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Doppler Weather Radar analysis of short term cyclonic storm

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सार – दक्षिण पश्चिम मानसून के समय भारत के पूर्वी तट पर भीषण चक्रवातीय तूफान काफी कम आते हैं और यदि वे तूफान कम अवधि वाले हों तो तंत्र की तीव्रता में तेजी से होने वाले परिवर्तनों के कारण उनका पूर्वानुमान कर पाना काफी कठिन हो जाता है। ऐसे में सिनॉप्टिक प्रेक्षण अपर्याप्त होते हैं और उपग्रह से प्राप्त प्रेक्षणों से भी इस प्रकार के तंत्रों के निश्चित चित्र नहीं मिल पाते हैं जिससे ऐसी स्थितियों में मौसम एजेंसियाँ समय रहते इन तूफानों की चेतावनी जारी नहीं कर सकती हैं। इसी प्रकार का एक तंत्र 19 सितंबर 2006 को कोलकाता के दक्षिण–पूर्व में लगभग 250 कि. मी. की दूरी पर बना। इस तंत्र के बनने की वजह से बहुत भारी वर्षा हुई और अनेक लोग हताहत हुए और संपत्ति को भारी नुकसान पहुँचा। समाचार एजेंसियों के अनुसार 19 से 21 सितंबर 2006 को आए चक्रवात के समय भारी वर्षा और तेज हवाओं की वजह से 100 लोगों को जान से हाथ धोना पड़ा और लाखों लोग बेघर हो गए। 0600 यू. टी. सी. पर कोलकाता में लगे हुए डॉप्लर मौसम रेडार से अवदाब जैसे तंत्र के आरंभिक लक्षणों के बारे में पता चला। अंततः 0900 यू. टी. सी. पर लिए गए प्रेक्षणों से तंत्र के और अधिक घनीभूत होकर गहन अवदाब की उच्च स्थिति में परिणत होने का पता चलता है। लगभग 1200 यू. टी. सी. पर डॉप्लर मौसम रेडार द्वारा रिकार्ड किए गए वृत्तकार केन्द्र वाले स्पष्ट चक्करदार धारियों से इस तूफान के एक पूर्ण विकसित भीषण चक्रवातीय तूफान के रूप में पुष्टि की गई। 1630 यू. टी. सी. पर यह तंत्र भूमितल के संपर्क में आने से कमज़ोर पड़ कर गहन अवदाब में परिणत हुआ किंतु 19 सितंबर 2006 को 2100 यू. टी. सी. पर पुनः चक्रवातीय तूफान के रूप में परिणत हुआ। इस शोध–पत्र में यह समझाया गया है कि लघु अवधि वाले चक्रवातीय तूफान की गति की दिशा और उससे होने वाली भारी वर्षा का पूर्वानुमान देने के लिए डॉप्लर मौसम रेडार बहुत ही उपयोगी सिद्ध हुए हैं। 32 मी./सेकेण्ड (64 नॉट्स/115 कि. मी. प्रति घंटा) के परिमाण वाली अधिकतम त्रिज्य हवाओं को भी तूफान के केन्द्र की दीवार पर 2.5 कि.मी. ऊपर से डॉप्लर मौसम रेडार ने रिकार्ड किया है। डॉप्लर मौसम रेडार द्वारा प्रेक्षित किए गए उच्च पवन गति और चक्रवात की सुपरिभाषित संरचना टी. नबंर की 3.5 के भीषण चक्रवातीय तूफान की पुष्टि करती है। इस क्षेत्र की सतह वेधशालाओं से 110 कि.मी. प्रतिघंटा की रफ्तार से तेज हवाओं के चलने के रिकार्ड प्राप्त हुए है। इस अध्ययन से यह भी पता चलता है कि डॉप्लर मौसम रेडार के आँकड़ों का पहले से ही उपयोग करते हुए इस प्रकार के कम अवधि वाले उष्णकटिबंधीय चक्रवात के विकसित होने पर तेज हवाओं और भारी वर्षा की पूर्व चेतावनी जारी की जा सकती है।

ABSTRACT. On the east coast of India, during South-West monsoon period severe cyclonic storms are very rare and if they are short term cyclones then their prediction becomes very difficult due to rapid change in the intensity of the system. Though synoptic observations failed and satellite observations also cannot give decisive picture about such systems, in that case timely warning can not be issued by the weather agencies. Such a system was formed on 19 September, 2006 at about 250 km South-East of Kolkata (India). Very heavy rainfall associated with the system caused several human casualties and extensive damage to the property. According to news agencies, more than 100 people died and a million people became homeless due to heavy rainfall and strong winds associated with the cyclone during 19 September -21, 2006. At 0600 UTC, Doppler Weather radar (DWR) at Kolkata observed initial signatures of the system like a depression. Subsequently at 0900 UTC the observations indicated that the intensification of the system has taken place to a higher stage of deep depression and at about 1200 UTC clear spiral bands with a circular eye recorded by DWR confirmed for a fully developed severe cyclonic storm. The system weakened in to a deep depression at 1630 UTC after the landfall but again became a cyclonic storm at 2100 UTC of 19 September, 2006. Present study establishes that DWR is very useful for prediction of this short term cyclonic storm, its direction of movement and heavy rainfall associated. The maximum radial winds of the magnitude 32 m/s (64 knots/115 km/h) were also recorded by DWR at an altitude of 2.5 km in the eye wall region of the system. The high wind speed and the well defined structure of the cyclone observed by DWR confirmed that the system was a Severe Cyclonic Storm of T number 3.5. Records are available with surface observatories in the region for strong winds of the order of 110 km/h. This study also revealed that an early warning for strong winds and heavy rainfall could have been issued for development of such a short duration tropical cyclone using DWR data well in advance.

Key words – Doppler Weather Radar, Severe cyclonic storm, Depression, Tropical cyclone.

1. Introduction

As one of the most catastrophic weather phenomena in nature, tropical cyclone needs the early prediction and tracking in respect of accurate place and precise time of landfall. Frank M. William (1985) has analyzed that although only 7% of the global tropical cyclones occur in the North Indian Ocean (Bay of Bengal) they are the most deadly in the world. The shallow waters of the Bay of Bengal, the low flat bathymetry and funneling shape of the coast line can lead to devastating losses of life and property due to the storm surge. Frank (1977) estimated that the average rainfall within the inner 200 km radius of a cyclone averages about 10 cm/day. No numerical model could successfully predict the track of the tropical cyclone due to lack of data over the sea. Moreover, the accuracy of landfall could not be established from models and sometimes inaccuracy in predicting landfall place and time is very large. A detailed study of the tropical cyclone has been compiled by the India Meteorological Department (2002) regarding the damage potential, the structure, the climatology, the causes of damage and associated damages. Doppler Weather Radar (DWR) is the best tool for providing the best estimate of associated wind velocities, reflectivity and tracking of the cyclone. However, the only limitation is the short range of tracking and limited duration of the forecast may be 8-12 hrs. Banerjee *et al.* (2004) conducted a study for tropical cyclone of 12 November, 2002 in the Bay of Bengal using data from Doppler Weather radar Kolkata. This was the very first study in India using DWR data for the analysis of cyclone movement and the estimation of wind velocity associated to the cyclone. Pradhan and Singh (2006) conducted a study using DWR Kolkata data for analyzing the vertical structure of the same tropical cyclone. In the study, an analysis of vertical wind shear associated to the tropical cyclone was done before and after the landfall of the cyclone. The study showed that the vertical wind shear of the order of 18 m/s was found in the layers 2-3 km above ground. The vertical wind shear associated with the cyclone had a very high value just before the landfall but the shear reduced very rapidly after the landfall of the cyclone.

As per World Meteorological Organization (WMO) report (1984), once a cyclone is located by radar, it is important to predict its motion and future positions and the most reliable feature of the cyclone that can be tracked to provide the direction and speed of the storm is the eye. Some idea of the direction of motion may be gained if the upwind ends of the bands can be observed as these are to the right of the direction of motion. DWR is capable of measuring radial winds in the innermost core of the storm. It has been well documented by Doviak and Zrnic (1979) and Wilson and Wilk (1982) 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 study of cyclone. Lhermitte and Atlas (1961) described how a single Doppler radar could be used to determine the vertical profile of horizontal uniform wind. They proposed a data collection mode in which the radar beam is directed at a constant elevation angle and the radial velocity is continuously recorded at several ranges as the radar beam sweeps through a full circle. This produces a series of traces called Velocity Azimuth Display (VAD). Since the wind is rarely uniform over the large volumes surveyed by the radar, it is considered that the analysis of Doppler velocities for wind, that is linear within the analysis volume or on horizontal area, necessarily lies over the radar. This technique was first submitted by Waldteufel and Corbin (1979) who introduced the term Volume Velocity Processing (VVP).

TABLE 1

Wind speed corresponding to different low pressure systems

Types of System	Associated wind speed	T. No. by D'Vorak Technique
Low pressure area	<17 knots	
Depression	17-27 knots	1.5
Deep depression	28-33 knots	2.0
Cyclonic Storm	34-47 knots	2.5-3.0
Severe Cyclonic Storm	48-63 knots	3.5
Very Severe Cyclonic Storm (I)	64-90 knots	4.0-4.5
Very Severe Cyclonic Storm (II)	91-119 knots	5.0-6.0
Super Cyclonic Storm	≥ 120 knots	6.5

Doppler Weather Radar located at Kolkata (22° 34′ 10″ N, 88° 20′ 45″ E) along east coast of India, is an S-Band radar with wavelength 10 cm, operating at 2875 MHz frequency and being utilized for the study of tropical cyclones, severe thunderstorms, hailstorms and other weather related events in the Gangetic West Bengal and adjoining regions. Round the clock Doppler data is being archived in addition to real time nowcasting of such events. In the present case study, analysis of a very short term but very severe cyclonic storm has been performed using Doppler radar data. The cyclone was virtually unreported by synopticians and satellite meteorologists of India also could not identify it whereas the first author at Kolkata observed the signatures of the cyclone on 19 September, 2006 and reported to the forecasters for issue of warning.

2. Methodology

Table 1 depicts the classification of cyclonic storms based on the wind speed. D' Vorak (1975) used satellite picture pair technique to estimate the intensity of cyclonic storms of Atlantic and Pacific origin and used to estimate maximum sustained wind speed and pressure drop very accurately. Both visible and Infra Red (IR) pictures were used in the picture pair technique. A cyclone has a Central Dense Overcast area known as Central Feature (CF) around a dark 'eye' (free from cloud) around which inflow feeder bands of cyclone coil around is known as 'Banding Feature' (BF). According to D'Vorak, strength of a cyclone is given by T number by the following relation:

$$T = CF + BF \qquad (i)$$

The CF depends upon the shape and type of central overcast region, the feature of the 'eye', nature of protruding of 'eye' inside the cyclone centre, and spiral binding features, ½ turn, 1 turn, 1½ turn etc. As suggested by D'Vorak, T number has a maximum value of 8 and minimum value of 0.5. The relation of T number with the maximum sustained wind speed is shown in the Table 1. The table shows that one of the basic criteria for declaring a cyclone is the high wind speed associated to the system in addition to the pressure drop in the eye wall region, the existence of the circular "eye", spiral bands surrounding the eye and cyclonic circulation. The DWR provides a very good measurement of the radial wind, the intensity of the cyclone (in terms of reflectivity measured in dBz) and its well defined structure showing an eye and the spiral bands. During the cyclonic circulation of the wind with the low pressure systems, the radial wind measurement provides a very accurate measurement of the actual wind associated to the system.

2.1. *Concept of velocity folding*

DWR measures the radial component of wind velocity and the corresponding value is presented in pictorial form as per the velocity scale in pseudo colours. The radial component of wind velocity towards the radar is represented in "Blue" colours whereas the away from the radar is shown by "Orange and Red" colours. The maximum measurable velocity range depends upon various factors including distance of measurement, wavelength and Pulse Recurrence Frequency (PRF) selected by the user. The maximum unambiguous velocity detectable by a Doppler Weather Radar is given by

$V_{max} = PRF \times \lambda / 4$ (λ represents the wavelength of radar signals)

TABLE 2

Scheduler parameters for Radar observations

Parameter	Reflectivity	Radial velocity
Scan Range	500 km	300 km
Scan Resolution	1 km	0.3km
Display range	250 km for Max_Z 500 km for PCAPPI_Z	300 km
Display resolution	1.25 km / 2.5 km	1.5 km
Pulse Width	2 μ sec	1 μ sec
PRF	300 Hz	500 Hz / 333 Hz
Antenna Scan rate	9.0 deg/sec	6.0 deg/sec

And the maximum unambiguous range is given by

$R_{max} = 2c / PRF$ (c represents the speed of light)

Therefore,

$R_{max} \times V_{max} = c\,\lambda/8$, also known as Doppler Dilemma.

$V_{max} = c\,\lambda / (8\,R_{max})$

In the present observations, R_{max} = 300 km, $c = 3.0 \times 10^8$ m/s , $\lambda = 10$ cm

$$V_{max} = 12.5 \text{ m/s} \qquad (1)$$

Using Dual PRF/PRT (Pulse Recurrence Time) technique also known as staggered PRT suggested by Zrnic & Mahapatra (1985), the two PRF's are in ratios of either 3:2, 4:3 or 5:4. The unambiguous velocity is given by

$V_{max} = \pm \lambda / \{4(T_2 - T_1)\}$
where $T_1 = 1/(PRF_1)$ & $T_2 = 1/(PRF_2)$

$$V_{max} = \pm \lambda\, PRF_1 \times PRF_2 / \{4(PRF_1 - PRF_2)\} \qquad (2)$$

The unambiguous range using Staggered PRT becomes

$$R_{max} = c(T_1 + T_2)/2 \qquad (3)$$

Table 2 shows that the PRF's used in the radar observations are 500 Hz and 333 Hz (unfolding ratio is 3:2), the maximum unambiguous velocity becomes 25 m/s which is two times that as calculated at Eqn. (1). Therefore, with the present set of radar parameters, the maximum measurable velocity could be 25 m/s only.

However, if the actual wind velocity associated to the cyclone is more than the maximum value of the scale, it is presented in combination of two opposite velocities together *i.e.*, red and blue colours together. This presentation of two opposite colours for the actual velocity crossing the scale of measurement is known as "velocity folding" or "velocity aliasing". The calculation of the actual or unfolded velocity is known as "velocity unfolding" or "velocity De-aliasing". The Doppler Signal Processor takes care of the radial velocity exceeding the measurement range of the velocity and accordingly velocity folding takes place. The unfolded value of the radial velocity (actual radial velocity) may be determined manually by the meteorologists by adding the resolution of the scale to the maximum unambiguous velocity.

For example - If the extreme blue color is folded to the extreme red color then,

Unfolded radial velocity = Maximum unambiguous velocity + resolution of the scale
= 25 m/s + 3.5 m/s = 28.5 m/s.

However, if the penultimate blue color is folded with extreme red or *vice versa* then,

Unfolded radial velocity = Maximum unambiguous velocity + 2 × (resolution of the scale)
= 25 m/s + 2 × 3.5 m/s = 32 m/s.

The folding can also be removed by initially setting the two PRF's in the ratio of 4:3 (provides three times the unambiguous velocity) or 5:4 (provides four times the unambiguous velocity) such that the measured (actual) wind velocity lies within the range of measurement. During the observational period (19 September, 2006) when the SW monsoon was active over the Gangetic West Bengal region, formation of severe cyclonic storm was not very much expected and hence the maximum range was set as 25 m/s only.

3. Data

The continuous radar data was available using an automatic scheduler at an interval of 30 minutes containing two volume scans *viz*., one for reflectivity in 500 km range and another for radial velocity in the 300 km range. The radar and scan parameters set for reflectivity and radial velocity observations in the scheduler are given in Table 2. Radar data has been analyzed at half hourly interval from 0000 UTC to 2300 UTC of 19 September, 2006. In addition to radar data, satellite images (IR) from Indian Communication satellite (KALPANA 1) have also been used for the analysis. The standard derived products like Maximum Reflectivity

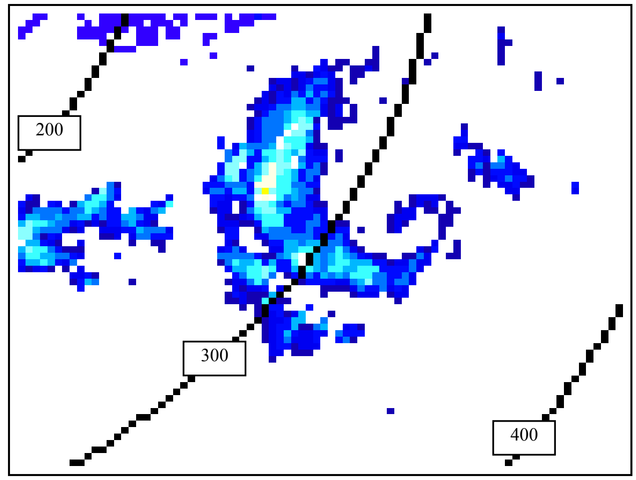

Fig. 1. PCAPPI_Z (0600 UTC)

(MAX_Z), Plan Position Indicator velocity (PPI_V) and Pseudo Constant Altitude PPI for reflectivity (PCAPPI _Z) have been utilized for the analysis of the system. A brief introduction of these products is given below.

3.1. *MAX_Z (Maximum Reflectivity)*

This is a derived product from volume reflectivity data in the form of 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 shown on 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 description of the algorithm has been given in the technical manual of Gematronik, Germany the manufacturer of the DWR installed at Kolkata.

This is a very useful product in determining the location of the system, the intensity of precipitation associated to the system in terms of dBz and vertical extent of the system. The range of this product is about 300 km from radar.

3.2. *PPI_V (Plan Position Indicator _velocity)*

This is a derived product from basic radial velocity data. The PPI observations are taken at a fixed elevation angle of 0.2 deg. The height of the radar beam increases as the range increases. At a distance of 250 km from the radar the height of the radar beam becomes 4.5 km above the ground and therefore, the radial velocity measured at 250 km corresponds to the height of 4.5 km above the ground.

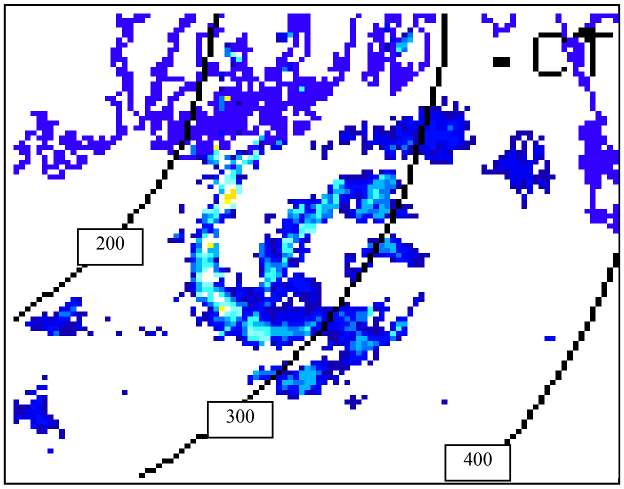

Fig. 2. PCAPPI_Z (0700 UTC)

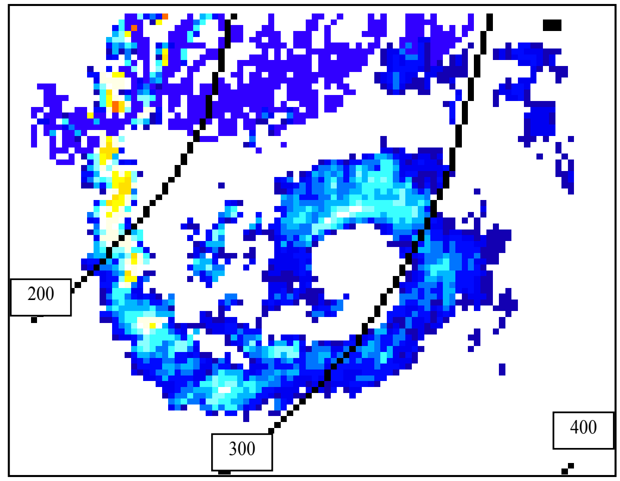

Fig. 4. PCAPPI_Z (0830 UTC)

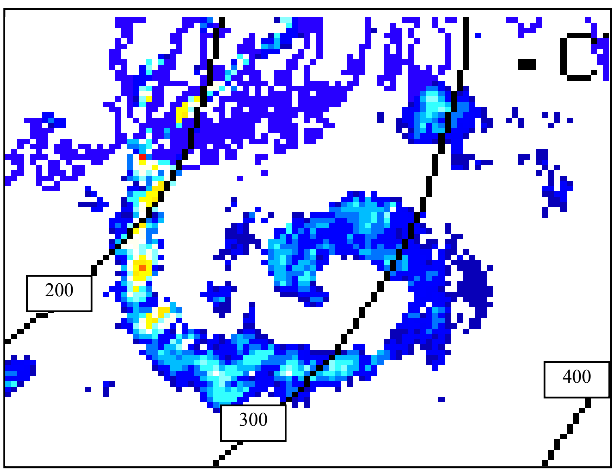

Fig. 3. PCAPPI_Z (0800 UTC)

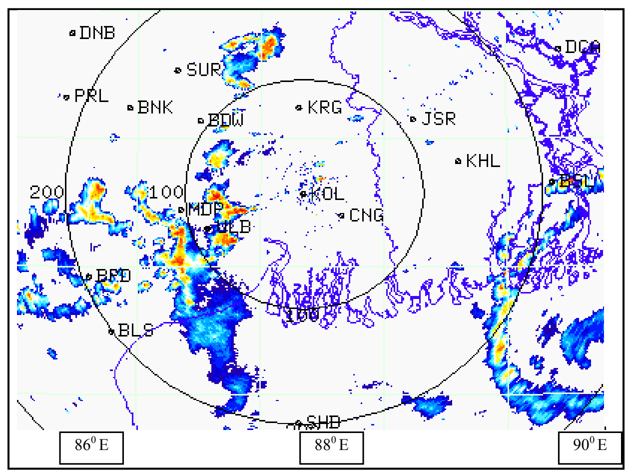

Fig. 5. Max_Z (0800 UTC)

3.3. *PCAPPI_Z (Pseudo Constant Altitude PPI _Reflectivity)*

This product is derived from the volume reflectivity data and it provides two dimensional presentation of all echoes observed at a fixed altitude above ground. This is similar to CAPPI (Constant Altitude PPI) except that the areas of "no data" close to the radar site and at large ranges are filled with data of the corresponding elevation. PCAPPI_Z may be derived from an altitude of 1 km to 16 km for analyzing the extent of Tropical cyclone and associated reflectivity at these levels. In the present study, PCAPPI_Z at 1 km height has been considered for analysis.

4. Results and discussion

4.1. *Analysis of PCAPPI_Z (1 km) pictures*

DWR observed the first signature through PCAPPI (500 km) product at 0600 UTC (Fig. 1) in which two spiral bands were observed at a distance of about 280 km SE of Kolkata. A circulation like "eye" formed by a spiral band structure at a distance of about 330 km was also visible.

The spiral bands appeared to get disorganized at 0630 UTC observation but reorganized at 0700 UTC (Fig. 2). The sequence of the pictures showed that the

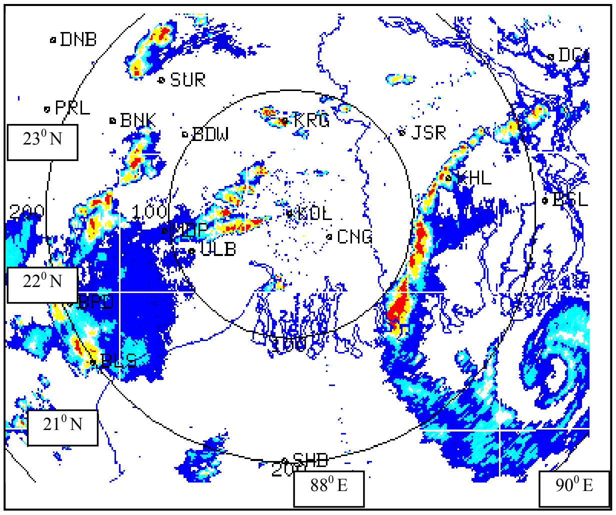

Fig. 6. Max_Z (1000 UTC)

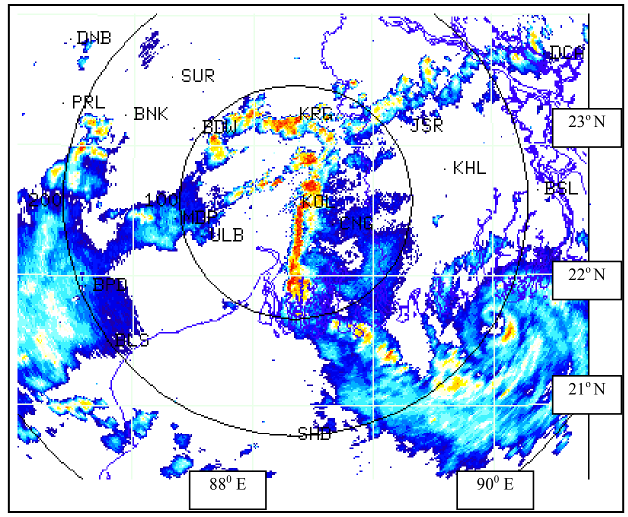

Fig. 7. Max_Z (1200 UTC)

system moved in westward direction. The spiral band structure became very prominent at 0730 UTC with a high reflectivity band in the forward direction. The structure of the system became more circular and like a tropical cyclone at 0800 UTC (Fig. 3) with centre of the cyclone at a distance of 300 km SE of Kolkata. The span of the spiral band structure was about 100 km and a squall line structure was also formed ahead of the system which was more than 100 km in length. This squall line ahead of the system is a pre-cursor of the cyclone containing very high rainfall. The intensification of the system was observed at 0830 UTC (Fig. 4) with better organization of the eye of the cyclone with a diameter 40 km. If the Dvorak technique is applied for the intensity of the system then both CF and BF are observed for the system and the intensity lies close to T 2.0 corresponding to deep depression. Since the system was away from Kolkata (more than 250 km) the radial velocity information could not be collected. However, the pattern recognition may be done on the basis of reflectivity analysis.

4.2. *Analysis of Max_Z pictures*

The Maximum reflectivity picture at 0800 UTC (Fig. 5) measured at 300 km range (similar to the PCAPPI picture at 0800 UTC) shows the formation of a system with centre at a distance of about 290 km SE of Kolkata. Another squall line structure at about 350 km ahead of the centre of the cyclone and about 80 km West and NW of Kolkata was formed by the series of convective clouds over Midnapur (MDP), Bardhman (BDW), Ulubaria (ULB) and other places in the surroundings. A band of lower reflectivity may also be seen to the South-West of the Kolkata indicating moisture incursion from the Bay of Bengal towards the land.

The system further advanced in the North-West direction and its centre was observed at 260 km at 0900 UTC showing the speed of the movement of the system by 30 km/h. The pre-squall line structure of length 150 km became more prominent with a high reflectivity of the order of 45 dBZ at a distance of 170 km SE of Kolkata near the border of Bangladesh. The next observation at 1000 UTC (Fig. 6) shows the intensification of the system with increased reflectivity (about 50 dBZ) in the pre-squall line reaching at a distance of 110 km from Kolkata. A closed eye surrounded by spiral bands can be seen in this figure, indicating signatures like a cyclone. The centre of the eye was observed at a distance of 240 km from Kolkata. The system became a tropical cyclone at 1100 UTC in which nearly circular eye is seen with centre at a distance of about 210 km from Kolkata. The cyclone moved towards NW direction with an average speed of 30 km/h. The squall line ahead of the system also advanced and reached close to Kolkata at a distance of about 60 km acquiring a velocity of 50 km/h. This is easily observed that the distance of the squall line from the centre of the cyclone has increased in comparison of the previous observation at 1000 UTC (Fig. 6). This is an established fact that squall line always moves with an average speed of 50-60 km/h creating wind squall whereas the movement of the cyclone is usually about 25-30 km/h. The Max_Z picture at 1200 UTC (Fig. 7) shows all features of a matured cyclone with a closed circular eye, double spiral bands and a clear cyclonic circulation with lot of precipitation content in the outer and inner spiral bands. The diameter of the eye became very small (about 15 km only) showing in general a severe cyclonic storm. A high reflectivity squall line of length exceeding 150 km may be seen over Kolkata traveling a distance of about 60 km during 1100 UTC and 1200 UTC.

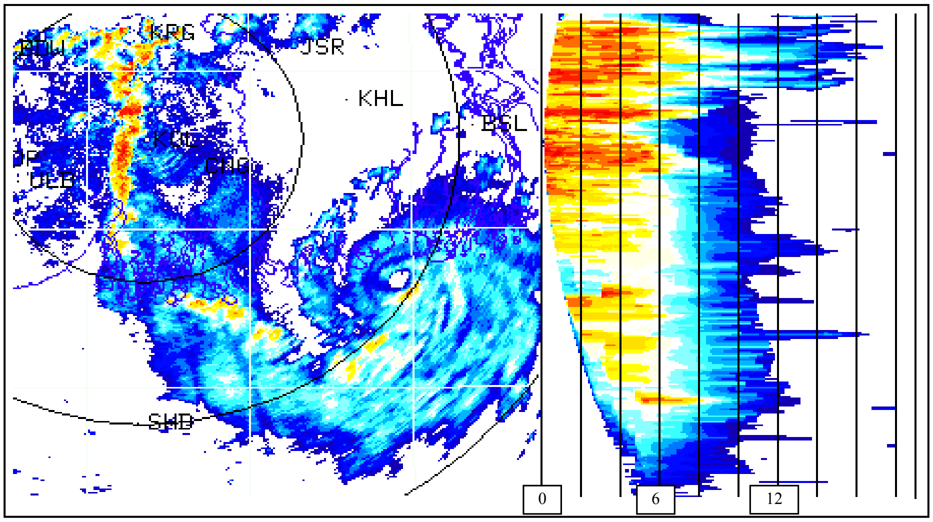

Fig. 8. Max_Z (1230 UTC)

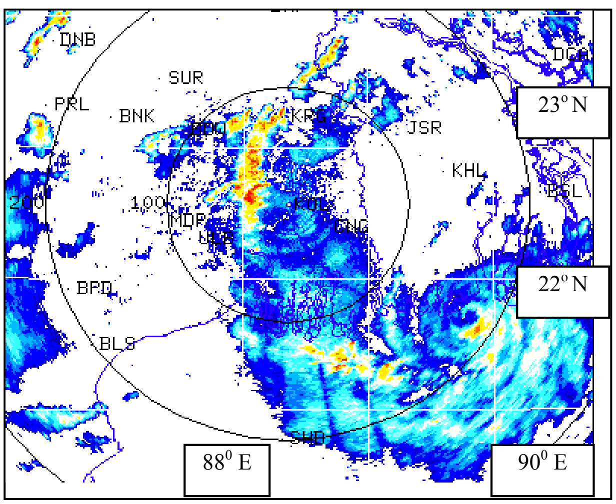

Fig. 9. Max_Z (1300 UTC)

The Max_Z picture at 1230 UTC (Fig. 8) shows all the characteristics of a severe cyclonic storm. The centre of the tropical storm was about 190 km from Kolkata. The reflectivity associated with the squall line over Kolkata was in the range of 49-52.3 dBz (indicating a high precipitation content with the clouds) and the vertical extent of the clouds associated with the squall line was in the range of 10-14 km (that may be seen from the right part of the figure which shows the vertical extent of the radar reflectivity associated to the clouds). The height of the wall clouds surrounding eye region was lying in the range from 8-12 km. The next MAX_Z picture (Fig. 9) at 1300 UTC also shows the matured cyclone moving in the NW direction. The Max_Z picture at 1630 UTC (Fig. 10)

TABLE 3

Variation of radar beam height with range at fixed elevation

Elevation angle (Deg)	Range (km)	Height (km)
0.2	100	0.94
0.2	150	1.85
0.2	200	3.16
0.2	250	4.59
0.2	275	5.41
0.2	300	6.28

showed that cyclone moved in the NW direction and lay centered at a distance of 110 km from Kolkata. The average speed of movement of the severe cyclonic storm during 1230 UTC and 1630 UTC was 20 km/h.

The above discussion shows that the system intensified from a depression at 0600 UTC to a fully matured Tropical Cyclone at 1200 UTC. As per the records of Self Recording Rain Gauge (SRRG) installed at Alipore observatory, Kolkata (which is located at a distance of 5 km from DWR), 22.5 mm of rain was recorded during 1200 UTC to 1500 UTC on 19 September, 2006.

4.3. *Analysis of PPI_V Pictures*

The velocity observations are analyzed from PPI_V picture at 0.2 deg elevation. Table 3 displays the range-height correspondence for 0.2 deg elevation for the radar

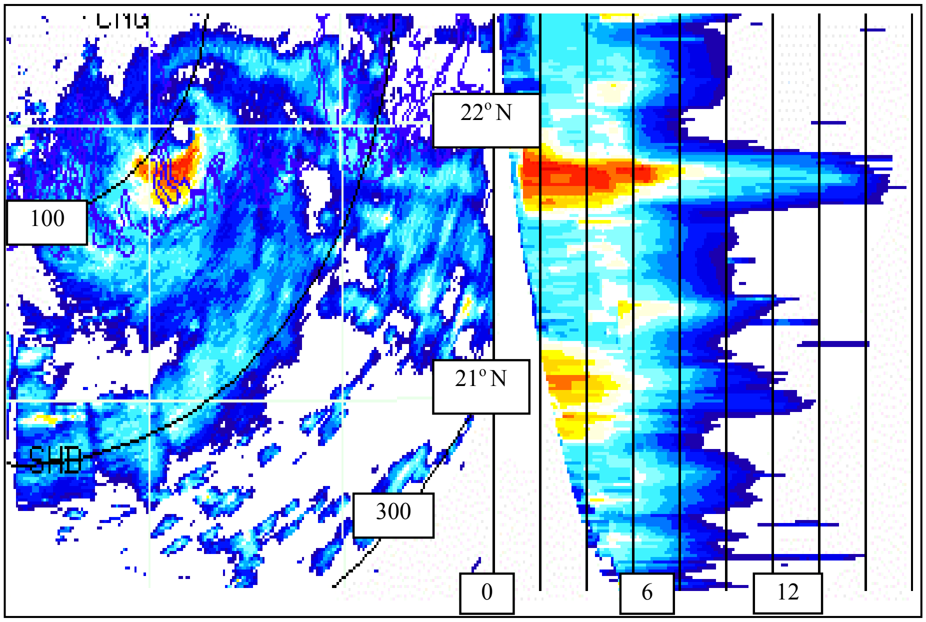

Fig. 10. Max_Z (1630 UTC)

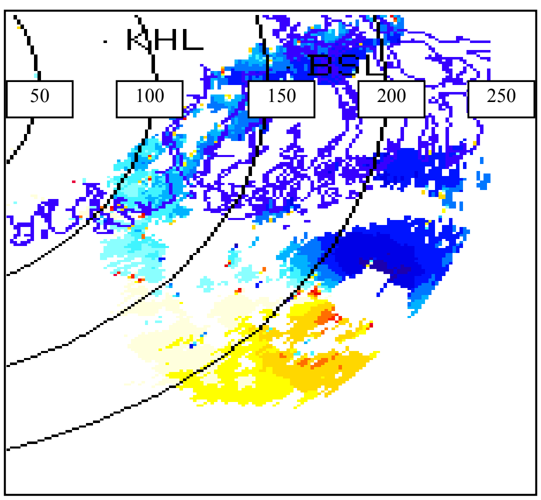

Fig. 11. PPI_V (0830 UTC)

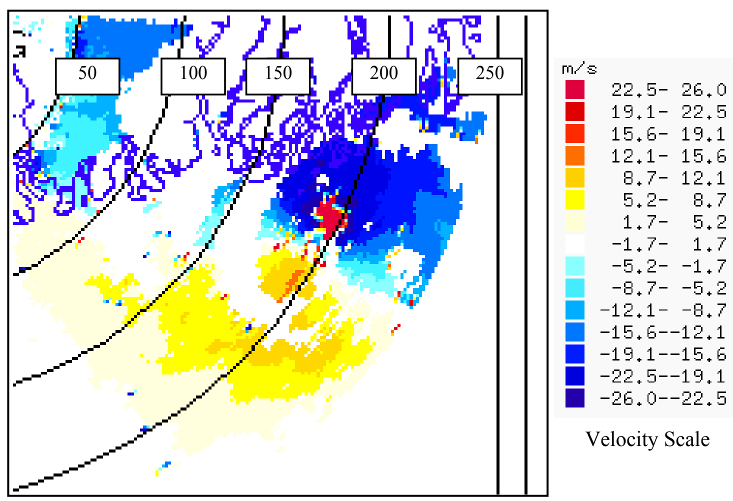

Fig. 12. PPI_V (1000 UTC)

beam height. The velocity signatures of the cyclonic circulations were first observed at 0830 UTC (Fig. 11) when the centre of the system was 275 km away from DWR. The velocity presentation in the spiral bands clearly show cyclonic circulation (blue color as wind component towards the radar and the red color as moving away from radar). At this distance the radar beam was at a height of 5.4 km (being elevation at 0.2 deg) and therefore, the velocity is related to this height. A closed eye is observed with the wind velocity 25 m/s (50 knots) in the eye wall region. This picture is very similar in structure to the PCAPPI_Z at 0830 UTC (Fig. 4). However, two spiral bands could be seen in the velocity picture (Fig. 11) instead of only one spiral band in reflectivity picture. The

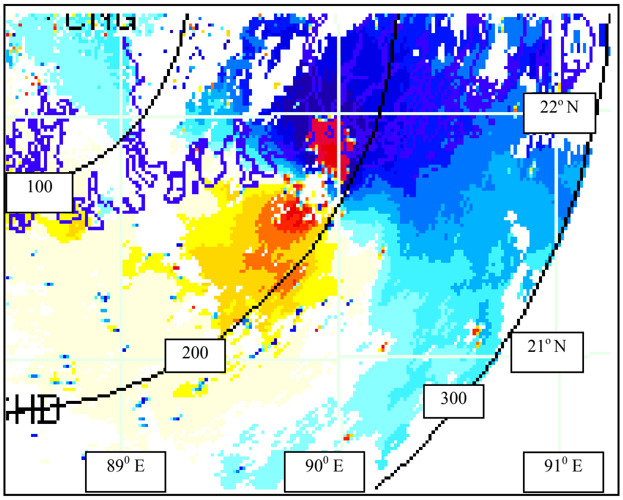

Fig. 13. PPI_V (1230 UTC)

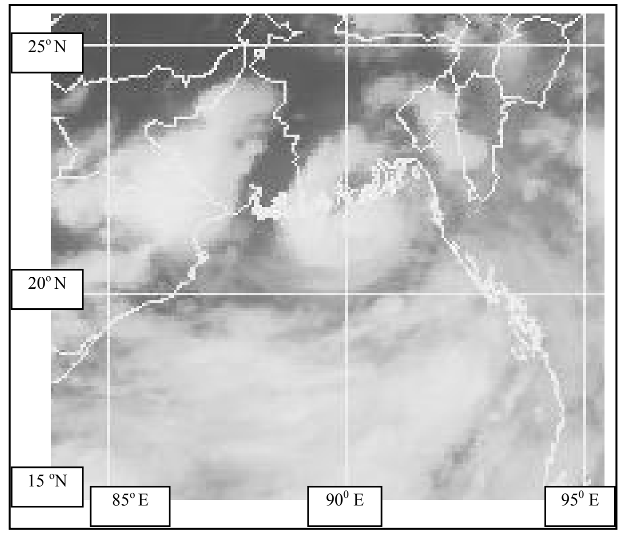

Fig. 15. Satellite imagery (IR) of 19 September 2006 (1100 UTC)

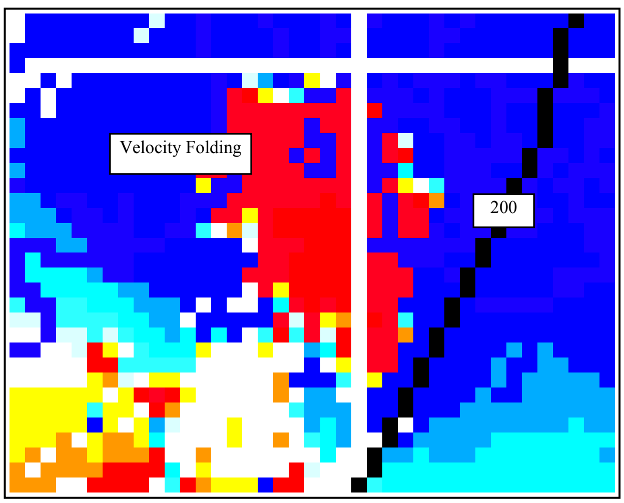

Fig. 14. Zoomed view of PPI velocity showing Velocity Folding (1230 UTC)

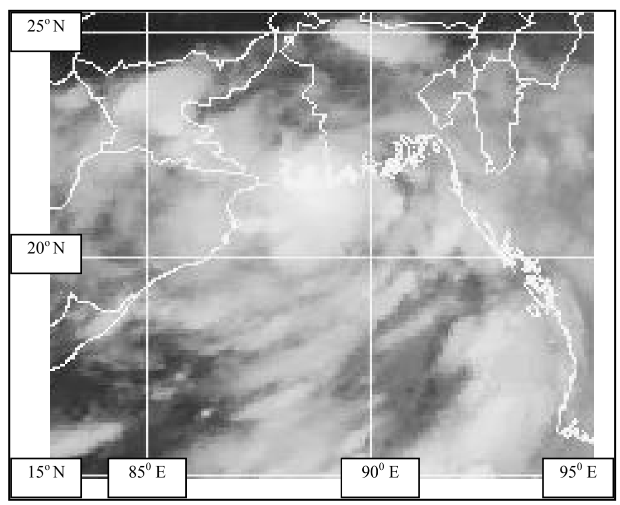

Fig. 16. Satellite imagery (IR) of 19 September 2006 (1700 UTC)

system appears to be a deep depression with spiral bands and a closed structure like eye. The diameter of the Radius of Maximum Winds (RMW) as seen from the velocity pictures was about 40-50 km.

The velocity picture at 1000 UTC (Fig. 12) shows higher velocity at the centre of the system. The velocity folding may be observed at the centre of the system. The actual velocity (unfolded) is 28.5 m/s as calculated in the section 2.1. This velocity picture resembles to the structure of Max_Z picture at 1000 UTC. The centre of the storm may be seen at a distance of 240 km from DWR. The velocity of movement of the cyclone is about 24 km/h in the NW direction. The velocity picture at 1100 UTC showed that the system further advanced steadily in NW direction. The centre could not be seen clearly as the wind occupies the inner area of the eye of the system but verified from the reflectivity picture of the same time of observation where a closed eye was seen at a distance of 215 km from DWR. The wind velocity appears to be same as observed earlier as 28.5 m/s (57 knots) at a height of 3.4 km above the ground. The moisture feeder bands are also visible in a wider area surrounding the centre of the system. The features as seen in the velocity picture are also available in the reflectivity pictures. The system appears to be a matured cyclone at this stage. The next velocity observation at 1230 UTC (Fig. 13) shows increased velocity in the wall cloud region surrounding the eye of the cyclone. The centre of the cyclone lies at a distance of 190 km from DWR. A small core system with a radial velocity exceeding 32 m/s (64 knots, as calculated in section 2.1) at a height of 3 km above the ground may be seen clearly. A zoomed view of the same picture is given in Fig. 14, showing velocity folding in the eye wall region with the no wind area (represented by white color) to the southwest of the velocity folding region As discussed by Pradhan *et al.* (2006) the wind velocity remains almost the same from surface up to 5 km and then it gets reduced gradually with height, the wind velocity at the lower levels will also be of the order of 32 m/s (64 knots) which is an indicator of a very severe cyclonic storm.

IR Satellite image at 1100 UTC (Fig. 15) shows a circular eye with many clouds around it in the form of spiral bands and is in close agreement with the existence of a cyclonic storm showing the centre of the eye located at 21.6° N / 90.2° E. The existence of cyclonic storm is not so conspicuous at the satellite image at 1700 UTC (Fig. 16). However, the system was successfully tracked by DWR Kolkata. The reflectivity picture at 1630 UTC (Fig. 10) shows the circular eye and the spiral bands associated with the cyclonic storm.

5. Conclusions

The system which could not be predicted synoptically or decisively by satellite images, was very well observed and tracked by Doppler Weather Radar at Kolkata. The system was a fully matured Tropical Cyclone with maximum radial wind velocity of the order of 32 m/s *i.e.*, 64 knots at 1230 UTC of 19 September, 2006 which is equivalent to T Number 3.5 (severe cyclonic storm). The vertical extent of the system was more than 12 km as seen from the Max_Z pictures of the cyclone. The system moved initially towards NW of the Kolkata but after 1630 UTC it moved towards West. The system had a landfall around 1700 UTC of 19 September, 2006 and the system got weakened to a deep depression for sometime but again got intensified and became a cyclone over the land. Very heavy rainfall occurred during next two days in the Gangetic West Bengal region, Bihar, Jharkhand and adjoining areas. The study establishes the importance of ground based Doppler Weather Radar for the study of cyclone observation and its structural analysis through reflectivity and radial velocity images in the real time mode. However, off line processing may also conclude some very specific results for the weather scientists.

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