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Development of nowcasting technique and evaluation of convective indices for thunderstorm prediction in Gangetic West Bengal (India) using Doppler Weather Radar and upper air data

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सार – गर्ज के साथ तूफान और औलावृष्टि अल्प अवधि प्रचंड मौसम की परिघटना के नाम से जानी जाती है जो कभी–कभी भारत के विशेष कर पश्चिमी बंगाल के गांगेय क्षेत्र में प्राकृतिक आपदा का रूप ले लेती है। इस क्षेत्र में मानसून–पूर्व अवधि में कपासी स्तरी मेघ की विस्तृत उर्ध्वाधर सीमा, अति उच्च परावर्तकता, कभी कभी 100 कि. मी./प्रति घंटा से अधिक चंडवाती पवन गति और भारी वर्षा होना इन गर्ज वाले तूफानों के प्रमुख लक्षण है। वर्ष 2005 की मानसून पूर्व ऋतु (मार्च–मई) के दौरान डॉप्लर मौसम रेडार और उपरितन वायु के आँकडों का उपयोग करते हुए कोलकाता के आस पास (22.5 उ., 88.5 पू.) आए 70 गर्ज वाले तूफानों का अध्ययन किया गया। इसके लिए मानक संवहनी सूचनाओं जैसी सी. ए. पी. ई., सी. आई. एन. ई., एल. आई., बी. आर. एन. और वी. जी. पी. का आकलन किया गया और इनका सांख्यिकीय रूप से विश्लेषण किया गया। चूँकि इस क्षेत्र में गर्ज वाले तूफानों का पूर्वानुमान लगाने के लिए संवहनी सूचनाओं की कोई निश्चित प्रभाव सीमा उपलब्ध नही थी अतः वर्ष 2005 के दौरान गर्ज वाले तूफानों का विशलेषण करने के पश्चात् पश्चिमी बंगाल के गांगेय क्षेत्र में गर्ज वाले तूफानों की संभावित घटनाओं के लिए इन सूचनाओं की प्रभाव सीमा का पता लगाने का प्रयास किया गया है। इन संवहनी सूचनाओं की वेधता का पता लगाने की लिए कोलकाता के डॉप्लर मौसम रेडार द्वारा अभिलेखित वर्ष 2006–2007 के गर्ज वाले तूफानों की 34 घटनाओं की जाँच की गई। इस अध्ययन से यह पता चला है कि मात्र डाप्लर रेडार उत्पादों का उपयोग करते हुए सही परिशुद्धता के साथ कम से कम 2–3 घंटे पहले गर्ज वाले तूफानों का तात्कालिक पूर्वानुमान लगाया जा सकता है। तथापि डी. डब्ल्यू. आर. आँकड़ों के अलावा यदि संवहनी सूचनाओं का भी विश्लेषण किया जाए और इनका उपयोग किया जाए तो तात्कालिक पूर्वानुमान की समय अवधि में सुधार लाया जा सकता है। इस शोध पत्र में कम से कम 3–4 घंटे पहले गर्ज वाले तूफानों के बेहतर पूर्वानुमान के शोधकर्ताओं द्वारा एक सरल तकनीक सुझाई गई है।

ABSTRACT . Thunderstorm and hailstorm are well known short term severe weather phenomena which sometimes turn in to natural hazard especially in Gangetic West Bengal region of India. Large vertical extent of the cumulonimbus cloud, very high reflectivity, squally wind speed sometimes exceeding 100 km/h and heavy rainfall are the main features of these thunderstorms during pre-monsoon period in this region. A study of 70 thunderstorms has been carried out during the pre-monsoon season (March-May) of the year 2005 around Kolkata (22.5° N, 88.5° E) using Doppler Weather Radar and Upper air data. Standard convective indices like CAPE, CINE, LI, BRN and VGP have been evaluated and analyzed statistically. As no definite thresholds of the convective indices are available for thunderstorm prediction in this region, an attempt has been made to find threshold of these indices for possible occurrences of thunderstorms in Gangetic West Bengal region after the analysis of the thunderstorms during year 2005. The validity of these convective indices has been checked with 34 occurrences of thunderstorms during 2006-2007 recorded by Doppler Weather Radar Kolkata. The study reveals that nowcasting of thunderstorms may be done at least 2-3 hrs in advance with a fair degree of accuracy using Doppler radar products only. However, the lead time of nowcasting may be further improved if the convective indices are also analyzed and used in addition to the DWR data. A simple technique has been suggested by the authors for better prediction of thunderstorms at least three to four hours in advance.

Key words - Doppler Weather radar (DWR), Gangetic West Bengal (GWB), Convective Available potential Energy (CAPE), Convective Inhibition Energy (CINE), Lifted Index (LI), Bulk Richardson Number (BRN), Vorticity Generating Parameter (VGP).

1. Introduction

Thunderstorm is a meso-scale system of space scale ranging from a few kilometers to a few hundreds of kilometers and time scale of less than an hour to several hours. A severe thunderstorm includes some of the attributes among heavy rain shower, lightning, thunder, hail storm, dust-storm, surface wind squall, down-burst and tornado. During the pre-monsoon season of March, April and May, Gangetic West Bengal (GWB) and surrounding areas get severe thunderstorms called "Norwester" also termed locally as "Kalbaisakhi". Typical features of these Norwesters are squally wind with speed exceeding 100 km/h, heavy rainfall at the rate more than 100 mm/h and sometimes accompanied with hailstorm of hail size more than 30 mm in diameter. It is well documented that many people die every year due to lightning strike, damaging winds flash flood arising due to intense rainfall associated to the norwesters. De and Sen (1961), De (1963), Mukherjee *et al*., (1972) and Narayanan and Krishnamurthy (1966) and many other authors have reported the results of their studies of these thunderstorms, particularly during the pre-monsoon season. These studies indicated that a large no of severe thunderstorms move towards Calcutta (now renamed as Kolkata) from NW direction during pre-monsoon season every year. The details of the damage caused by the thunderstorms have also been recorded in these studies. Alvi *et al*., (1966), Raman and Raghvan (1961), Rao *et al*., (1971), Koteshwaram and Srinivasan (1958) and Krishna Rao (1966) have studied the role of conditional Instability (CAPE) in the outbreak of severe thunderstorms. These studies showed that the convective indices play a key role in the prediction of instability and genesis of thunderstorms. Earlier radar observations had played a vital role in understanding of severe storms like time taken to develop and dissipate and its propagation, particularly about Kalbaisakhi qualitatively. As these radars were not digitized, quantitative information on rainfall associated with thunderstorm was not available.

1.1. *Role of Doppler weather radar in thunderstorm studies*

The development of Doppler Weather Radar (DWR) has provided a very good quantitative analysis of severe weather phenomena along with several derived products useful for research purpose. The research field programs (Staff, 1979, Doviak *et al*., 1979, Wilson *et al*., 1980) showed that significant nowcasting information can be obtained from Single Doppler radar. This has been accepted worldwide by the meteorological community that DWR is an indispensable tool for the study of severe weather phenomena like thunderstorm, hailstorm, tornado, cyclone (hurricane) etc. Presently the identification of Tornadoes, gust fronts, downbursts and fronts can be easily accomplished by the forecasters monitoring and interpreting the DWR products. It is one of the most useful observational tools for the detection of thunderstorm cell, to monitor their development and to predict their movement. Three base products available from DWR are :

(*i*) *Radar Reflectivity (Z)* : The amplitude of the radar returned echoes is directly proportional to the sixth power of the rain drop diameter and therefore this parameter is mainly used for the quantitative estimation of precipitation contents, liquid water content, rainfall rate associated with a thunderstorm, vertical and horizontal developments of the cloud and to study the three dimensional structure of a thunderstorm cell.

(*ii*) *Radial Velocity (V)* : Using Doppler principle for electromagnetic waves, the radial component of the velocity of winds may be estimated by this parameter. Derived products from radial velocity data provide information for the direction of movement of the system, horizontal components of the wind velocity and wind shear. It has been well documented by Doviak *et al*., (1979) and Wilson and Wilk (1981) that the radial wind information obtained from a single DWR can be used to derive and estimate the horizontal wind, wind shear and other products useful for the study of severe weather phenomena.

(*iii*) *Spectrum width (W)* : The spectrum of variability of radial velocity of the individual drops with respect to the mean radial velocity of the system is called spectrum width. It is an indicator of turbulences associated with the winds and thus turbulent environment.

Many products have been derived from these basic data using standard algorithms approved by the meteorological scientists. In this paper, capabilities of DWR have been analyzed to develop a nowcasting technique for the occurrence and movement of thunderstorms in the Gangetic West Bengal region. A statistical study of 70 thunderstorms which occurred during pre-monsoon period of the year 2005 has been performed using reflectivity and velocity data generated by DWR Kolkata along with upper air data from the meteorological office Kolkata to find a range of convective indices for prediction of development of thunderstorms. Thunderstorms during 2006 and 2007 have also been recorded and analyzed for validation of nowcasting technique and proposed convective indices.

1.2. *Typical features of norwesters of north east India*

The months of April and May account for most of the thunderstorm development. A majority of these thunderstorms are accompanied by squalls and the frequency of squalls increases from northwest to southeast. The squalls are mostly from northwesterly direction. The highest wind speed recorded in these squalls reached up to 140-150 km/hr. A definite time sequence had been observed for occurrence and movement of these Norwesters by various authors in India. They generally develop over Bihar plateau, southeast Madhya Pradesh or West Orissa and travel east or southeastwards towards Gangetic West Bengal or head Bay of Bengal. They do not advance more than 130 to 160 km into the sea. Desai (1950) mentioned that thunderstorms approach most frequently from west to northwest and their occurrence takes place during 1200 UTC and 1500 UTC with a movement speed of 50 to 60 km/hr. The intensity of echoes received by analog radars were quite strong and showed qualitatively the potential of heavy rainfall. The vertical extent of such thunderstorm clouds exceeded 18 km in many cases but on few occasions crossed 20 km.

1.3. *Classification of storms*

To discuss the various aspects of cloud cells movement, authors have classified the storms in the following categories :

1.3.1. *Based on structure*

(a) *Single cell storm* : A single cloud cell moving independently without combining with any other cell has been considered as a single cell storm in this study. Usually the life cycle of such storms is between 30 minutes to 1 hour as studied by many authors in India, however, through DWR observations it was found that many single cell thunderstorms lived for more than 1 hour.

(b) *Multiple cell storms* : This storm system consists of a series of evolving cells. Cells typically form on or near the storm periphery at 10-15 minutes intervals and each cell eventually becomes the dominant cell of the storm complex, building to higher levels as it approaches and finally merges with the main storm complex. Precipitation forms in the new updraft and is held aloft temporarily while the cell matures. Finally, precipitation unloads as the cell matures resulting in a heavy gush of rain. The cluster of cells formed by the combination of neighboring cells and the whole system moves together is taken as a multiple cell storm. The duration of such storms has been found to be 3-6 hrs.

(c) *Squall line* : A chain of thunderstorms connected together and moving like a single entity, usually associated with a very high speed wind. As per the literature available, the minimum width to length ratio for a squall line should be 1:10.

1.3.2. *Based on DWR estimated reflectivity and vertical extent*

(a) *Severe thunderstorm* : Thunderstorm in which the height of 50 dBz reflectivity is more than 16 km has been considered as severe thunderstorm. Usually multiple cell thunderstorms generate severe thunderstorms, however, the possibility of single cell thunderstorms to become severe may not be ruled out. It has been observed from the rainfall data that such thunderstorms provide heavy rainfall at the rate of 30 mm/hr or more.

(b) *Moderate thunderstorm* : Thunderstorm in which the height of 50 dBz reflectivity lies within 12 km and 16 km has been considered as moderate thunderstorm. The study of the rainfall data revealed that such thunderstorms produce rainfall in the range of 5- 30 mm/hr.

(c) *Weak thunderstorm* : Thunderstorm in which the maximum reflectivity lies below 40 dBz has been considered as weak thunderstorm. The vertical extent of weak thunderstorms may reach up to 10 km where the reflectivity is not more than 20 dBz. Such thunderstorms may be accompanied with thunder and lightning but provide a rainfall in the range of 1- 5 mm/hr.

(d) *Very weak thunderstorm* : Thunderstorm in which the maximum reflectivity lies below 30 dBz has been considered as weak thunderstorm. The vertical extent of such thunderstorms does not exceed 6 km and they dissipate very quickly but produce thunder and lightening for a short interval. A drizzle or very light rain has been observed with such thunderstorms.

2. Data

India Meteorological Department (IMD) installed two DWR's at Chennai & Kolkata during the year 2002 (August & October respectively) and two more radars in the year 2005 at Machilipatnam and Visakhapatnam (June & Sept). All these DWR stations are located on the East Coast of India for a continuous surveillance of severe weather system in Bay of Bengal. These are S-Band radars (10 cm wavelength) operating at 2875 MHz, transmitting a peak power of about 750 KW using Klystron as amplifying device. The unambiguous range for reflectivity measurement in surveillance mode is 400 km and maximum unambiguous radial wind estimates (using velocity unfolding technique) within 250 km radius is 64 m/s (230 km/hr). With the installation of these radars along east coast of the Bay of Bengal, round the clock weather observation and analysis capabilities of IMD have been enhanced to a great extent. DWR generates voluminous data related to observed weather phenomena by performing a volume scan of duration 15-20 minutes. The time for a volume scan may be reduced to 10 minutes or even less as per requirement of the data.

A sequence of reflectivity and radial velocity data of more than 100 thunderstorms has been collected at every

20 minutes interval during pre-monsoon period (March-May) of the years 2005-2007 and analyzed statistically. Some of the standard convective indices for the corresponding days are also evaluated for the purpose of validation. Rainbow 3.4 software has been supplied by the manufacturer for deriving the products from the base data. A brief of two products Max_Z and VVP_2 of Rainbow software used in this radar by M/S Gematronik, Germany are given below :-

2.1. *Max_Z (Maximum Reflectivity)*

This is a derived product from volume reflectivity data, which gives a three dimensional view of the cloud. The algorithm calculates each vertical column of the cloud and finds the maximum reflectivity in that column. The reflectivity is presented in pseudo colours and scale is shown to the right of the product. The overall three dimensional cloud is presented in the form of a composite of three partial images in to a single imagery. The partial images are:-

(*i*) A top view as the highest measured reflectivity values in *Z* - direction. This image shows the highest reflectivity value for each vertical column seen from the top of the cartesian volume.

(*ii*) A north-south view of the highest measured reflectivity values in *Y* - direction. This image is appended above the top view and shows the highest measured reflectivity value for each horizontal line scan from north to south. The height of the cloud can be observed with respect to reflectivity from this image.

(*iii*) An east-west view of the highest measured values in *X* - direction. This image is appended to the right of the top view and shows the highest measured reflectivity value for each horizontal line scan from east to west. This image is also an indicator of height of the cloud and avoids the overlapping of the clouds in N-S projection if any.

2.2. *VVP_2 (Volume Velocity processing)*

Waldtenfel and Corbin (1979) proposed a technique to derive horizontal winds from radial velocity observed by single DWR over a limited area of about 50 km around the radar. A vertical profile of horizontal winds up to 7.5 km may be derived at equal steps selectable by users. This product displays the horizontal wind velocity and the wind direction in a vertical column of the radar site. Authors have compared the winds derived from Doppler Weather Radar with the RS/RW data and found that there is a close agreement in both. This means that for local observations for winds over an area of 50 km this product (VVP_2) may be taken as a standard product. A linear wind field model is used to derive the additional information from the measured radial velocity data. An algorithm for evaluating the product from radial component of the velocity is described below for better understanding. The algorithm calculates velocity and wind direction for a set of equi-distant layers.

2.3. *Convective Indices*

2.3.1. *CAPE (Convective Available Potential Energy)*

It is the positive area on the sounding between the level of free convection (LFC) and the equilibrium level and expressed in J/kg. As per the studies performed by Stensrud *et al*. (1997), following ranges have been proposed as an indicator of instability criterion :

0 to 999 - Marginal Instability	: 1,000 to 2,500- Moderate Instability
2,500 to 4,000 Strong Instability	: > 4,000 Extreme Instability

Stensrud *et al*., (1997) also stated that any thunderstorm that develops in an environment > 4,000 J/kg should be considered extremely hazardous. However, it is just the available energy for a parcel to rise above due to convection and cannot be taken as a true measure of instability. It can vary drastically on the mesoscale depending on surface heating, moisture, and thermal advection.

2.3.2. *CINE (Convective Inhibition Energy)*

Convective inhibition is the negative area on a sounding found between the lowest condensation Level (LCL) and LFC and is expressed in J/kg. Rassmussen and Blanchard (1998) suggested some threshold values from the studies performed over several hundreds of thunderstorms in US.

< 25 J/kg associated with significant tornadoes.

~ 50 J/kg associated with moderate echoes.

> 100 J/kg precludes thunderstorm development without significant forcing

2.3.3. *BRN (Bulk Richardson Number)*

Through this index an attempt is made to predict the storm type by balancing instability and shear (Strensrud *et al*., 1997, Davies 1998). The various limits available in the literature are as follows :

40 to 140 m^2/s^2	: potential for significant supercells.
35 to 40 m^2/s^2	: potential for marginal supercell events.
< 40 m^2/s^2	: associated with outflow dominated storms.

Weisman and Klemp (1984) have quoted this index as good discriminator between storm types, but Rasmussen and Blanchard (1998) refute this.

2.3.4. *LI (Lifted Index)*

It is defined as difference between a given saturated parcel temperature and the 500 hPa environmental temperature (0° C).

0 to -2° C (Weak Instability)	: -3 to -5° C (Moderate Instability).
-6 to -9° C (Strong Instability)	: < -9° C (Extreme Instability).

The more negative the number, the more unstable is the environment.

2.3.5. *VGP (Vorticity Generation Parameter)*

This index is calculated by the formula (Rasmussen and Blanchard, 1998)

VGP = [S (CAPE) $^{1/2}$] where S is the hodograph length/depth.

When the value of VGP exceeds 0.2, it indicates increasing possibility of tornadic supercell. This index is associated with physical concept of tilting of the vorticity axis.

Values of the convective indices as suggested by various authors vary from place to place and season to season and therefore, cannot be taken as standard for the area under study. Ludlam (1980) showed that when vertical wind shear (VWS) is very high, the updrafts and downdrafts of the thunderstorm become so organized that they do not interfere with each other, with the result that a severe thunderstorm is formed realizing the maximum potential of Convective Available Potential Energy (CAPE). Chaudhary (2006) conducted a study using technique called "Ampliative reasoning", to see if minimization of CINE or maximization of CAPE is pertinent for the genesis of severe thunderstorms of pre-monsoon season over North East part of India. The study revealed that for the genesis of severe thunderstorms in Gangetic West Bengal region, minimization of CINE is fundamental, whereas neither very high nor very low value of CAPE is of any significance. As suggested by Chaudhary (2006), CAPE value of 7000 J/kg and CINE value 100 J/kg will support the occurrence of severe thunderstorms in Gangetic West Bengal region.

3. Methodology

3.1. *DWR Data*

Thunderstorms in Gangetic West Bengal region during pre-monsoon period usually follow a fixed pattern based on the thermodynamic instability and the wind direction. Since speed and direction of wind around Kolkata are always available from the DWR derived products like Plan Position Indicator (PPI_V) and VVP_2, forecasters can easily issue the nowcasting by observing the initiation and development of the system and its direction of movement. An analysis of DWR recorded observations of about 250 days during 01 March to 31 May, 2005, 2006 and 2007 has been performed in the present work. More than 100 thunderstorms of various types have been analyzed using DWR data for intensive study. Convective indices of the same period have also been evaluated and analyzed. Based on the analysis of the year 2005 data, a range of convective indices has been proposed for the prediction of severe and moderate thunderstorms in GWB region. The upper air and DWR images during the years 2006 and 2007 have been analyzed for the validation of the results obtained from the analysis of year 2005 and to validate the proposed range of convective indices.

3.2. *Upper air data and convective indices*

Upper air data of 0000 UTC and 1200 UTC for all thunderstorm days has been collected from Meteorological Office Kolkata. Using RAOB software (The RAwinsonde Observation Program from Environmental Research Services, Shreeji and Company for automated drawing of *T*-Phi gram and derivation of convective indices), some of the standard convective parameters CAPE, CINE, LI, VGP and BRN have been derived. These parameters are studied in conjunction with actual occurrences of thunderstorms recorded by Doppler Weather Radar, Kolkata. Based on the analysis of convective indices observed on a thunderstorm day and the actual occurrences of thunderstorm, threshold values for severe and moderate type of thunderstorms have been

TABLE 1

(Severe thunderstorms during 2005 and convective indices)

Date	CAPE	CINE	LI	VGP	BRN	Time & sector of initiation (UTC)	Time of Dissipation (UTC)	Duration/ Direction of movement
23 Mar 2005	4257	0	-6.4	0.674	356	0504/ NW	1104	6 hrs/SE
10 Apr 2005	4618	0	-6.1	0.599	242	0832/ NW	1232	4 hrs/ SE
19 Apr 2005	3989	-5	-5.8	0.856	286	0727/NW	1147	4 hrs 20 mts/ SE
05 May 2005	4730 (12Z)	-10	-7.2	0.665	195	0748/NE	1328	5 hrs 40 mts/ W
17 May 2005	5290	0	-6.9	0.754	214	0418/NNW	1201	7 hrs 43 min/ SSE
19 May 2005	6317	-8	-13.1	0.329	553	0821/NW	1221	4 hrs/NW
22 May 2005	5604 (12Z)	0	-10.3	0.770	272	0921/NW	1341	4 hrs 20 mts/ SE

TABLE 2

(Moderate thunderstorms during 2005 and convective indices)

Date	CAPE	CINE	LI	VGP	BRN	Time & sector of initiation (UTC)	Time of Dissipation (UTC)	Duration/ Direction of movement
11 Mar 2005	2889	-25	-8.3	0.419	180	0827/SW	1207	3 hrs 30 min/E
18 Mar 2005	1955	-51	-5.9	0.240	87	0934/NW	1114	1 hr 40 min/SE
19 Mar 2005 (12Z)	2476	-31	-	0.421	120	0914/NW	1334	4 hrs 20 min/SE
24 Mar 2005	3567	-58	-5.8	0.567	187	0424/SW	0924	5 hrs/SE
30 Mar 2005 (12Z)	2897	-89	-6.9	0.331	56	0922/NW	1442	5 hrs 20 min/E
29 Apr 2005	4570	-47	-7.0	0.578	71	0814/SW	1334	5 hrs 20 min /E
03 May 2005 (12Z)	3526	0	-5.6	0.392	57	1228/NW	1848	6 hrs 20 min/SE
04 May 2005	602	-101	-3.1	0.181	13	0828/NW	1328	5 hrs /SE
06 May 2005	3996	-103	-3.9	0.23	33	0808/NW	1348	5 hrs 40 min/SE

TABLE 3

(Local Thunderstorms during 2005 and convective indices)

Date	CAPE	CINE	LI	VGP	BRN	Time & sector of initiation (UTC)	Time of dissipation (UTC)	Duration/ Direction of movement
16 Mar 2005	3135	-3	-6.5	0.395	209	0744/E	0904	01 hr 20 min/W
02 May 2005	556	-154	0.2	0.133	208	1022/NE	1208	01hr 46 min/E

proposed for the prediction in GWB region (Tables 6 & 7). These indices have not been proposed so far in this region for the nowcasting of deadly thunderstorms (Norwesters) and these were very much needed for forecasters to issue timely prediction of heavy rainfall and squally winds at least 2-3 hrs in advance.

4. Analysis

4.1. *Analysis of thunderstorms during year 2005*

DWR Kolkata has recorded 70 thunderstorms during 01 March to 31 May 2005 around Kolkata within a radius of 300 km. These thunderstorms have been categorized as severe, moderate, weak and very weak thunderstorms under the definitions given above. Another classification has also been done on the basis of multiple and single cell thunderstorms.

In the present study, only severe and moderate thunderstorms have been analyzed as their damaging potential is very severe. The data collected during year 2005 depicts that during May 16 days, April 11 days and March 12 days of thunderstorm activities took place. Data also shows that during the months of March and May, on an average two thunderstorms were developed on the thunderstorm day. The analysis shows that out of 70 thunderstorms, 55 were multiple cell type and 15 were single cell type. Multicellular storms were of moderate and severe categories whereas single cell thunderstorms have been found to be all types including weak and very weak thunderstorms. The height and reflectivity analysis showed that vertical extent of some of these thunderstorms exceeded more than 20 km and reflectivity more than 60 dBz. The great vertical extent confirms that the updrafts associated with severe thunderstorms in this region are very strong.

Table 1 shows the analysis of severe thunderstorms, indicate that duration of severe thunderstorms varies from 2 hrs to 6 hrs. Thunderstorm on March 23, which arrived from NW direction, traveled a distance of more than 300 km and lasted for 6 hrs. This thunderstorm combined with another multiple cell thunderstorm, coming from SW direction developed slightly later and produced a squall line of length exceeding 400 km (Fig. 1). On several other occasions the multiple cell thunderstorms generated "Squall lines" associated with strong gusty winds of the order of 100 km/hr or more. On 10 April and 05 May, hailstorms occurred along with severe thunder, lightning and heavy rainfall. Many other thunderstorms may also be associated with hailstorms but due to lack of awareness in the general public and non-reporting by media, they remained unnoticed. The analysis also shows that all severe thunderstorms in the year 2005 arrived from NW direction except one on 05 May 2005 which came from NE direction towards Kolkata. Some of the moderate category thunderstorms which were generated in the SW and traveled towards Kolkata are presented in Table 2. As stated by many scientists in their studies that energy redistribution takes place between the adjacent cells during their movement, the same has been confirmed by consecutive DWR observations as degeneration and re-generation of cells could be seen very clearly during their propagation.

4.1.1. *Analysis of multiple cell thunderstorms*

Out of 55 multiple cell thunderstorms observed by DWR, 29 thunderstorms moved towards Kolkata and arrived within 50 km range before dissipation (52.7%). The sector wise statistics of thunderstorm cells developed and hit Kolkata is given below :

(*i*) NW direction, 18 hit out of 24 developed (75%).

(*ii*) SW direction, 07 hit out of 20 developed (35%).

(*iii*) SE direction, 03 hit out of 05 developed (60%).

(*iv*) NE direction, 01 hit out of 06 developed (16.6%).

4.1.2. *Analysis of single cell thunderstorms*

Out of 15 single cell thunderstorms, 07 thunderstorms arrived Kolkata (48%). Sector wise statistics is given below:-

(*i*) NW direction, 03 hit out of 07 developed (42.8 %).

(*ii*) SW direction, none hit out of 03 developed (00 %).

(*iii*) SE direction, 01 hit out of 01 developed (100 %).

(*iv*) NE direction, 03 hit out of 04 developed (75 %).

4.1.3. *Analysis of locally generated thunderstorms*

As Kolkata is about 100 km away from the coast, some thunderstorms were locally generated in the vicinity of Kolkata. Table 3 shows detailed analysis of locally generated thunderstorms. Most of these storms were single cell moderate thunderstorms which moved around the place of origin and did not move far away. Their life span was not more than 2 hrs but provided heavy rainfall over a small area creating heavy damage to crops as reported by media.

4.1.4. *Analysis of squall lines*

Table 4 shows the analysis of squall lines formed during the period of analysis. Out of 8 squall lines generated in the region, 5 were formed (62.5%) due to combination of multiple cell thunderstorms developed in both NW and SW sectors. The time of formation was different in these sectors but they moved almost together with the same speed and generated squall line configuration. 3 Squall lines were formed (37.5%) due to multiple cell thunderstorms in NW sector only. No squall line was formed when thunderstorms were developed in other sectors. Max_Z pictures of squall lines analyzed in

TABLE 4

(Squall lines during 2005)

Date	Time of formation	Length of squall line	Speed of movement	Sector of formation	Direction of movement
23 Mar 2005	1124 UTC	400 km	60 km/h	SW+NW	SE
24 Mar 2005	0724 UTC	250 km	55 km/h	SW+NW	E
30 Mar 2005	1202 UTC	200 km	50 km/h	NW	SE
29 Apr 2005	1234 UTC	175 km	50 km/h	SW+ NW	SE
05 May 2005	1328 UTC	200 km	50 km/h	NE	W
06 May 2005	1308 UTC	175 km	50 km/h	NW	SE
17 May 2005	0921UTC	200 km	50 km/h	SW+NW	E
19 May 2005	1101 UTC	200 km	50 km/h	SW+NW	SE

TABLE 5

Average wind pattern estimation during 2005

Height	March	April	May
0.3 km	S/SW	S/SW	S/SW
1.5 km	W/SW	WNW	W/SW
2.1 km	SW	W	NW
3.1 km	SW	W	NW

TABLE 6

Proposed Convective indices for severe thunderstorms

CAPE	CINE	LI	VGP	BRN
4000-6000	-30 to 0	-6.1 to -10.3	> 0.5	200-400

TABLE 7

(Proposed Convective indices for Moderate Thunderstorms)

CAPE	CIN	LI	VGP	BRN
2000-4000	-100 to -30	-2.0 to -7.0	0.2 to 0.5	80-200

Table 4 are shown in Figs. 1 to 8. This is observed that most of the squall lines were formed around 1200 UTC (23, 30 March, 29 April, 17, 19 May). The case of 05 May, was an exception when the thunderstorm arrived from NE direction and lasted for 5 hrs 40 min.

4.1.5. *Analysis of convective indices*

The convective indices for all the category of thunderstorms have been collected, tabulated and analyzed. It is found that a fixed pattern and trend is shown by these indices for moderate and severe thunderstorms but no such values could be obtained for locally generated thunderstorms and therefore, such locally generated thunderstorms may not be predicted accurately by these indices.

4.1.6. *Analysis of VVP_2*

The vertical profile of the wind (VVP_2) over Kolkata provides an idea of the prevailing winds in the region at various levels up to 7.5 km with a step of 0.3 km. The movement of the clouds may be estimated up to a very good accuracy by this product. As evident from Fig. 9, a strong S/SW wind at the lower levels around Kolkata feeds the moisture from Bay of Bengal to the environment which helps thunderstorm to develop. Therefore, the probability of the development of a thunderstorm over Kolkata may be high if the direction of the winds at 0.3 km and 0.6 km is either Southerly or south easterly with speed between 15-20 knots. This has also been analysed that the setting of S/SE winds during 0600-0700 UTC period will have more probability of the system formation in the North West sector and their propagation towards Kolkata. Table 5 shows the variation of the wind direction from March-May during the year 2005 as observed by VVP_2 pictures. The low level wind at 0.3 km is mainly southerly or southwesterly during all the months indicates the availability of moisture from the Bay of Bengal because of the nature of the topography of the region. During March and May the winds at 1.5 km are Southerly or South-westerly whereas during April the direction of wind was found to be North-NorthWesterly. The genesis of thunderstorm indicates that during the developmental phase of the cell, when the updraft is predominant, the transfer of horizontal momentum to upper layer may cause the movement to be influenced by

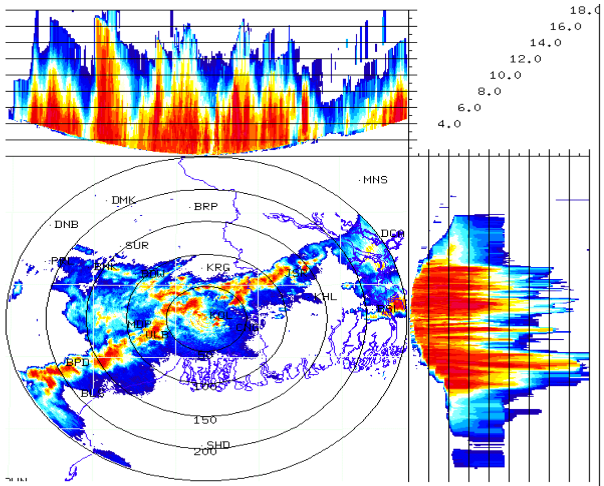


Fig 1. Squall line on 23 Mar 2005 (1124 UTC)

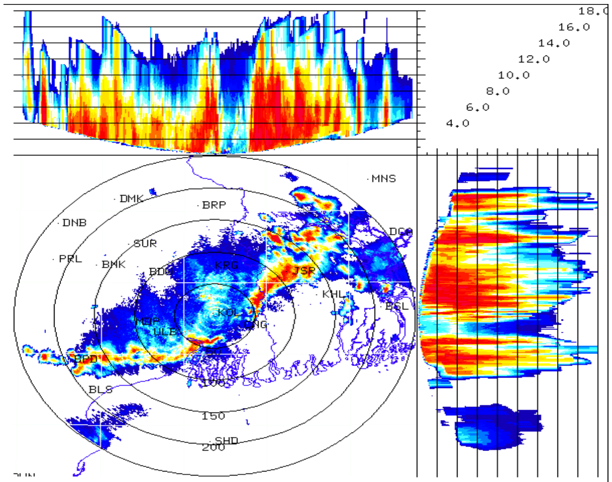


Fig 2. Squall line on 24 Mar 2005 (0724 UTC)

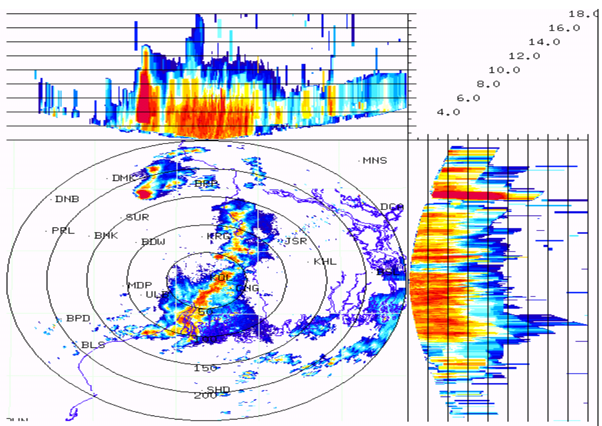


Fig 3. Squall line on 30 Mar 2005 (1202 UTC)

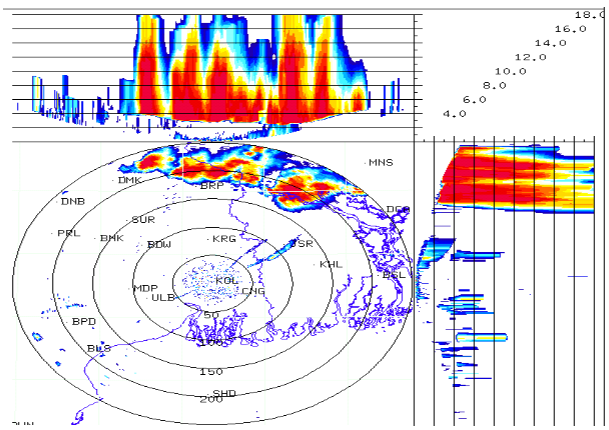


Fig 4. Squall line on 29 Apr 2005 (1234 UTC)

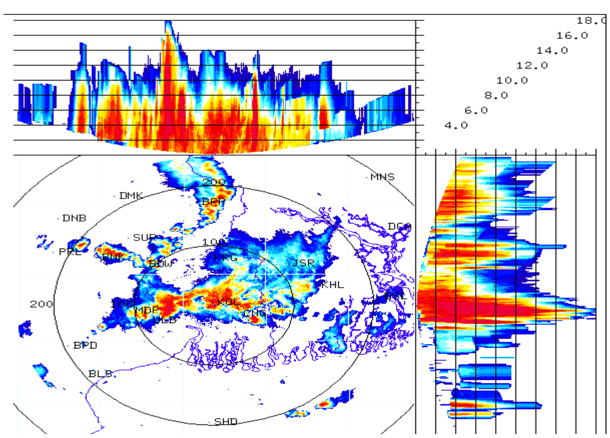


Fig 5. Squall line on 5 May 2005(1328 UTC)

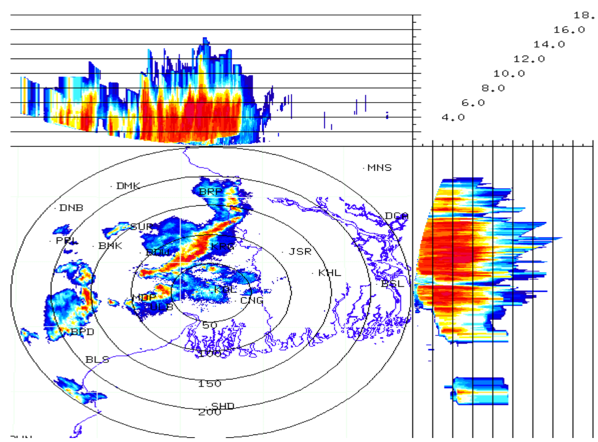


Fig 6. Squall line on 06 May 2005 (1308 UTC)

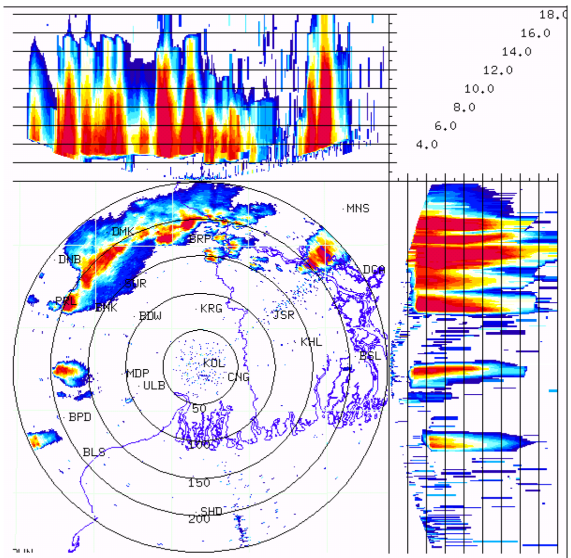


Fig 7. Squall line on 17 May 2005 (0921 UTC)

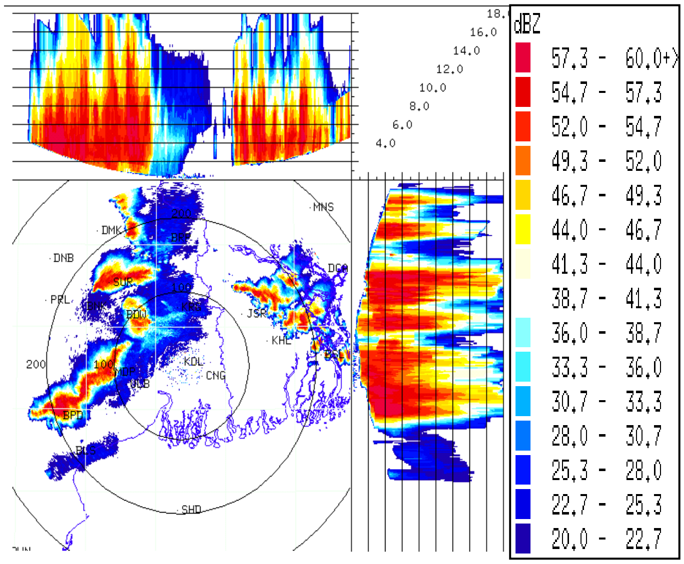


Fig 8. Squall line on 19.May 2005 (1101 UTC) Reflectivity Scale

the lower level wind pattern; but once the cell attains maturity the down draft transportation of momentum ensures that the movement is governed by the winds at 3-4 km levels.

4.1.7 *Wind squall and Hailstorm during year 2005*

Table 8 shows the occurrences of Wind squall and Hailstorm as recorded by the Meteorological observatories during year 2005 in the neighborhood of Kolkata and adjoining areas of Odisha(earlier named as Orissa). It is observed that meteorological observatories recorded the events (Wind squall/ hailstorm) for 13 days only. This is possible that the wind squall might have occurred at some different places outside the observatory area and therefore could not be recorded. Table 8 depicts that on 23 March 2005, Wind squall at speed 49 km/hr from NW direction was recorded by Alipore at 1205 UTC. Fig. 1 is the DWR recorded image of Squall line at 1124 UTC arriving from NW direction, when it was about 40 km away from Alipore (Kolkata). The linear stretch of the line was 400 km and was traveling at the speed of about 55 km. It means that during next 40 minutes (1205 UTC) when the distance of squall line was approximately 5-10 km, squally winds from NW direction were recorded by Alipore Met. Office. It is well known fact that the wind squall is originated from a Cb cloud ahead of the thunderstorm over that region, the same has been confirmed by DWR image and the observation by Alipore observatory.

This may be seen from the Tables 1, 2 & 8 that wind squall was reported by the different stations on those days when there was a severe or moderate type of thunderstorm was formed. Hailstorms were also reported by the observatories and listed in Table 8.

4.2. *Analysis of thunderstorms during 2006*

During 26 April, 2006 to 15 May, 2006, DWR Kolkata was unserviceable hence no observation could be available during that period. The study of 14 moderate and severe thunderstorms during rest of the period has been performed along with convective indices of corresponding days. It was observed that only two severe and one moderate thunderstorm developed during March 2006. Thunderstorms were associated with the hailstorms on 10 March, 08, 10 & 13 April whereas Squall lines were formed on 22 April and 30 May. As proposed in Tables 9 and 10 for severe and moderate thunderstorms, it was found that CAPE and CINE agree very closely for almost all cases except on 08 April, 2006 when the CAPE and CINE values were on the higher side and BRN was lower. On an average the values of convective indices lie in the range and substantiate to the proposed ranges of convective indices (Tables 9 & 10). Comparison of severe and moderate thunderstorms from Tables 9 and 10 showed that duration of severe thunderstorm was much higher than those of moderate types (except on 31 May, 2006). The VVP_2 product (Fig. 11) of 13 April, 2006 shows a

TABLE 8

Wind squall/hailstorm recorded by the Meteorological observatories during year 2005

Date	Squall Time (UTC)	Station	Squall Speed/direction	Duration of squall	Time (UTC)/ Duration of hailstorm	Size of hailstones	Station reported
11 Mar 2005	0726	Malda	55 km/h (W)	2 min	Nil	Nil	Nil
19 Mar 2005	Nil	Nil	Nil	Nil	0900 /10 min	2 cm	Bankura
23 Mar 2005	1205	Alipore	49km/h (NW)	3 min	Nil	Nil	Nil
30 Mar 2005	1130	Alipore	64 km/h (NW)	1 min	Nil	Nil	Nil
10 Apr 2005	1300	Alipore	59 km/h (NW)	2 min	Nil	Nil	Nil
	1635	Alipore	55 km/h (S)	2 min			
	2000	Alipore	59 km/h (SW)	1 min			
	1315	Dumdum	50 km/h (NW)	2 min			
19 Apr 2005	1410	Bhubaneshwar	58 km/h (NNE)	2 min	Nil	Nil	Nil
29 Apr 2005	Nil	Nil	Nil	Nil	1647/4 min	4.4 cm	Malda
02 May 2005	1127	Dumdum	90 km/h (S)	3 min	Nil	Nil	Nil
03 May 2005	0910	Bhubneshwar	78 km/h (SSW)	2 min	Nil	Nil	Nil
04 May 2005	1300	Alipore	76 km/h (NW)	1 min	1248	2 cm	Alipore
	2350	Alipore	76 km/h (NW)	1 min			
17 May 2005	0820	Malda	55 km/h (N)	2 min	Nil	Nil	Nil
18 May 2005	2000	Malda	56 km/h (NW)	3 min	Nil	Nil	Nil
19 May 2005	Nil	Nil	Nil	Nil	10 min	2 cm	Sriniketan

TABLE 9

Severe thunderstorms during 2006 and convective indices

Date	CAPE	CINE	LI	VGP	BRN	Time & sector of initiation (UTC)	Time of dissipation (UTC)	Duration/direction of movement
15 Mar 2006	4896	0	-7.45	0.765	312	0912/NW	1142	2 hrs 30 min /SE
04 Apr 2006	4335	-23.5	-6.62	0 .564	236	0938/NW	1238	3 hrs/SE
08 Apr 2006	4434	0	-7.6	0.684	234	0908/NW	1238	3 hrs 30 min SE
10 Apr 2006	4235	-11	-6.8	0.646	288	0738/ NW	1308	5 hrs 30 min /SE
13 Apr 2006	4384	0	-9.0	0.503	446	0812/ NW	1322	5 hrs 10 min /E
24 Apr 2006	3598	0	-9.8	0.453	289	0827/ NW	1327	5 hrs SE
30 May 2006	3990	-5	-7.5	0.440	176	0934/ W	1440	5 hrs 06 min E

similar wind pattern as on 29 April, 2005 (Fig. 10) with low level southerly winds and upper level northwesterly winds and severe thunderstorms occurred both the days. Fig. 12 shows that VVP_2 pattern on 24 April, 2006 was somewhat different from other days when lower level winds had the magnitude of 5 knots and upper level winds were also not very strong, a severe multiple cell thunderstorm system occurred that day which survived for about 5 hours (Table 9). The system traveled more than 200 km before dissipation. Fig. 13 shows two strong clusters of convective clouds having vertical development more than 18 km penetrating tropopause. Fig 14 also shows two severe thunderstorms in the vicinity. The cell at 100 km distance NW from DWR produced a hailstorm

TABLE 10

Moderate thunderstorms during 2006 and convective indices

Date	CAPE	CINE	LI	VGP	BRN	Time & sector of initiation (UTC)	Time of dissipation (UTC)	Duration/Direction of movement
04 Mar 2006	3120	-56	-5.62	0.435	152	0924/ NW	1224	3 hrs /E
10 Mar 2006	3570	-88	-7.32	0.343	228	2119/ SW	2249	1 hr 30 min /SE
08 Apr 2006 (12Z)	4751	-112	-7.2	0.746	50	1438/ NW	1638	2 hrs/SSE
19 Apr 2006	2014	0	-5.9	0.249	28	0810/SW	1210	2 hrs/SE
22 Apr 2006	2585	-30	-8.2	0.492	245	0910/NW	1410	5 hrs/E
29 May 2006	1586	-5	-3.7	0.26	541	1221/NW	1414	1 hr 53 min /SE
31 May 2006	3666	-41	-9.5	0.564	102	1103/ NW	1534	4 hrs 31 min/ SE

TABLE 11

Wind squall/hailstorm recorded by the Meteorological observatories during year 2006

Date	Squall Time (UTC)	Station	Squall Speed/Direction	Duration of Squall	Time(UTC)/Duration of hailstorm	Size of hailstones	Station reported
31 Mar 2006	Nil	Nil	Nil	Nil	1120/15 min	1 cm	Dumdum
04 Apr 2006	Nil	Nil	Nil	Nil	1100 /5 min	1 cm	Balasore
08 Apr 2006	1130	Bankura	56 km/h (NW)	2 min	Nil	Nil	Nil
10 Apr 2006	1430	Malda	55 km/h (SW)	3 min	1132/3 min	2 cm	Sriniketan
13 Apr 2006	1244	Alipore	72 km/h	2 min	0125/20 min	1 cm	Keonjhar
	1220	Dumdum	65 km/h	1 min			
22 Apr 2006	1300	Alipore	70 km/h (NW)	2 min	1230/5 min	0.7 cm	Dumdum
	1258	Dumdum	48 km/h (NW)	1 min			
24 Apr 2006	1032	Bankura	56 km/h (N)	2 min	Nil	Nil	Nil
	1308	Alipore	109 km/h (NW)	1 min			
	1255	Dumdum	76 km/h (NW)	2 min			

TABLE 12

Severe thunderstorms during 2007 and convective indices

Date	CAPE	CINE	LI	VGP	BRN	Time & sector of initiation (UTC)	Time of dissipation (UTC)	Duration/ Direction of movement
22 Mar 2007	3564	-10	-7.3	0.165	269	1216/ NW	1717	5 hrs /
09 Apr 2007	2809	-19	-11.2	0.545	98	1444/ NW 1704/ NW	1904 2324	4 hrs 20 min /SE 6 hrs 20 min/E
12 Apr 2007	2318	-71	-9.1	0.375	54	0644/ NE	1318	6 hrs 34 min/W
						1000 /SW	1338	3 hrs 38 min/NE
								(Cells merged)
13 Apr 2007	4346	-14	-8.6	0.224	324	0806/ SW	1206	4 hrs /SE
26 Apr 2007	2924	-16	-10.8	0.43	100	0826/ SW	1226	4 hrs /E
18 May 2007	4653	0	-8.6	0.233	265	0928/ NW	1228	3 hrs /SE

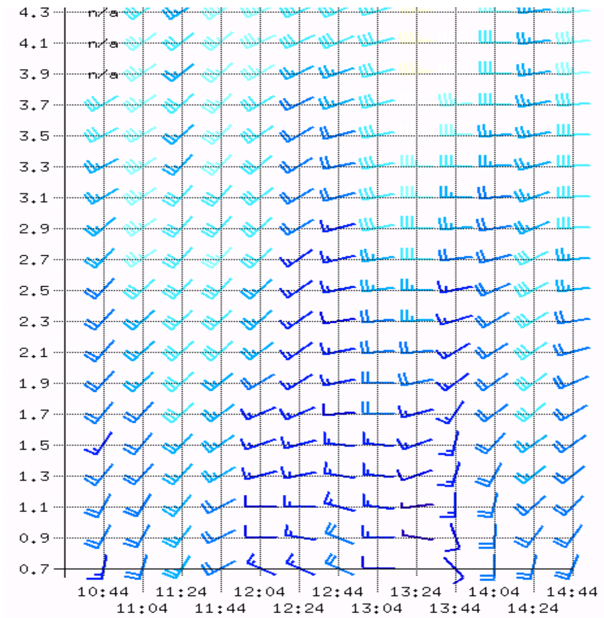


Fig .9. VVP_2 picture of 23 Mar 2005

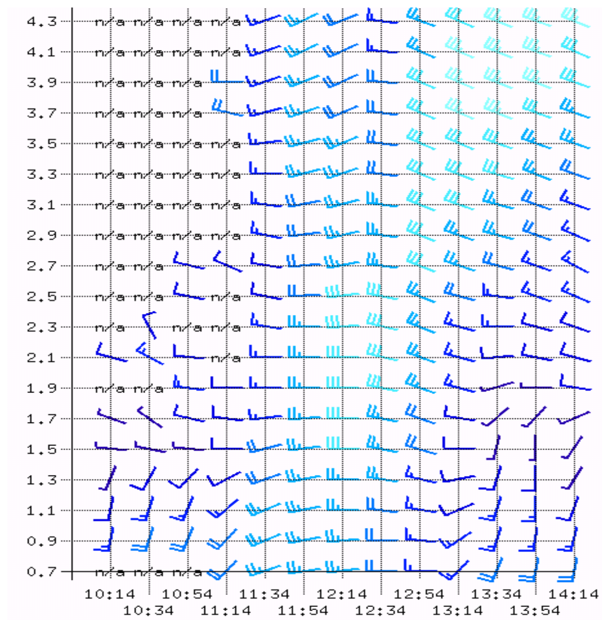


Fig 10. VVP_2 picture of 29 Apr 2005

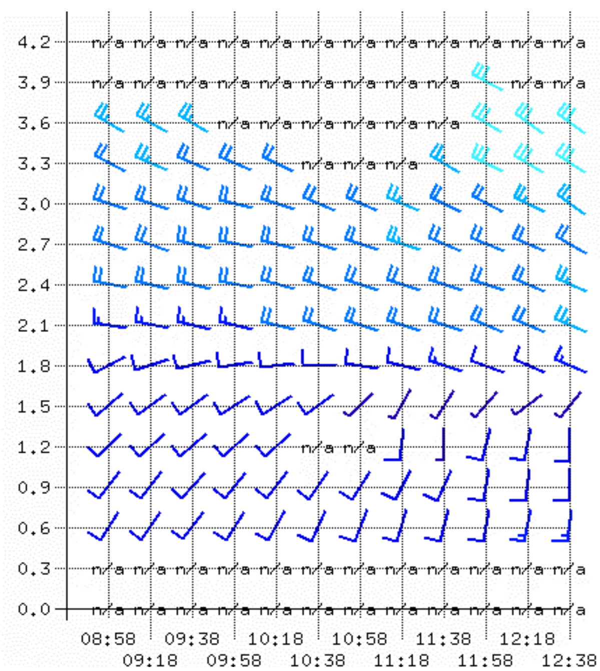


Fig. 11. VVP_2 picture of 13 Apr 2006

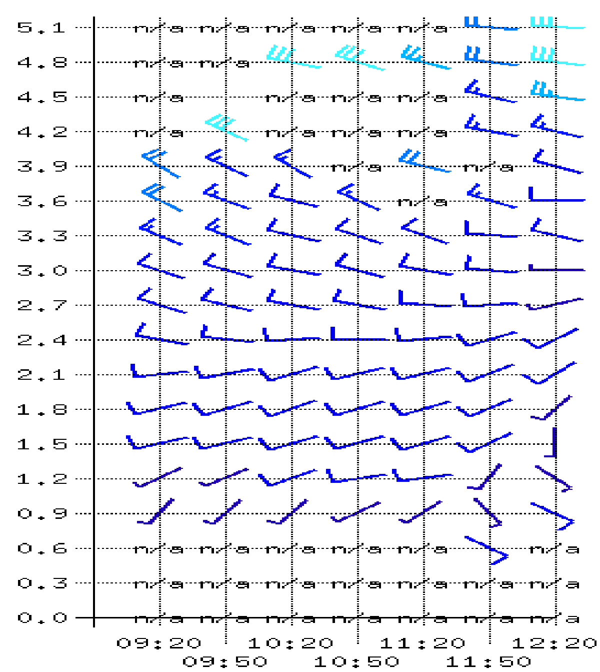


Fig. 12. VVP_2 picture of 24 Apr 2006

around 1140 UTC as reported by newspapers. Fig. 15 is the Max_Z picture of the thunderstorm on 13 April, 2006 at 1122 UTC which also resembles with that of 29 April, 2005 in terms of severity (Fig. 4). Values of convective indices were also in agreement on these days.

4.2.1. *Wind squall and hailstorm during year 2006*

Tables 9 & 10 depict the occurrence of severe and moderate thunderstorms within 300 km radius from Kolkata during the year 2006 and Table 11 shows the

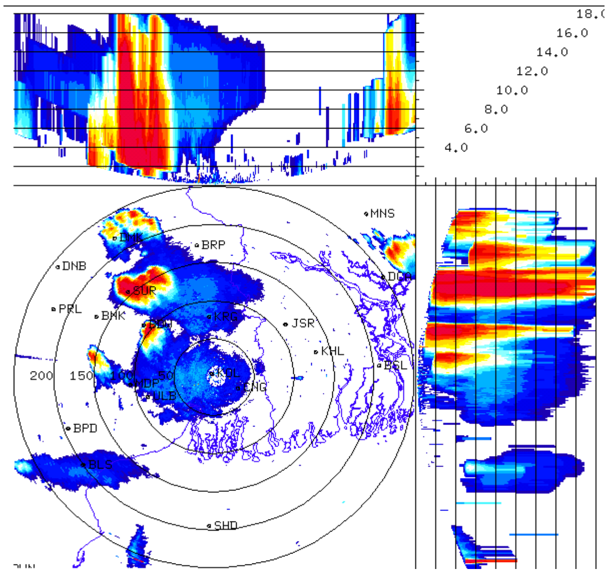


Fig. 13. Thunderstorm on 08 Apr 2006 (1208 UTC)

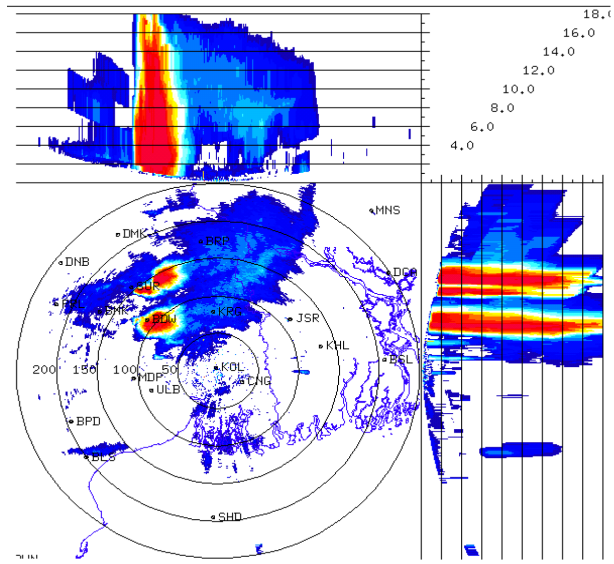


Fig. 14. Thunderstorm associated with hailstorm on 10 Apr 2006 (1138 UTC)

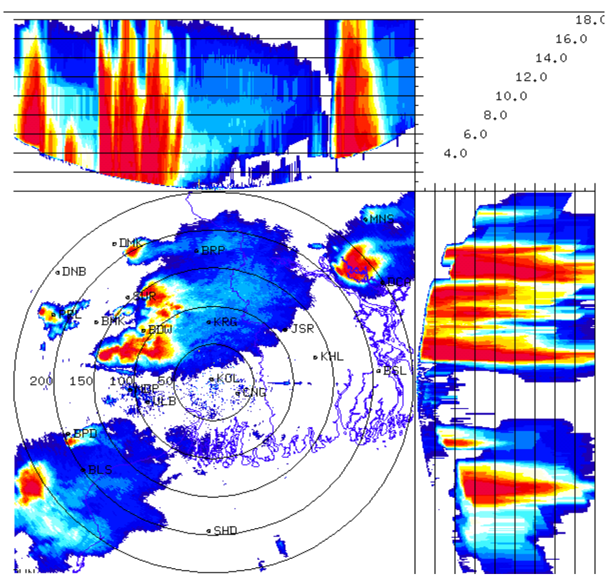


Fig. 15. Thunderstorm on 13 Apr 2006 (1122 UTC)

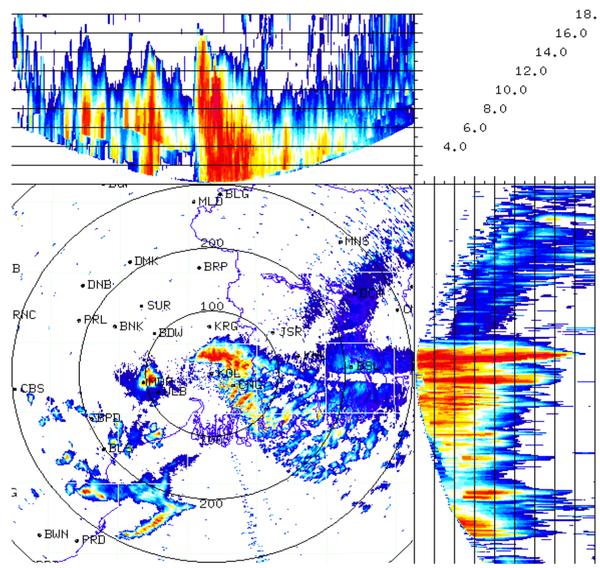


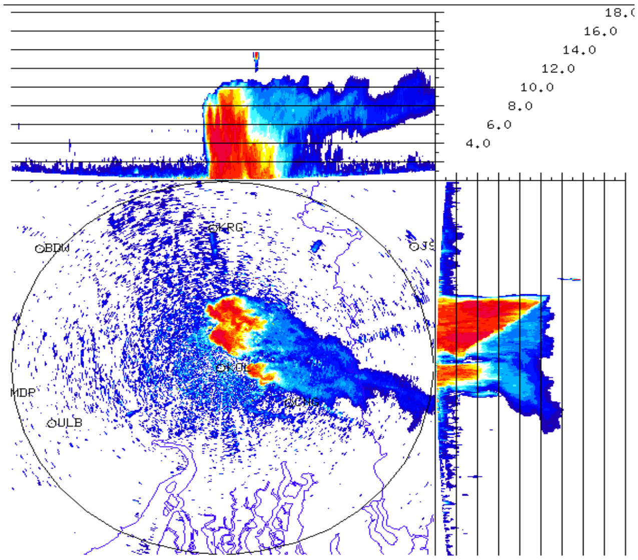
Fig. 16. Thunderstorm on 12 Apr 2007 (1238 UTC)

occurrence of wind squalls and hailstorms reported by the meteorological observatories.

(a) On 04[th] April, a severe thunderstorm arrived from NW and travelled through SW sector of Kolkata and lasted for 3 hrs. A hailstorm was reported by Balasore (200 km SW from Kolkata) at 1100 UTC with 1 cm hailstones and lasted for 5 minutes.

(b) On 08[th] April a severe thunderstorm lasted for 3 hrs 30 min arrived from NW direction during 0908-1238 UTC. Meteorological Office at Bankura (located at 150 km NW from Kolkata) reported wind squall of the magnitude 56 km/hr at 1130 UTC.

(c) On 10[th] April a severe thunderstorm travelled from NW and lasted for 5 hrs 30 min during 0738-1308 UTC.



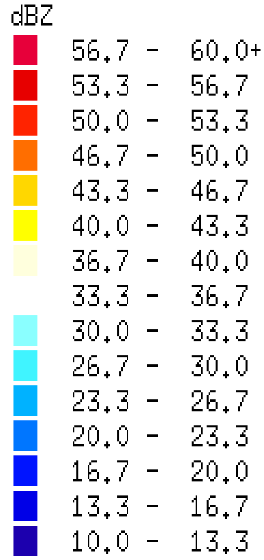


Fig. 17. Hailstorm on 06 May, 2007 (1002 UTC)

Reflectivity Scale

A hailstorm was reported by met observatory Sriniketan (about 170 km NW of Kolkata) at 1132 UTC of hail size 2 cm for 3 minutes.

(d) Another severe thunderstorm occurred on 13th April during 0812-1322 UTC (5 hrs 10 min) from NW direction. Dumdum and Alipore observatories reported wind squalls of magnitudes 65 km/hr and 72 km/hr at 1225 and 1244 UTC respectively. DWR images showed that the same system has generated these wind squalls during its path from NW to SE direction.

(e) A multiple cell thunderstorm of moderate intensity occurred on 22nd April and travelled through NW direction during 0910-1410 UTC. Alipore and Dumdum recorded the wind squalls of the magnitude 70 km/hr & 48 km/hr respectively at about 1300 UTC. This is also seen from Table 11 that a hailstorm was reported by Dumdum at 1230 UTC of hail size 0.7 cm in diameter and lasted for 5 minutes. Above observations show that the system was very strong and had a potential of generating hailstorm and wind squalls.

(f) Another severe thunderstorm was developed on 24th April at 0827 UTC in the NW sector and traveled in SE direction and lasted for 5 hrs till 1327 UTC. During its journey, it generated a wind squall at Bankura of magnitude 56 km/hr at 1032 UTC, another wind squall observed by Dumdum at 1255 UTC of magnitude 76 km/hr and one more observed by Alipore at 1308 UTC.

4.3. *Analysis of thunderstorms during 2007*

The analysis of 20 moderate and severe thunderstorms during the year 2007 shows that there was only one thunderstorm (severe) occurred in March, whereas 14 thunderstorms (2 severe and 12 moderate) occurred in April and 5 thunderstorms (one severe and 4 moderate) in May. Severe thunderstorms during 2007 have been analysed in Table 12. It is revealed that although CAPE value on 09 April, 2007 was only 2809 J/kg, there were two multiple cell thunderstorm systems formed after 1200 UTC. One thing may be noted that 0000 UTC observations of convective indices mainly indicate the generation of a system before 1200 UTC, however, those developed in the later part are not predicted very well by convective indices at 0000 UTC. The first system developed around 1444 UTC in NW sector moved towards SE direction lasted for 4 hrs 20 min and converted in to a squall line formation before dissipation and crossed over Kolkata. However, second system developed at 1704 UTC survived for about 6 hrs 20 min and it passed to the south west part of Kolkata. The convective indices at 0000 UTC on 27 April, 2007 predicted the development of moderate thunderstorm and the day experienced three moderate thunderstorms in different sectors. Two of these thunderstorms were formed at same time around 0830 UTC whereas the third one was developed at 0730 UTC (Table 13). However, the third was developed locally in SE sector near Kolkata and lasted for about 5 hrs. Table 13 shows that convective

TABLE 13

Moderate thunderstorms during 2007 and convective indices

Date		CAPE	CINE	LI	VGP	BRN	Time & sector of initiation (UTC)	Time of dissipation (UTC)	Duration/Direction of movement
09 Apr 2007		2809	-19	-11.2	0.545	98	0946/ NW	1126	2 hrs 40 min /SSE
11 Apr 2007		3074	-54	-8.8	0.329	131	1024/ NE	1324	3 hrs/SE
13 Apr 2007	(12 Z)	5029	-1	-11.0	0.377	129	0926/ NW	1246	3 hrs 20 min/SE
27 Apr 2007	(00 Z)	1929	-84	-8.8	0.338	52	0830 /NW	1310	4 hrs 40 min/ SE
	(12 Z)	2854	-26	-7.8	0.527	26	0830/ SW	1310	4 hrs 40 min/E
							0750/Local	1310	5 hrs 20 min/N
28 Apr 2007	(00 Z)	1627	-3	-8.8	0.341	64	0710 /SE	1210	5 hrs/E
	(12 Z)	2589	-28	-7.8	0.37	182			
29 Apr 2007		2236	-140	-7.7	0.423	232	0910/ SW	1110	2 hrs/SE
30 Apr 2007		2359	-104	-7.0	0.235	144	0840/ NW	1310	4 hrs 30 min/SE
		2943	-41	-8.1	0.318	143			
02 May 2007		2137	-108	-8.6	0.246	243	0829/Local	1029	2 hrs/NE
06 May 2007		2664	-38	-5.8	0.221	-	0801/ SE	1101	3 hrs/NE
16 May 2007		2040	-13	-5.3	0.142	313	0429/ SW	0829	4 hrs/E
17 May 2007		2379	-10	-5.6	0.235	587	0646/ NW	1122	4 hrs 36 min/ E

TABLE 14

(Wind squall/hailstorm recorded by the Meteorological observatories during year 2007)

Date	Squall time (UTC)	Station	Squall Speed/Direction	Duration of squall	Time(UTC)/Duration of hailstorm	Size of hailstones	Station reported
22 May 2007	1236	Jamshedpur	74km/h(N)	1 min	Nil	Nil	Nil
	1606	Digha	68 km/h(NW)	2 min			
09 Apr 2007	2110	Alipore	80 km/h(W)	3 min	Nil	Nil	Nil
	2128	Dumdum	50 km/h(NW)	1 min			
12 Apr 2007	1245	Alipore	61 km/h(SSW)	2 min	Nil	Nil	Nil
	1315	Dumdum	70 km/h(NW)	1 min			
	1500	Digha	41 km/h(NE)	1 min			
13 Apr 2007	2052	Bhubaneshwar	64 km/h(NE)	2 min	1415	1 cm	Jamshedpur
26 Apr 2007	1132	Bankura	59 km/h(NW)	2 min	Nil	Nil	Nil

indices at 0000 UTC and 1200 UTC were very favourable for moderate thunderstorms.

Fig. 16 shows a typical thunderstorm on April 12, 2007 which was developed in NE sector in Bangladesh and moved towards Kolkata after traveling a distance of about 200 km. DWR Kolkata observed the system initiation at 0644 UTC and subsequent radar pictures showed that the system is moving towards west. The movement was very unusual as most of the thunderstorms during pre-monsoon period are generated in the western sectors of GWB region and move towards South-East or Easterly direction. The radar reflectivity was more than 55 dBZ and the vertical extent was exceeding 16 km. As the movement of the system was quite steady and straight (as seen from DWR images), it was highly expected that the system will pass through north of Kolkata. On the basis of above observations, an alert of severe thunderstorm within next two hrs was issued from Met. Office Kolkata at 1130 UTC to Air Traffic control when the system was about 80 km away from Kolkata. Ignoring the warning issued from IMD, an aircraft from a domestic airline took off around 1300 UTC from the airport and within minutes it suffered a severe hail strike on the front windscreen and got severely damaged. The aircraft had to come back for emergency landing.

Fig. 17 shows a hailstorm occurrence over Kolkata on 06 May, 2007 at 1002 UTC. The size of hails was about 2 cm and the hailstorm lasted for 10 minutes. Authors found some typical signature of the system in the DWR observations as a very long "Anvil" ahead of the main cloud and extended up to a distance of 100 km towards east of Kolkata. Vertical extent of the cloud was only 8 km and the radar reflectivity was lying in the range of 53.3 dBz to 56.7 dBz. Authors have taken up a separate study for such cases of hailstorms using DWR images and the results are being analysed.

4.3.1. *Wind squall and hailstorm during year 2007*

Tables 12 & 13 depict the occurrence of severe and moderate thunderstorms within 300 km radius from Kolkata during the year 2007 and Table 14 shows the occurrence of wind squalls and hailstorms reported by the meteorological observatories. Analysis of some of the coincident events is done in the following paragraph.

(a) On 22nd March, a moderate thunderstorm arrived from NW and travelled through SW sector of Kolkata and lasted for 5 hrs during 1216 UTC to 1717 UTC. Wind squall was reported by M.O. Jamshedpur at 1236 UTC at a speed of 74 km/hr from North direction and by M. O. Digha at 1606 UTC of magnitude 68 km/hr from NW direction.

(b) On 09th April two severe thunderstorms occurred in the NW sector lasted for 4 hrs 20 min during 1444-1904 UTC & 6 hrs 20 min during 1704-2324 UTC respectively and arrived Kolkata from NW direction. One moderate thunderstorm was also developed in the NW sector and lasted for 2 hrs & 40 min during 0946-1126 UTC. Wind squalls were reported by Meteorological Offices at Alipore and Dumdum at 2110 & 2128 UTC respectively at wind speed 80 km/hr (W) & 50 km/hr (NW). It is observed that these wind squalls were associated with the second severe thunderstorm which was lasting in the duration 1704-2324 UTC.

(c) On 12th April two severe thunderstorms were developed in the NE and SW sectors (Table 12) and travelled towards Kolkata from opposite directions and merged to a single thunderstorm. The merged cells in the form of a single thunderstorm further moved in SE direction. Met. offices at Alipore, Dumdum and Digha reported wind squalls (Table 14) generated by this system.

(d) Another severe thunderstorm occurred on 26th April during 0826-1226 UTC (4 hrs) from NW direction. Bankura observatory reported wind squalls of magnitudes 59 km/hr at 1132 UTC on its way towards Kolkata.

5. Results

(*i*) The analysis of 70 thunderstorms in 2005 and related convective indices and their validation by the analysis of 34 thunderstorms in 2006-2007 showed that Doppler radar is capable of predicting the development and speed of movement of the thunderstorms for the next 1-2 hrs using reflectivity and radial velocity images. However, if the convective indices of 0000 UTC and 1200 UTC are also evaluated and used with DWR images then a better now casting of at least 2-3 hrs may be done with a sufficiently good accuracy.

(*ii*) The role of VVP_2 has been established by the DWR in predicting the genesis and expected movement of the system once the cloud development is observed in the radar images.

(*iii*) Max_Z image has provided much valuable information in understanding the severity of the system by observing the vertical extent of the clouds and associated radar reflectivity. In this study authors have found a very good correlation between the severity of the system, the vertical extent and the radar reflectivity. The larger be the values of these factors, the more is the severity of thunderstorms. So far, this is the qualitative result of the analysis but more studies in this area may provide some formulation to evaluate quantitatively the intensity of rainfall and severity of the system. The horizontal extent of the system gives an idea for expected rainfall over an area in next few hours and to understand the structure of the cloud system (single cell, multiple cell, bow echo or squall line).

(*iv*) The convective indices proposed in Tables 6 & 7 decide the probability of thunderstorm development and their severity. Severe thunderstorm will be characterized by heavy rainfall of the order of 50-100 mm/hr and moderate thunderstorms provide rainfall in the range of 20 to 50 mm/hr. (The rainfall has been verified from the observations of the self recording rain gauges in a separate study undertaken by the authors).

6. Nowcasting technique

Based on above analysis of thunderstorm occurrences and corresponding convective indices, following procedure has been suggested for nowcasting of thunderstorms :

(*i*) Convective indices CAPE, CINE, LI, VGP and BRN from 0000 UTC upper air data to be observed.

(*ii*) Thunderstorm detection to be monitored from DWR observations in the range of 300 km using PPI_Z & Max_Z pictures. The radar volume scan may be performed at an interval of every 10 minutes in automatic mode.

(*iii*) VVP_2 product to be observed for the wind direction and speed around Kolkata. If the wind direction at lower levels (up to 0.9 km) is either Southerly or South-Easterly then moisture incursion takes place over this area from Bay of Bengal and the chances of formation of thunderstorm are very high (Fig. 16). PPI_V product also suggests the wind surrounding the thunderstorm but its interpretation is more complicated than VVP_2. Moreover, the speed of wind at different levels also plays an important role in the development of thunderstorm. Southerly winds of the order of 15-20 knots at levels 0.3 - 0.6 km before 0600 UTC provide the moisture in Chhota Nagpur region at a faster rate and the chances of severe thunderstorm development are more between 0800-1000 UTC. If the wind direction at upper levels (3.6-5.0 km) is northwesterly or westerly then the movement of the thunderstorm will be towards Kolkata. Authors have found from the analysis of more than 100 cases that winds at levels 3.6 to 5.0 km are the “Driving Winds” of the system because all thunderstorms move according to the direction of these winds.

(*iv*) Emphasis should be given for single/multiple cell system generated in northwest/southwest sectors, as the time taken by a system to arrive at a place depends upon the type of thunderstorm, sector of initiation and the distance. For example, a single cell thunderstorm at a distance of more than 100 km from Kolkata will have almost no chance to reach Kolkata however, a multiple cell system or squall line may reach Kolkata from a distance more than 200 km.

(*v*) If the values of convective indices mentioned above lie within the suggested range and initiation of thunderstorm is seen through DWR observations then using PPI_V product, wind direction and speed may be estimated for movement of the system. Estimation for their arrival/non-arrival towards a particular area may be done and warning for high wind speed/ wind squall and heavy rainfall may be issued accordingly.

7. Conclusions

The products Max_Z, PPI_Z, PPI_V and VVP_2 have been found very useful in the prediction of the thunderstorm movement over a place with a high degree of precision in space and time. The convective indices on the other hand indicate a probability of development of a system. As VVP_2 product provides a vertical profile of horizontal winds up to 7.5 km round the clock at a very short interval, it can be used to estimate wind direction/speed any time around Kolkata in the range of 50 km and also as a supplementary to the winds derived from RS/RW.

Convective indices generated from 0000 UTC upper air observations are basic indicators for most of the storm formations before 1200 UTC. However, 1200 UTC indices also play crucial role to determine the atmosphere being conducive for thunderstorm development after 1200 UTC. (19, 20 March & 03, 05, 22 May during the year 2005 and 08 April, 2006, 13, 27, 28 April, 01, 03, 16 May, 2007). CINE is the next most significant convective parameter in addition to CAPE, whose large value does not support formation of thunderstorm even if CAPE and other parameters are favourable.

Authors have found that very high value of CAPE exceeding 6000 J/kg and CINE exceeding 200 J/kg are not favourable for the genesis of thunderstorm in Gangetic West Bengal region during pre-monsoon period. Very high values of BRN (>400) and LI (> -10, magnitude wise) do not support the formation of a thunderstorm.

8. Suggestions

The study reveals that in most of the days during pre-monsoon period, thunderstorm initiation takes place around 0600 UTC in the Chhota Nagpur region and their subsequent arrival occurs after 0900 UTC in the surroundings of Kolkata. So, the convective indices in this region at 0660 UTC may provide better information about the favourable conditions for initiation of thunderstorm and their subsequent motion. Presently, no RS/RW flight is conducted at 0600 UTC from any station in India, it is suggested that an additional RS/RW flight may be performed on the experimental basis and similar studies may be conducted for better nowcasting of such severe weather events in Gangetic West Bengal region.

9. Future scope of the work

Nowcasting technique as suggested may need further studies in the real time mode for more year's data for improved and better prediction. As more Doppler Weather Radars are being installed in various parts of India by IMD and many more are expected in the near future, this study will provide guidance to other scientists of IMD for improvement in the accuracy of nowcasting and extension of prediction period.

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