqrt{\mathrm{CAPE}}$$

where, $C = C_o - U$; C_o is the speed of squall relative to the ground; U is the mid-level wind vector difference between 700 hPa and 500 hPa levels; 'r' is a constant to be determined by regression method.

TABLE 1

Thermodynamic parameters during thundersqualls in pre-monsoon season at Calcutta (Dum Dum)

Dates of occurrence	CAPE	CIN	Non-dimensional parameter (*L*)	Maximum altitude CB (km)	Equilibrium level height (km)	Jet level hPa/kmph
30 March 1997	1417.4	300.1	3.7	--	--	250 / 60
02 April 1997	3288.7	235.0	13.0	10	10.5	300 / 70
10 April 1997	2229.7	302.3	6.4	13	12.0	300 / 60
13 April 1997	4809.7	93.3	50.6	14	--	250 / 60
14 April 1997	4067.8	163.4	23.9	12	--	--
30 April 1997	4442.4	66.8	65.5	--	--	250 / 75
08 May 1997	2561.1	458.2	4.6	--	--	400 / 55
24 May 1997	3639.6	105.7	33.4	14	--	--
26 May 1997	1694.0	262.1	5.5	12	12.5	300 / 55
28 May 1997	5354.3	80.6	65.4	--	--	--
29 May 1997	2328.0	218.1	9.7	14	--	--
10 June 1997	2745.8	153.5	16.9	14	--	--
23 March 1998	733.8	331.0	1.2	10	10.5	500 / 80
23 March 1998	3036.8	414.1	6.3	14	11.5	500 / 60
24 March 1998	1220.7	137.8	7.9	14	11.0	--
29 March 1998	2356.2	325.0	6.3	15	11.5	250 / 75
09 April 1998	5192.6	82.0	62.3	16	--	400 / 70
23 April 1998	5284.8	129.5	39.8	16	--	--
26 April 1998	4790.4	105.7	44.3	15	--	300 / 60
28 April 1998	3016.2	422.2	6.1	16	--	200 / 75
02 May 1998	4212.1	64.0	64.8	15	above 12	--
05 May 1998	3659.8	46.9	77.1	12	above 12	--
07 May 1998	5066.0	140.7	35.0	15	above 12	--
25 May 1998	6320.2	70.8	88.3	13	above 12	--
06 June 1998	2064.8	379.9	4.4	14	--	--

The propagation speed C_o of thundersquall can be determined from the radar-echoes position in respect of space and time during its movement.

3.5. *Vertical wind shear of horizontal wind speed*

The vertical wind shear of the horizontal wind speed generates kinetic energy at the lower levels of the atmosphere resulting in a vertical motion. When the wind shear in the lower levels are large, a favourable condition for the formation of convective cloud occur with moisture convergence. By considering the condition of wind shear in three different layers of the atmosphere , namely, lower layer (surface to 850 hPa), middle layer (850 hPa to 500 hPa) and upper layer (above 500 hPa), multiple squalls for a few hours gap have been examined through hodograph analysis.

4. Results and discussion

4.1. *Instability condition for formation of thundersqualls*

The wind close to the ground is decelerated due to frictional effect of the surface which leads to development of turbulent eddies. These are constituted in vertical motions resulting in a wind shear which together with instability condition in the atmosphere helps in the development of convective systems. Such systems when supplied by sufficient moisture develop convective cloud cells. The potential energy available for convective vertical motion is the total amount of integrated value of CAPE between the environmental curve and the saturation profile. Successive convective cells are grouped within a system to form multi-cell storms which produce precipitation over large areas. The system is associated with convergence in the lower troposphere and divergence aloft. Moreover, with the conditions of strong instability and strong wind shear, severe thunderstorms may develop with a persistent updraft and downdraft (Browning and Gurney, 1999).

The integrated CAPE values calculated from T-ϕ grams of Calcutta Airport before occurrences of squalls are given in Table 1. It is seen from Table 1 that on most cases the observed top heights of cumulonimbus (CB) from radar echoes are generally close to the thermodynamic equilibrium heights under latent instability conditions, but in some cases the top height is greater than the computed height. The gaining of the height of CBs are due to 'over-shooting' for acquiring inertia from kinetic energy available during instability

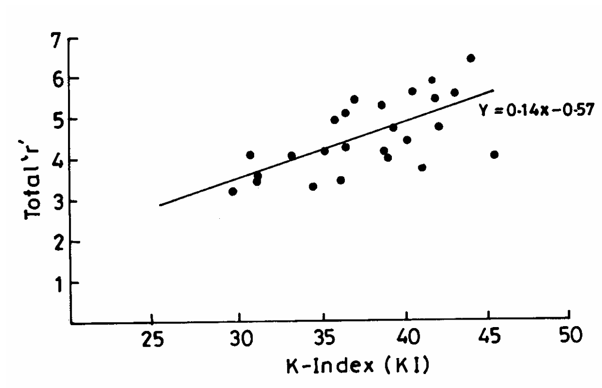

Fig. 1. Scatter diagram for total precipitable water content r and K-Index (KI) for different squalls at Calcutta Airport

conditions as explained by Mukherjee (1983). The existence of thermodynamic parameter L for each squall condition and the synoptic conditions like 'jet-stream' (Koteswaram and Srinivasan, 1958) passing over the station have been examined and shown in Table 1. It is observed from Table 1 that 'jet-stream' has come down to 500 hPa level on 23 March 1998 when multiple thundersqualls occurred within a few hours interval. It is seen that greater the value of parameter L alongwith low values of CIN, *i.e.*, small negative area, greater will be the possibility of maximum altitude of CB cell. With the passage of 'jet-stream' over Calcutta at lower levels on some occasions during pre-monsoon season, convective activities are more likely to occur due to perturbation, resulting in the formation of CB clouds which produces a few squalls in association with thunderstorms.

4.2. *Stability/instability indices of thundersquall occurrences*

The latent atmospheric instability condition for the entire troposphere is understood by measure of static stability / instability indices like Showalter Index (SI) and K-Index (KI), based on temperature lapse rate between some specified levels (mid-levels) in the atmosphere. The negative value of SI indicates instability condition of the atmosphere. The greater the negative value of SI, severity of thunderstorm is more probable (Showalter, 1953), but it is not necessary in all cases. Indices KI measure for air-mass type CB-formation in large scale convergence system. The values of indices SI and KI on thundersquall days at Calcutta Airport are given in Table 2. The correlation between KI and the precipitable water content in the atmosphere during thundersquall occurrences in Calcutta is positive (0.72) and is shown in Fig. 1. Thus, the greater the values of KI, the greater will be the

TABLE 2

Static stability indices SI, KI and the total precipitable water content r (cm) for different squall occasions at Calcutta Airport

S. No. of Occasions	SI	KI	Precipitable water content 'r'
		Year 1997	
1	- 8.0	40.1	4.40
2	- 7.7	38.9	4.01
3	-10.0	45.5	4.01
4	- 6.8	38.8	4.12
5	- 5.0	35.0	4.18
6	- 0.3	31.1	3.52
7	- 2.5	30.7	4.07
8	- 2.7	31.1	3.43
9	- 7.9	38.6	5.27
10	- 7.1	39.3	4.73
11	- 8.7	41.9	5.40
12	- 5.1	40.5	5.61
13	- 5.6	37.0	5.41
		Year 1998	
1	- 1.3	33.2	4.03
2	- 0.2	29.7	3.19
3	- 1.3	34.4	3.29
4	- 1.5	25.5	2.88
5	- 3.0	36.1	3.46
6	- 0.4	36.4	4.23
7	- 7.3	35.8	4.91
8	- 5.1	36.4	5.08
9	- 7.8	43.1	5.54
10	- 7.6	41.7	5.87
11	- 2.9	35.1	4.15
12	- 7.3	44.1	6.41
13	- 6.2	42.1	4.70

possibility of precipitable water content (r) in the atmosphere and is given by a regression line as below

$$Y = 0.14\,X - 0.57 \qquad \text{where } X = \text{KI, and } Y = r$$

The atmospheric condition before thundersqualls occur over Calcutta Airport shows that the equivalent potential temperature (θ_e) falls with height from the surface upto 4–5 km and it rises further aloft. The minimum values of θ_e profiles indicate presence of warm and moist air–masses below and cold and dry air-masses aloft. Thus **Error! Bookmark not defined.Error! Bookmark not defined.** $\partial\theta_e$**Error! Bookmark not defined.**$/\partial z < 0$ in lower tropospheric layers implies that the atmosphere is convectively unstable.

4.3. *Pressure change and rain-spell during thundersqualls*

It is seen from barographic charts during thundersqualls at Calcutta Airport that on most occasions pressure changes (hPa) are positive (rises), but in a very few cases, the pressure changes are negative (falls) first and then become positive (rises). The rise in pressure during thundersquall may be due to cold air coming down from the CB cloud associated with the storm downdraft. These are given in Table 3. A scatter diagram between the

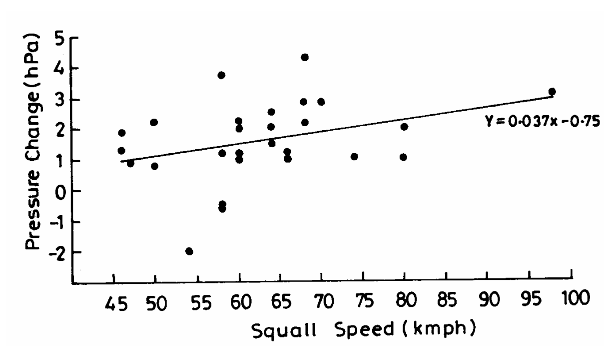

Fig. 2. Scatter diagram of squall speed and pressure change during squall hit at Calcutta Airport in pre-monsoon season

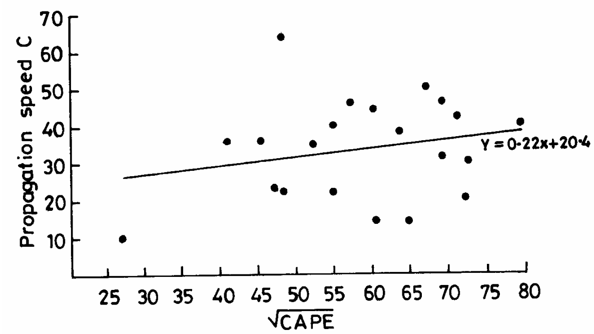

Fig. 3. Regression between propagation speed of thundersquall and CAPE for different squalls at Calcutta Airport

TABLE 3

Pressure changes (in hPa) and rain-spell during squalls in pre-monsoon season at Calcutta (Dum Dum)

Date	Time of squall (IST)	Squall direction	Squall speed (kmph)	Pressure change during squall (hPa)	Rainfall amount (mm) during thundersquall	Duration of rain-spell (IST)
30 March 1997	2227	W	60	+ 2.0	13.0	2227-2345
02 April 1997	1826	NW	58	+ 3.7	8.9	1850-2030
10 April 1997	1912	NW	68	+ 4.2	18.5	1900-2000
13 April 1997	1841	SW	68	+ 2.8	5.2	1845-2000
14 April 1997	2132	NE	58	+ 1.2	0.1	2145-2200
30 April 1997	0647	NW	50	+ 2.2	1.3	0645-0700
08 May 1997	1912	W	68	+ 2.2	10.0	1915-2135
24 May 1997	1814	SW	98	+ 3.0	23.7	1745-1815
25 May 1997	1952	W	64	+ 2.0	--	--
26 May 1997	1517	N	47	+ 0.9	0.7	1519-1523
26 May 1997	1815	W	46	+ 1.3	--	--
28 May 1997	1902	N	60	+ 2.2	--	--
29 May 1997	1509	NW	60	+ 1.0	16.8	1500-1545
10 June 1997	1735	W	46	+ 1.9	17.3	1745-1815
23 March 1998	0458	NW	66	+ 1.2	--	--
23 March 1998	0915	NW	70	+ 2.8	2.2	0915-0940
23 March 1998	2217	NW	60	+ 1.2	23.2	2220-2245
23 March 1998	2358	NW	80	+ 1.0	30.6	2345-2420
24 March 1998	0553	NW	80	+ 2.0	28.4	0550-0630
29 March 1998	1445	NW	54	- 2.0	--	--
29 March 1998	2002	NW	56	+ 1.3	24.5	2002-2100
09 April 1998	1840	N	66	+ 1.7	0.1	1845-1900
10 April 1998	0120	N	64	+ 2.5	10.3	0110-0140
23 April 1998	1800	N	58	- 0.5	1.0	1740-1810
26 April 1998	2051	W	74	+ 1.0	--	--
28 April 1998	1909	SW	64	+ 1.5	0.3	1930-2020
02 May 1998	0058	NE	58	- 0.6	--	--
05 May 1998	0955	NW	50	+ 0.8	--	--
07 May 1998	2112	SW	64	+ 2.0	3.8	2115-2135
25 May 1998	0545	SW	58	+ 1.2	6.4	0525-0550
06 June 1998	1910	SW	66	+ 1.0	--	--

speed of squalls those recorded at Calcutta Airport and the associated pressure changes (Fig. 2) indicates that there is a positive correlation (0.33) and the corresponding regression line is given by

$$Y = 0.037\,X - 0.75$$

where

X = squall speed and Y = pressure change

Rainfall amount (mm) alongwith the duration of rain-spell during thundersqualls at Calcutta Airport

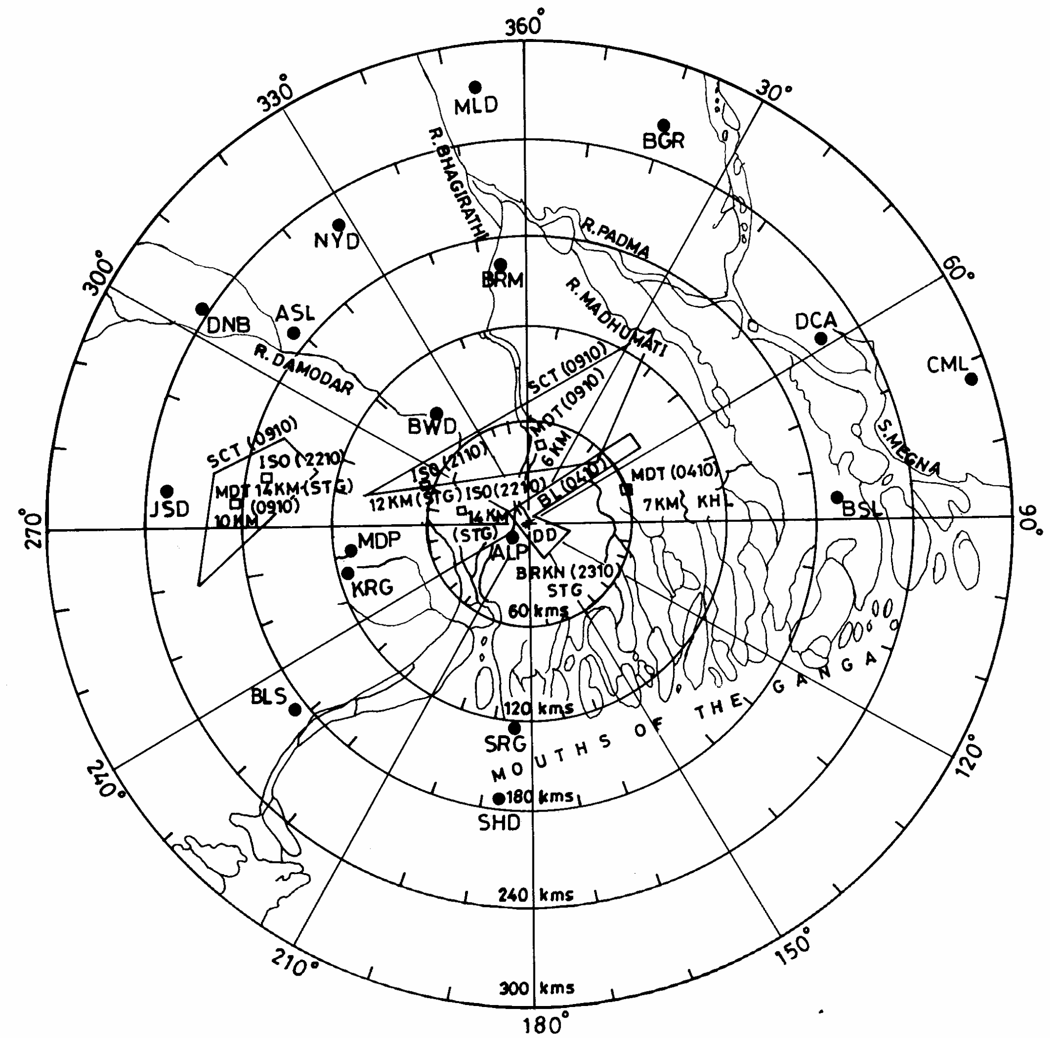

Fig. 4. Radar-echo positions of multiple thundersqualls occurred at Calcutta Airport on 23-24 March 1998

obtained from self-recording rain-gauge charts are also given in Table 3.

4.4. *Movement of thunderstorm and its collective effect*

The large-scale convergence system has an important role on vertical transport of moisture. The shear field can influence the depth of the convective layer and also the structure of CB-cells. A series of multi-cells are formed due to the transfer of momentum by decaying CB-cells in the large scale convergence system of the atmosphere. Among them, any cell having sufficient strength may give rise to thundersquall. Their movements and intensities are required to be observed carefully (hourly/half-hourly) through radar-echo positions. Moreover, conditions for formation of severe thunderstorms/thundersqualls are favoured by

(*i*) abundant supply of moisture at lower levels,

(*ii*) strong convective instability condition,

(*iii*) dynamic lifting mechanism and

(*iv*) strong wind shear with height upto a considerable depth.

Thunderstorm cell may extend through a deep layer of atmosphere. Wind flow in some levels is responsible

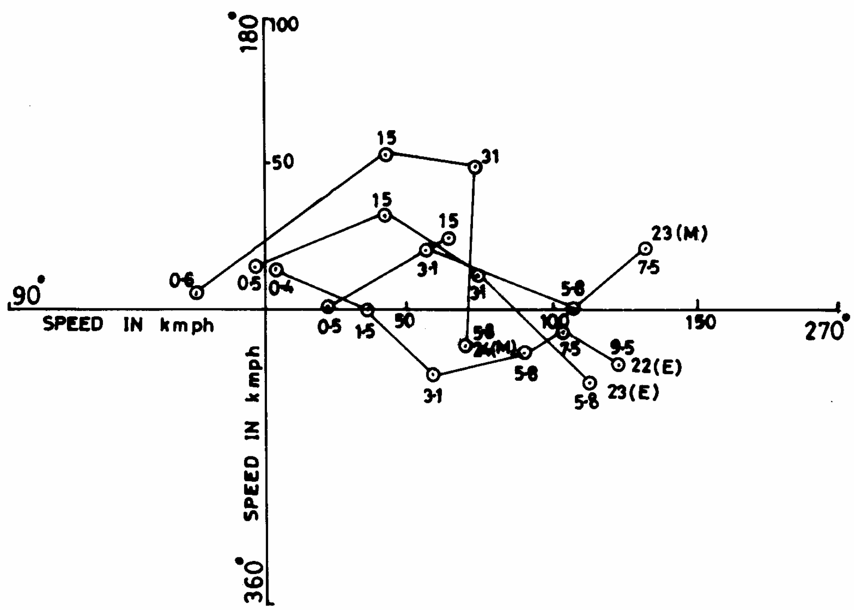

Fig. 5. Hodographs of multiple thundersqualls occurred at Calcutta Airport during 22 (evening) to 24 (morning) March 1998

for the movement of thunderstorms, sometimes move in tilting way, called the 'steering levels'. A series of hourly radar-echo positions of thunderstorm movement for different squall occasions at Calcutta Airport during pre-monsoon season are examined. The propagation speed C of thunderstorm (CB-cell) movement relative to mid-level wind U (horizontal wind vector difference between levels 700 hPa and 500 hPa) is found out, $C = C_o - U$ (where C_o is the observed speed relative to the earth). These propagation speeds C (kmph) for each occasion of thundersqualls are tabulated with the corresponding values of $\sqrt{\text{CAPE}}$ (Moncrieff and Miller, 1976), as shown in Table 4 and plotted as shown in Fig. 3. The graph shows a positive correlation (0.21) and the regression line is given by

$$Y = 0.22\,X + 20.4$$

where

$$X = \sqrt{\text{CAPE}} \quad \text{and} \quad Y = C$$

Thus, the prediction of propagation speed of thunderstorm during thundersquall can be estimated by CAPE value and mid-level wind.

TABLE 4

Propagation speed of squall in respect of mid level wind and CAPE value during occurrence of thundersqualls at Calcutta Airport

S. No. of observations	$\sqrt{\text{CAPE}}$	C_O (kmph)	U (kmph)	$C = C_O - U$ (kmph)
		Year 1997		
1	57.35	60	14	46
2	47.22	49	26	23
3	69.35	50	4	46
4	63.78	40	2	38
5	67.37	60	10	50
6	60.33	68	24	44
7	41.16	40	4	36
8	48.25	78	14	64
9	52.40	47	12	35
		Year 1998		
1	27.09	58	48	10
2	55.11	60	20	40
3	48.54	70	48	22
4	72.15	70	50	20
5	72.70	70	40	30
6	69.21	55	24	31
7	54.92	58	36	22
8	64.90	60	46	14
9	60.50	42	28	14
10	71.17	76	34	42
11	79.50	62	22	40
12	45.44	42	6	36

4.5. *Multiple thundersqualls on 23-24 March 1998*

It is observed that five thundersqualls occurred at Calcutta Airport between 23/0430 and 24/0600 IST when 'jet-stream' came down to lower level (500 hPa) over Calcutta, though the thermodynamic parameters L and CAPE were small (Table 1). It is seen from a sequence of available radar-echo positions (Fig. 4) that a good number of CB-cells were formed on 23 with sufficient strength to produce a series of thundersqualls. Moreover, on examining the T-ϕ gram data from 22 evening to 24 morning, relative humidity values for 1000 hPa, 850 hPa and 700 hPa (lower levels) showed an increasing tendency, suggesting gradual moisture incursion in lower levels during the period.

Following Saucier (1959), the variation of wind with height from 22 (afternoon) to 24 (morning) is analysed by hodograph diagram (Fig. 5). During occurrence of multiple squalls at Calcutta Airport between 23/0458 hr IST and 24/0553 hr IST (Table 3), it is observed from the hodograph that wind shear of moderate to large value occurred in layers (0.4-1.5 km) and (3.1-5.8 km) and low to moderate value in layers (1.5-3.1 km) and beyond 5.8 km during squalls' period, while low to moderate wind shear occurred throughout on 22 afternoon, before the occurrence of thundersquall. Thus, it may be stated that low to moderate wind shear in the layer (1.5-3.1 km), but moderate to large wind shears in layers below and above the layer (1.5-3.1 km) are favourable for the occurrence of thundersqualls.

5. Concluding remarks

The prediction of occurrence of thundersqualls is not an easy task by synoptic chart analysis alone. Sometimes, it is observed that synoptic conditions are more favourable for the formation of sporadic thundersquall activity, but unfortunately the observed station does not experience even thunderstorm. All the CB-cells formed, may dissipate in the mid-atmosphere due to unfavourable condition in the atmosphere. Hence, both synoptic as well as thermodynamic conditions of the atmosphere are required to be studied.

The following salient features are revealed during the study of the thundersquall over Calcutta in pre-monsoon season.

(*i*) On some occasions, CB-top heights obtained from radar-echo positions are greater than computed heights from thermodynamic equilibrium level (Table 1) which are due to 'over-shooting' for gaining inertia from the available kinetic energy.

(*ii*) On most occasions, atmospheric pressure rises during thundersqualls and its trend with squall speed is positive.

(*iii*) Static instability KI indices are positively correlated with the precipitable water content in the atmosphere during thundersquall occurrences which indicates higher moisture content with higher values of KI.

(*iv*) Propagation speed C of CB-cells during thundersquall at Calcutta Airport can be predicted by the graph (Fig. 3) and as discussed in 4.4 after computing CAPE value and mid-level wind.

(*v*) Five number of thundersqualls hit Calcutta Airport within a few hours' interval on 23–24 March 1998, though the thermodynamic parameter L and CAPE values were small, moderate to large wind shear in the layer 3.1-5.8 km was observed. Hence, occurrences of such multiple squalls may be due to passage of 'jet-stream' at lower levels over Calcutta. However, more cases of multiple squalls are to be analysed for a better understanding of such events.

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References

Betts, A. K., Grover, R.W. and Moncrieff, M.W., 1976, "Structure and motion of tropical squall-lines over Venezuela", *Quart. J. Roy. Met. Soc*., **102**, 395-404.

Bhattacharya, P.K. and Barma, C.M., 1981, "Study of pre-monsoon squalls from 1975 to 1979 over Dum Dum with reference to radar echoes", *Mausam*, **32**, 1, 97-100.

Bluestein, H.B. and Jain, M.H., 1985, "Formation of mesoscale lines of precipitation: Severe squall lines in Oklahoma during the spring", *J. Atmospheric Sci*., **42**, 16, 1711-1732.

Browning, K. A. and Gurney, R. J., 1999, "Global Energy and Water cycles : Atmospheric processes and their large-scale effects", Cambridge Univ. Press, 109-123.

Chaudhury, A. K. and Rakshit, D.K., 1970, "A radar study of pre-monsoon squall lines over Gangetic West Bengal", *Indian J. Met. & Geophy*., **21**, 459- 462.

David, O. B., 1998, "Assessing the vertical distribution of convective available potential energy", Weather and Forecasting, *Am. Met. Soc*., **13**, p870.

George, J. J., 1960, "Weather forecasting for Aeronautics", Academic Press, p673.

Kevin, K. and Gary, M. B., 1997, "Heavy rain events over the south facing slopes of Hawaii, attendant conditions", Weather and Forecasting, *Am. Met. Soc*., **12**, 2, 347-367.

Koteswaram, P. and Srinivasan, V., 1958, "Thunderstorms over Gangetic West Bengal in the pre-monsoon season and the synoptic factors favourable for their formation", *Indian J. Met. & Geophy*., **9**, 4, 301-312.

Moncrieff, M. W. and Miller, M. J., 1976, "The dynamics and simulation of tropical cumulonimbus and squall lines", *Quart. J. Roy. Met. Soc*., **102**, 373-394.

Mukherjee, A. K., 1983, "Cloud dynamics in local severe storms", *Vayu Mandal*, 1&2, 14-21.

Saucier, W. J., 1959, "Principles of Meteorological Analysis", University of Chicago Press, Illinois, USA, p27, 254

Showalter, A. K., 1953, "A stability index for thunderstorm forecasting", *Bull. Am. Met. Soc*., **34**, 250-252.