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Morphology of long lasting mesoscale convective system under weak synoptic forcing over the Gangetic plain in May 2010 during the STORM-2010 campaign

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सार – इस शोध पत्र में खराब मौसम के बारे में तात्कालिक पूर्वानुमान देने में मदद के लिए भीषण गर्ज वले तूफानों से सन्निहित लंबे समय तक बने रहने वाले मेघ पुंज का अध्ययन करने के लिए उपग्रह से प्राप्त आँकड़ों से इस तरह के सिस्टम्स की प्रभावोत्पादकता का पता लगाने का प्रयास किया गया है। इस सिस्टम में कुछ विलक्षण विशेषताएं थी जो उत्तराखंड क्षेत्र के ऊपर (6 मई 2010 को 1300 यू टी सी पर) बनी जो भारतीय गांगेय क्षेत्रों के ऊपर से गुजरते हुए अपने उद्भव से 24 से 36 घंटों के बाद ओडिशा/बंगलादेश तक पहुँच गयी। इसमें कल्पना-। से प्राप्त उपग्रह सूचना का मेघ शीर्ष तापमान (CTT) के संदर्भ में और उष्णकटिबंधीय वर्षा मापन मिशन (TRMM) डेटा से प्राप्त वर्षा का विश्लेषण किया गया है। इस सिस्टम की तीव्रता का निर्धारण मौसम विज्ञान संबंधी प्रेक्षणों, स्वचालित मौसम स्टेशन (AWS), एअरपोर्ट मौसम रिपोर्टों, स्वत: लेखी आँकड़े और राँची तथा खड़गपुर के मिटियोरोलॉजिक टावर डेटाके विश्लेषण से किया गया है। इस सिस्टम की तीवृता तथा इसके क्षेत्रीय विस्तार का निर्धारण करने के लिए प्राथमिक सूचना के रूप में उपलब्ध उपग्रह आँकड़ों का उपयोग किया गया है। इस शोध पत्र में संवहनीय प्रणाली के उद्भव का विवरण विस्तार से बताया गया है । इस सिस्टम की दीर्घ अवधि में संवहनीय प्रणाली दो चरणों में तीव्र हुई है। प्रथम चरण पश्चिमी उत्तर प्रदेश (UP) के ऊपर और द्वितीय चरण बिहार, झारखंड, पश्चिम बंगाल क्षेत्र के ऊपर था । जब यह सिस्टम कोलकाता के रेडार की निगरानी में आया तो द्वितीय चरण की तीव्रता का उपयोग रेडार की सूचना के लिए किया गया है।

ABSTRACT. A case study of long-lasting cloud cluster with embedded severe thunderstorms is conducted using the satellite data to demonstrate the efficacy of tracking such systems for help in nowcasting severe weather. The system had some unique features as it originated over Uttarakhand region (6 May 2010, 1300 UTC), travelled all across the Indo-Gangetic plains and reaching up-to Odisha/Bangladesh 24 to 36 hrs after its origin. The signature of the satellite information is analyzed in terms of cloud top temperature (CTT) from Kalpana-1 and associated rainfall from Tropical Rainfall Measuring Mission (TRMM) data. Intensity of the system is determined with the analysis of meteorological observations, automatic weather station (AWS), airport weather reports, autographic data and the meteorological tower data at Ranchi and Kharagpur. The use of satellite data provided one of the primary information for determining the intensity of the system and its areal dimensions. The paper discusses the evaluation of the convective system through its life history in some detail. In its long life, the convective system becomes intense in two phases. The first phase was over western Uttar Pradesh (UP) and the second phase was over Bihar, Jharkhand West Bengal belt. Radar information is used for the second phase of intensification as the system came under surveillance of Kolkata radar.

Key words – TRMM, AWS, CAPE, CINE, MCS, MCC.

1. Introduction

During the pre-monsoon season (March-May) convective weather develops in many places in the Indo-Gangetic Plains, which causes devastation both to life and property on several occasions. Very occasionally thunderstorms even become tornado with wind speed of over 150 km/hr. Such weather events are known as dust storms or Andhis when they occur over the dry northwestern part of India and severe local thunderstorms (Nor'westers) when they occur over rather moist eastern India, stretching from Bihar Jharkhand, Odisha, West Bengal, Sikkim and the seven northeast (NE) states (Arunachal Pradesh, Assam, Meghalaya, Nagaland, Manipur, Mizoram & Tripura). Such events also occur over Bangladesh. Researchers in India and Bangladesh have made several studies with conventional, radar and satellite data to understand the synoptic factors, which favour such convective weather developments (Srinivasan *et al*., 1973; Pradhan and Sinha 2005; Mukhopadhyay

Fig. 1. Area of the STORM program

et al., 2009). Thus, the synoptic situations causing the favourable conditions for the occurrence of thunderstorms and Nor'wester over different parts of India have been discussed from time to time. Mukhopadhyay *et al.*, (2009) also made a detailed study, using the satellite and radar observations, of two thunderstorm events on 12 March and 22 May 2003 over Kolkata region and found the utility of satellite and radar observation in capturing the evolution of Nor'westers.

Besides the early field programs conducted by India Meteorological Department (IMD) in 1930s to 1940s, the Indian atmospheric research community has launched a special program since 2006 known as Severe Thunderstorm Observation Research and Modeling (STORM) to understand the processes responsible for the development of severe local thunderstorm and predict it using regional mesoscale dynamical models, Department of Science & Technology (DST) Science Plan 2005. Under this program operational and special conventional, satellite, radar and surface layer tower data are utilized to keep a watch on convective weather development over the STORM region consisting of east and northeast India (Fig. 1). Since 2009 the neighbouring countries like Bangladesh, Nepal & Bhutan have also joined in addition to India. Tyagi *et al.*, (2012) examined the satellite observed cloud clusters data over the region for the years 2007-2010 and documented the preferred areas where such cloud systems originate, develop, mature and weaken. Some of the mesoscale convective systems (MCS) merge to produce huge region of cloudiness in the infrared channel and attain the size and characteristics of mesoscale convective complexes (MCC). Characteristics of MCC are described in Table 1. An isolated cumulonimbus (Cb) cloud of a few kilometer dimensions is capable of producing thunder and lightning. When a few Cb clouds develop in close vicinity to each other, some of them develop much deeper than many other Cb

TABLE 1

Characteristics of a Mesoscale Convective Complex (MCC)

Characteristic	Threshold
Size of MCC	A : Cold cloud shield with continuously low IR temperature ≤ -30 °C must have an area ≥ 100000 km^2 B : Interior cold cloud region with temperature ≤ -50 °C must have an area ≥ 50000 km^2
Initiation of MCC	Size and intensity definitions (A and B) are satisfied. Initiation for MCCs occurred when the IR convective cloud shields reached minimum initiation size of 10000 km^2
Development of MCC	Size definitions A and B must be met for a period ≥ 6 h
Dissipation or Termination Stage	Size definitions of MCC and cold cloud shield (A and B) no longer satisfied
Life Duration of MCC	Time in hours from the initiation stage of an MCC to its dissipation or termination stage

clouds in an identical synoptic atmospheric situation. Environmental conditions in term of circulation and thermo-dynamical parameters like convective inhibition energy (CINE) and convective available potential energy (CAPE) are not the only determinant of the structure and evolution of Cb clouds. Land surface processes such as surface wetness, vegetation, orography etc. also contribute to convective weather initiation, development and movement. The development may be initiated under strong or weak synoptic forcing, aided by the land surface processes and then sustained to maturity along the track followed by the cloud system, making it an MCS or even MCC as the case may be. Thus understanding the evolution of a few Cb clouds to their maturity as MCS or MCC in the form of overall aggregate of convective precipitation cells and ultimate dissipation is an important area of research under the STORM program.

Bhatia and Kalsi (1992) have used satellite data to study a thunderstorm in a weak synoptic environment. Pradhan and Sinha (2005) have used Kolkata Doppler weather radar data to examine development of thunderstorm over Kolkata recently.

Tyagi *et al*. (2012) have presented historical aspects of the studies undertaken in India on Pre-monsoon thunderstorms with special reference to Nor'westers. The Andhis or duststorm of northwest (NW) India are severe local weather under dry environmental conditions of the lower and middle troposphere accompanied with dry adiabatic lapse rate in the lower troposphere. They are accompanied with western disturbance, a large scale tropospheric system in the sub-tropical belt of India, moving east/northeastward from west of India. The convection associated with Andhis is favoured by the sub-tropical jet stream and the wind shear between the upper and lower troposphere. Unlike Andhis which are associated with strong synoptic forcing, Nor'westers occur in the environment which is associated with rather weak synoptic forcing. In case of Nor'westers the environment is moist in the lower troposphere under favourable inflow of moisture from the Bay of Bengal. Their development is aided by diurnal heating and land surface environment and hence convective weather is accompanied with significant rainfall. The intensity of convective development over eastern India and Bangladesh occasionally results into tornadic development even under weak synoptic conditions. The upper tropospheric winds and the vertical wind shear, though relatively weak in the case of Nor'westers as compared to Andhis, are still favourable for development of Nor'westers. Seasonally, CAPE is stronger and CINE is weaker over eastern India and adjoining region compared to northwest India. Many observational studies on Andhis and Nor'westers have focused on the structure and development of deep organized multi cellular convection over the two regions separately and have emphasized the role of environmental conditions in such developments. Such convective organization usually last for 3 to 12 hours. However on 6 May 2010, a very unusual case of such development occurred which was initiated in the hilly region of Uttarakhand, located near 30.0º N / 79.3º E and developed into a severe multi cellular thunderstorm complex on 7 May 2010 over the Gangetic plain. This is rather unusual case of development having a long life period of about 24 hours. The objective of the present study is to track the evolution of this MCS from early stage and bring out the role of synoptic situation and environmental conditions in its development. Section 2 describes the data and methodology used for the study. Section 3 gives the features of synoptic situation during the life history of the system. Section 4 provides growths and development history of the MCS. Section 5 discusses the weather associated with this MCS during its travel. Section 6 is regarding analysis of the mature stage using surface layer tower data from Kharagpur, Doppler weather radar data of Kolkata. Summary and concluding remarks are given in Section 7.

2. Data and methodology

STORM-2010 was carried out during 15 April to 31 May 2010 and a team of scientists/researchers used to meet on alternate days to monitor the development of Nor'westers over eastern India (Fig. 1). For tracking the evolutionary history of the MCS of 6-7 May, 2010, satellite imageries used is from the INSAT (Kalpana-1) visible (day lit hour) and infrared at every half an hour interval. The variations in intensity of the convection were measured by the analysis of cloud top temperatures (CTT) in infrared imagery as the lowest CTT temperature would indicate the intensity of convection. On 6 May 2010, an organised configuration of convective development was noted over Uttarakhand which was migrating southeastward towards Uttar Pradesh (UP). The cloud cluster approached from the western hilly region (Fig. 2). Fig. 3 gives the track of the centroid of the organized cloud cluster, which is henceforth denoted as MCS. In addition to the satellite imageries other observational tools

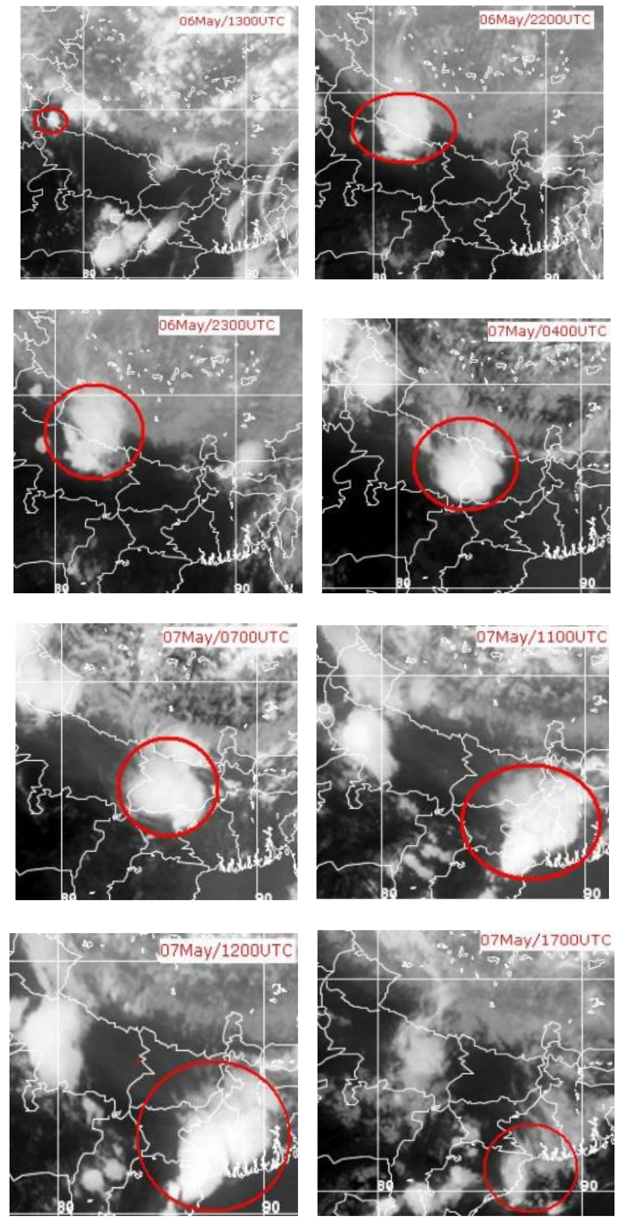


Fig. 2. Satellite infrared channel imageries from initiation to dissipation stages

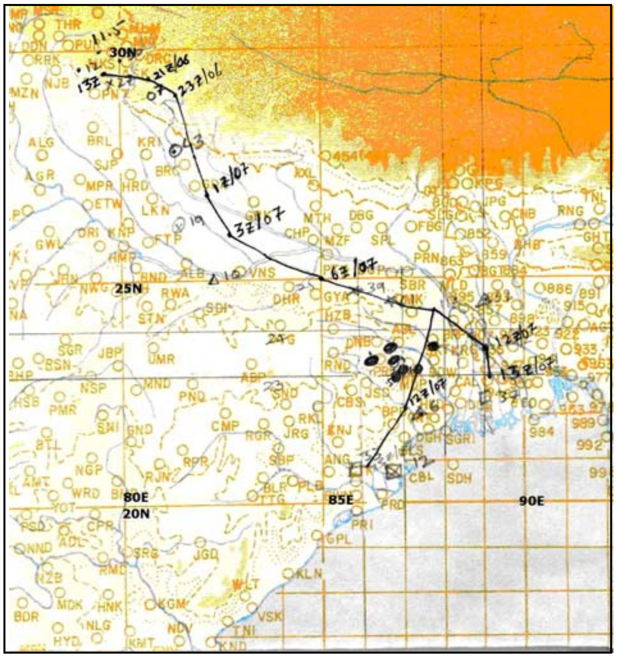


Fig. 3. Track of centroid of the convective cell

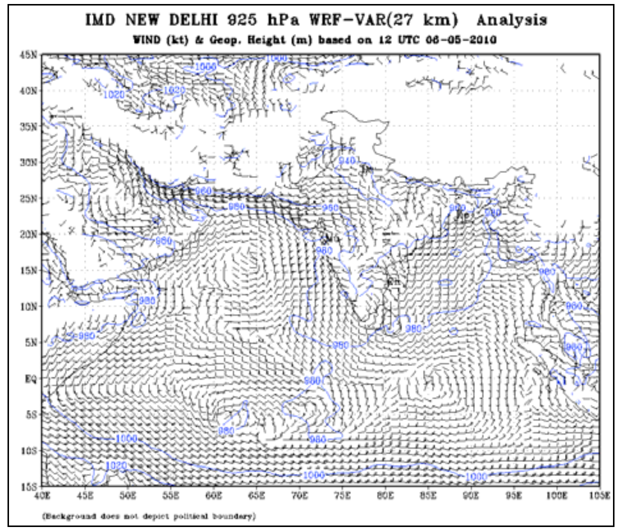


Fig. 4. WRF 27 km wind analysis at 925 hPa of 1200 UTC, 6 May, 2010

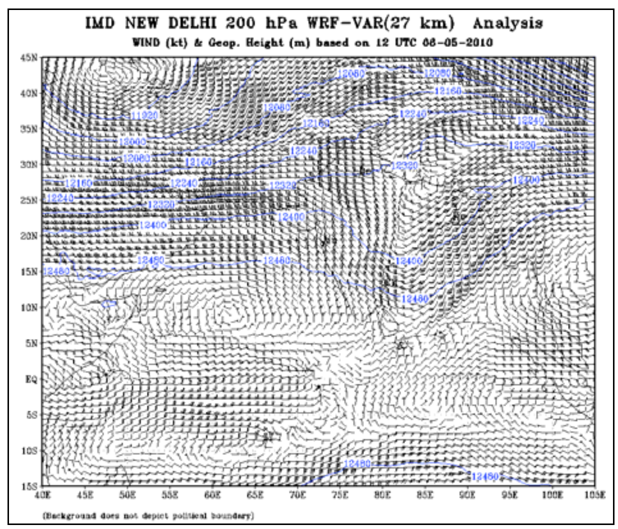


Fig. 5. WRF 27 km wind analysis at 200 hPa of 1200 UTC, 6 May, 2010

are used for this study as indicated in Appendix 1. The MCS passed through relatively dense network of surface observatories and automatic weather stations (AWS). Surface meteorological data of all the observatories of India Meteorological Department (IMD) and Indian Air Force (IAF) were collected from the regional offices. Data of upper air observatories (RS/RW and Pilot Balloon), though much less in density than the surface observatories, were also collected. A number of civil and IAF airports also exist in the Indo-Gangetic Plains and their half hourly METAR observations 3 to 6 hours prior and subsequent to the approximate time of passage of the MCS over the air field, were also collected. Data from two surface layer towers located at Ranchi (Lat. 23.42° N / Long. 85.24° E) and Kharagpur (Lat. 22.32° N / Long. 87.31° E) were also collected. Towards the end of the track of the MCS passed over densely situated AWS network over West Bengal under Jadavpur University and data of these stations were also obtained. Wherever available, records of wind, pressure, temperature and relative humidity were obtained. No radar data was available along the track from Uttarakhand to Bihar (Ranchi). However, the MCS came under the surveillance of Doppler weather radar at Kolkata from 0527 hrs to 1157 hrs (UTC) on 7 May and hence radar pictures were also collected. TRMM derived rainfall was also obtained over the region. Tower Data of IIT Kharagpur for wind speed, relative humidity, air temperature and air pressure at the interval of three minutes at six different levels 2, 4, 8, 16, 32 and 50 m above ground are also used. Besides these the regional analysis of winds at different levels based on the IMD global and WRF model for 0000 & 1200 UTC of 7 May as well as forecasts based on 6 May (0000 UTC) were also used as guidance material. Thus vast amounts of data have been used to investigate the life history of this large and long-lived MCS during its passage across the Indo-Gangetic plain.

Assembling of all the data sets took a lot of effort before their analysis could be made in a coherent manner. We note the shortage of AWS data and the total lack of radar data from the early development to first maturity of the MCS from Uttarakhand to Varanasi - Allahabad sector. Data from weather radar at Patna and Ranchi were missing and hence the possible weakening of the MCS while traveling between Varanasi to Ranchi could not be studied in detail.

3. Synoptic situation

A weak western disturbance was effecting North Pakistan and adjoining Jammu & Kashmir region of India on 5 May. This system progressed northeastward on 6 May. Fig. 4 shows the 925 hPa regional analysis based on WRF model. It shows the presence of a well-marked cyclonic circulation over the foothills of western Himalayas. A seasonal trough was also running across the Indo-Gangatic plains right upto Bangladesh. The global model analyses also showed the similar features. At 200 hPa level strong westerly to southwesterly flow prevailed over the area with a short wave trough lying over the western Himalayas as shown in Fig. 5. Region of western Himalayas and adjoining Pakistan was covered with multilayered clouds. Within this cloud system a small cellular region developed over the forested hilly region of Uttarakhand at about 1300 UTC hrs on 6 May. By 7 May 0000 UTC; the specific cloud cluster lay over the eastern edge of the western disturbance. The cluster continued to grow and develop during 0000 to 1200 UTC of 7 May but the regional model analysis as well as the global model analysis in the troposphere did not show any specific disturbance, which can be associated with the development of the cluster. It is inferred that with the trough lying in the eastern part of western disturbance, the cluster developed under diurnal heating of a vegetated elevated land area and subsequently it is advected by the westerly flow in the middle and upper troposphere. Regional and global analysis and the forecasts did not show any signature of the convection development of MCS throughout 7 May. Our analyses suggests that the development of the MCS occurred in a weakly forced environment but its sustenance during the travel across Indo-Gangetic plain was supported by the advection of moist easterly flow from Bay of Bengal across the foothills of central Himalayas and adjoining Gangetic plain under the influence of the seasonal trough over the plain

4. Growths and development history of the MCS

Any mesoscale convective system passes through a life cycle of initiation, development and growth, maturity and dissipation. In order to assess the growth and development history of the MCS under investigation, we have used the estimate of its area extent for its growth and the estimate of IR-imagery based on cloud top temperature (CTT) for its development. Fig. 3 shows the track of the centroid of MCS from origin on 1300 UTC of 6 May 2010 to its demise over Odisha at 1200 UTC of

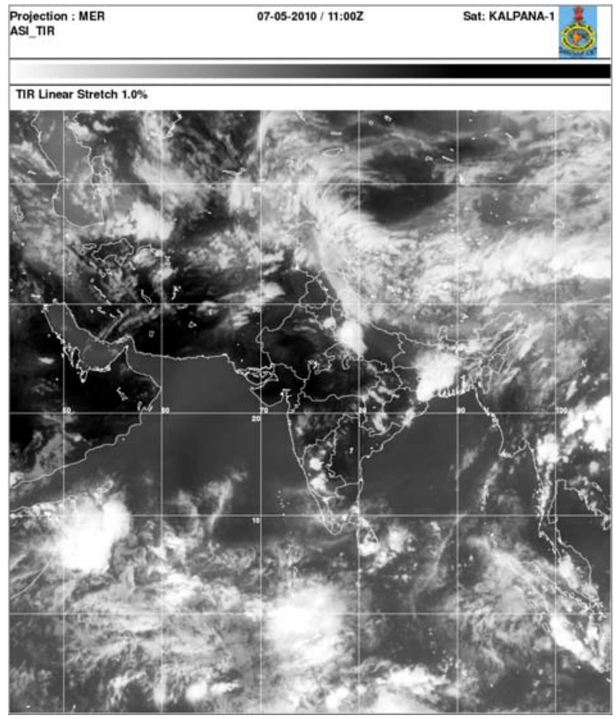


Fig. 6. IR image of 1100 UTC of 7 May, 2010

7 May (one portion) and 1300 UTC of 7 May (second portion) over Bangladesh. Initially for a couple of hours the MCS moved in east-southeast direction and from 2300 UTC of 6 May, it followed a southeast track upto 0300 UTC of 7 May. Thereafter again it followed east-southeast path upto Gangetic West Bengal (GWB). At this stage, when it lay in mature stage over GWB, it split into two parts near 24.5º N / 87.7º E between Dumka and Barrackpur. One part moved over Bangladesh and demised near 23.0º N / 89.1º E at 1300 UTC of 7 May. However the other part moved in southwest direction and finally dissipated over Odisha near 21.0º N / 86.1º E at 1300 UTC of 7 May. The part which moved over Bangladesh followed the steering current in the middle and upper troposphere; however the southwest movement of the part over Odisha is rather unusual. During its travel for nearly 24 hours, the MCS covered a distance of approximately 1275 km over the Indo-Gangetic Plain and its speed of movement showed some variations with faster movement over Uttar Pradesh and adjoining Bihar between 0300 UTC of 7 May to 1100 UTC when it split into two parts as shown in Fig. 6. The average speed of movement in the first phase was 35 km/hr and in the second phase was about 80 km/hr.

As stated earlier the development of the MCS was estimated from the minimum CTT value and the growth from the areal coverage. Again the areal coverage was

TABLE 2

Details about the MCS from its beginning to dissipation
(6th May 1300 hrs UTC to 7th May 1800 UTC for the year 2010) from INSAT (Kalpana-1) data

Date	Time (UTC)	Satellite Observation					Latitudinal (N) extent of the cell Min/Max	Latitudinal (N) extent of the cell Min/Max
		Region	Centroid (°N / °E)	Min. CTT	AREA I (km)	AREA II (km)		
06 May 2010	1300	Uttarakhand (UTTRKHND)	30.04/79.3	-48.8	25472		29.16/30.12	78.66/81.43
	1400	UTTRKHND	29.8/79.8	-54.5	37952	1088	28.64/30.93	77.66/82.01
	1500	UTTRKHND adj Nepal	29.6/79.6	-51.5	30208	640	28.81/30.42	77.7/81.4
	1600	UTTRKHND adj Nepal	29.7/79.3	-53.2	31424	3008	28.76/30.72	78.03/80.57
	1700	UTTRKHND adj Nepal	29.7/79.5	-53.3	37120	704 & 576	28.47/30.87	78.25/80.76
	1800	UTTRKHND adj Nepal	29.6/80.24	-52.8	47104	3648	28.29/30.97	78.5/81.98
	1900	UTTRKHND adj Nepal		NO DATA				
	2000	Uttar Pradesh (UP)	29.7/80.8	-53.2	69440	11904	27.63/31.84	79.16/82.36
	2100	UP	29.5/81.2	-53.7	75904	7168	27.26/31.76	79.7/82.73
	2200	UP	29.2/81.7	-52.4	78656	3712	26.73/31.76	80.18/83.18
	2300	UP	28.4/82.1	-49.3	75840		26.31/30.49	80.48/83.65
07 May 2010	0000	W. Nepal adj NE UP	28.4/82.5	-49.2	73152		26.1/30.75	80.85/84.1
	0100	W. Nepal adj NE UP	27.3/82.6	-50	55744		25.61/29.01	80.99/84.24
	0200	E. UP adj Nepal & W. Bihar (BHR)	26.6/83	-52	56000		25.19/28	81.28/84.79
	0300	E. UP adj Nepal & W. BHR	26.5/83.6	-52	60032		24.76/28.18	81.98/85.19
	0400	E. UP adj Nepal & W. BHR	26.3/83.9	-53	67520	3392	24.58/28	82.34/85.64
	0500	E. UP adj Nepal & W. BHR	26/84.3	-51	72192	704	24.31/27.8	82.64/85.98
	0600	E. UP adj Nepal & W. BHR	25.9/85.1	-51	83392	576	24.1/27.93	83.1/87.1
	0700	C.BHR adj Nepal, Jharkhand (JHRKND)	25.7/85.4	-51	84928		23.54/27.92	83.59/87.23
	0800	C.BHR adj Nepal, HRKND, Gangetic West Bengal (GWB)	25.6/86.1	-56	87744	8320	23.24/27.94	84.35/87.93
	0900	GWB adj BHR, JHRKND	24.5/86.9	-57	67904	19456	22.85/26.24	85.26/88.57
	1000	GWB adj BHR, JHRKND, Bangladesh (BD), Odisha (ORS)	23.6/87.5	-59	88896	27328	21.65/25.8	85.7/89.3
	1100	GWB adj BHR, JHRKND, BD, ORS	23.4/87.9	-65	108480	35200	21.24/25.5	85.8/90.2
	1200	GWB adj BHR, JHRKND, BD, ORS	22.3/87&23. /89	-64	128256	59584	20.6/25.4	85.3/90.5
	1300	GWB adj BHR, JHRKND, BD, ORS	22.2/87.3& 23/89.4	-62	148416	67008	20/25.3	85.2/90.6
	1400	GWB adj BHR, JHRKND, BD, ORS	22.0/87.2	-58	136128	16960 & 6400	20.2/24.5	85.3/90.99
	1500	GWB adj BD N. ORS	21.2/86.4	-53	95872	5760	20.1/24.6	85.6/89.4
	1600	GWB adj ORS	20.8/86.4	-48	36352		19.7/22.7	85.7/87.9
	1700	GWB adj ORS						
	1800	CELLS DISSIPATED						

CTT stands for cloud top temperature; AREA-I refers to area covered by CTT ≤ -30° C and AREA-II refers to area covered by CTT ≤ -50° C

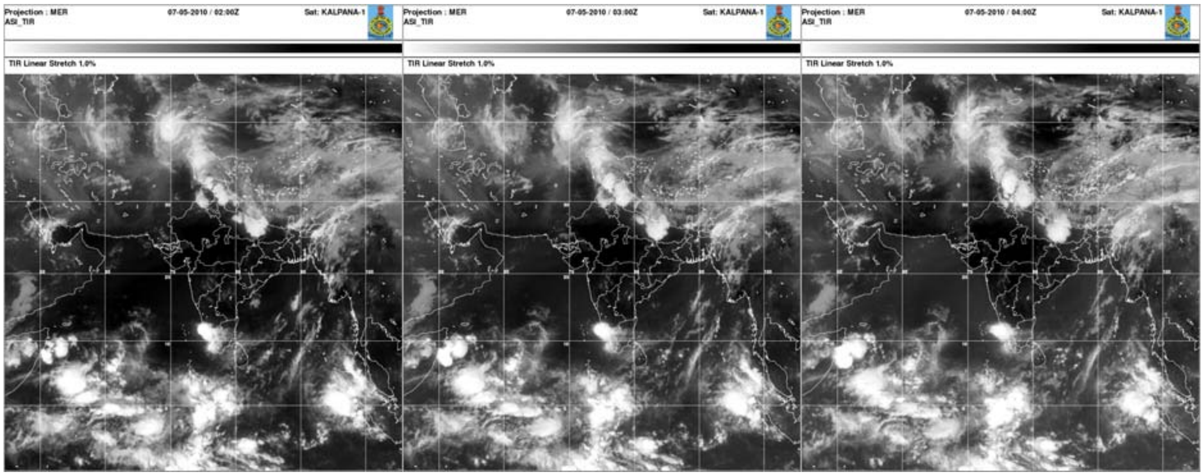


Fig. 7. IR imageries of 0200, 0300 & 0400 UTC of 7 May, 2010

estimated in two ways. Firstly the area covered by the CTT values below -30 °C, to depict the total average highly convective area and secondly the area covered by deep convection with CTT below -50 °C. These estimates were made on hourly basis with the help of IR imagery of the INSAT. Even though the MCS originated at 0600 UTC of 7 May consisted of a few cells only, we have provided information in the table when the areal extent of convection (CTT -30 °C or below) had covered an area of at least 25000 km^2. Table 2 shows that the rapid development (areal coverage above 37000 km^2) occurred at 1700 UTC of 6 May and explosive growth occurred at 2000 UTC of 6 May (area over 69000 km^2), Areal coverage decreased slightly between 0000 UTC of 7 May to 0100 UTC of 7 May. It began to grow again between 0400 UTC of 7 May and the maximum areal coverage (148416 km^2) occurred at 1300 UTC of 7 May. At this stage the MCS had crossed into the definition of a MCC. In terms of development minimum CTT was observed also in 5 stages as given below:

(*i*) 1st stage 1300 UTC of 6 May to 2100 UTC of 6 May (9 hours) ≈ -53 °C

(*ii*) 2nd stage (some weakening) from 2200 UTC of 6 May to 0000 UTC of 7 May (2 hours) ≈ -50 °C

(*iii*) 3rd stage from 0100 UTC of 7 May to 0700 UTC of 7 May (6 hours) ≈ CTT between -50 °C to -52 °C.

(*iv*) 4th stage from 0800 UTC of 7 May to 1300 UTC of 7 May (5 hours) ≈ ≤ -60 °C.

(*v*) 5th stage 1400 UTC of 7 May to 1800 UTC of 7 May (4 hours) -58 °C to -48 °C.

The above shows that the MCS was never in completely steady state except perhaps between 1st to 3rd stage form. Changes occurred in its intensity on the scale of 4-12 hours. It attained maximum intensity in the 4th stage and dissipated in the 5th stage close to Odisha and Bangladesh coast. Maximum intensity was recorded during noon hours and dissipation occurred in the evening hours. Along with the changes in development stages, fluctuations also occurred in its areal extent.

Deep convective area (CTT≤ -50 °C) in the beginning stage (Initiation) fluctuated (around 1000-3000 km^2) and was maximum about 12000 km^2 (17% of total area) at 2000 UTC of 6 May. Areal coverage of deep convection decreased at 2100 UTC of 6 May and remained low upto 0600 UTC of 7 May. It explosively grew at 0700 UTC of 7 May and reached its maximum value of about 67000 km^2 (about 50% of total area) at 1300 UTC of 7 May. Thus the maximum intensity of convection was of the areal coverage happened between 1100 UTC of 7 May at 1300 UTC of 7 May (for two hours) when the system could attained the status of the MCC according to the definition of the MCC (Tyagi *et al.*, 2012). There is enough evidence in the data presented in Table 2 that the MCS while passing through different stages had two major stages of growth and development *viz*., (*i*) at 2000 UTC of 6 May and (*ii*) at 1300 UTC of 7 May. In between these two stages it had somewhat weakened at 0200 UTC of 7 May and re-intensified at 0400 UTC of 7 May (2 hrs after weakened stage). Fig. 7 shows the IR imageries between 0200 to 0400 UTC of 7 May. Fig. 8 shows the plot of hourly minimum CTT values. The rapid fall of CTT value between 0100 UTC of 7 May & 1100 UTC of 7 May is most prominent observed in Fig. 8.

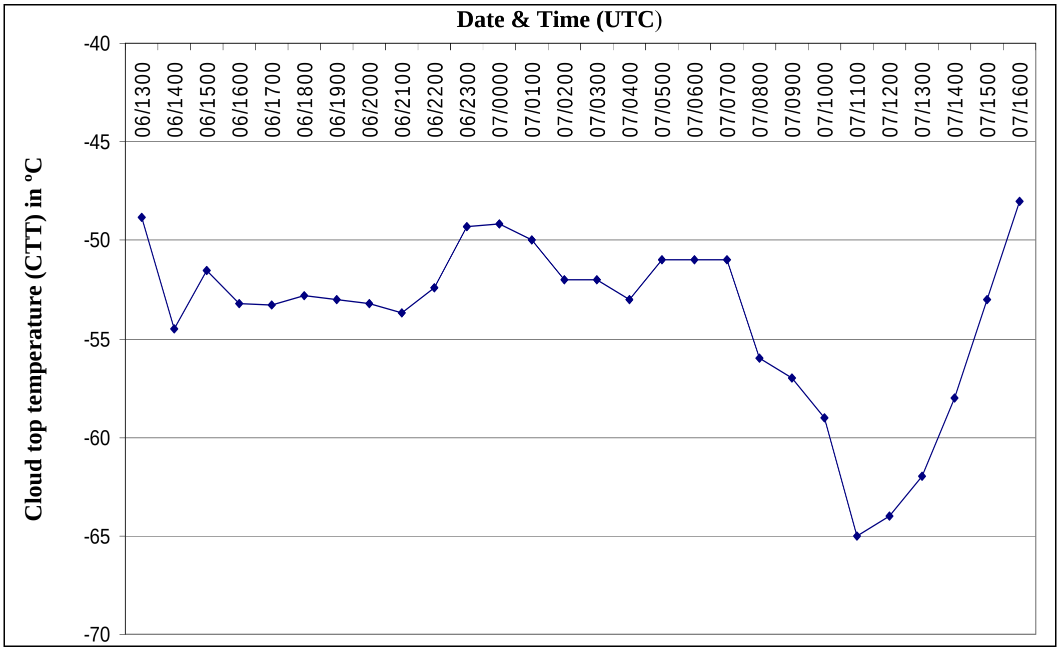


Fig. 8. Cloud Top Temperature (CTT) of the MCS from its initiation (1300 UTC/6th May) to dissipation stage (1600 UTC/7th May)

5. Weather associated with the MCS during its travel

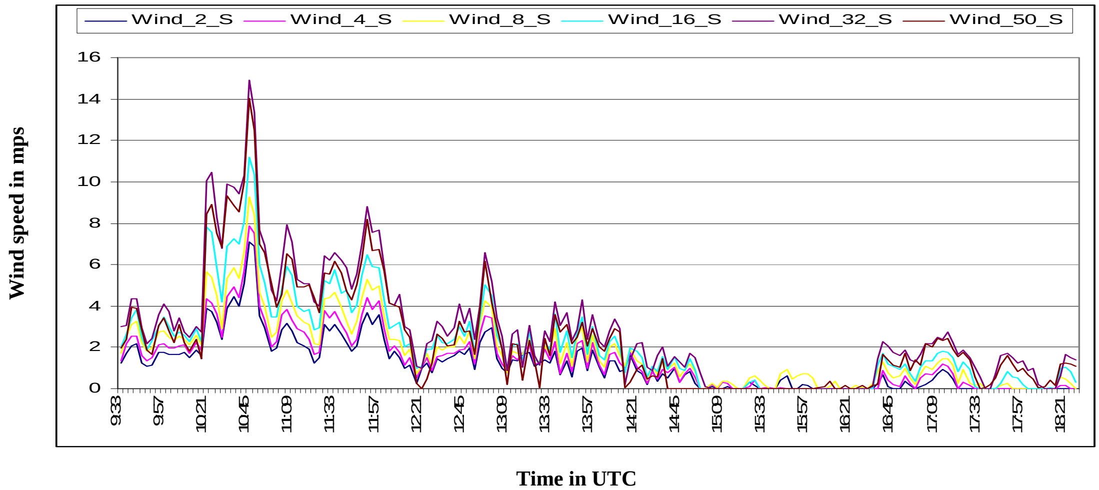
As already stated, the MCC passed through the synoptic network of IMD and IAF observatories; AWS network of IMD and airport stations, which take hourly observations. The synoptic network is not dense enough to monitor a mesoscale system. Also there are a few self recording surface instruments at a few observatories. Data from all these stations were collected. Appendix 2 gives the information about convective weather development over surface synoptic hours near about the relevant time when the MCS passed near a station (not necessarily over the station). Appendix 3 provides source details of the observations obtained from the traces of the self-recording instrument at different times of the convective weather over the stations. Whereas the data for thermographs and barographs were available in a satisfactory manner, records for hydrographic and rain recording instruments were not satisfactory, as these instruments were not functioning at the stations where data are missing. There are weather radars at Lucknow, Patna, Ranchi and Kolkata but except for Kolkata radar, no data was available for other three radars, as they were not functional. Hence vital radar data was not available for the first 3 stages. It was available for the mature stage when the MCS came under the surveillance of Kolkata radar between 0527 UTC and 1157 UTC on 7 May. Comment from the report of the inspecting officer who visited the affected areas of Varanasi and Jaunpur, Uttar Pradesh when the MCS was in the 3rd stage (active first stage) of development are provided for these stations where damage was reported. We now discuss the observations from the surface network as given in Appendices 2 & 3.

5.1. *Surface weather over synoptic observatories along the track*

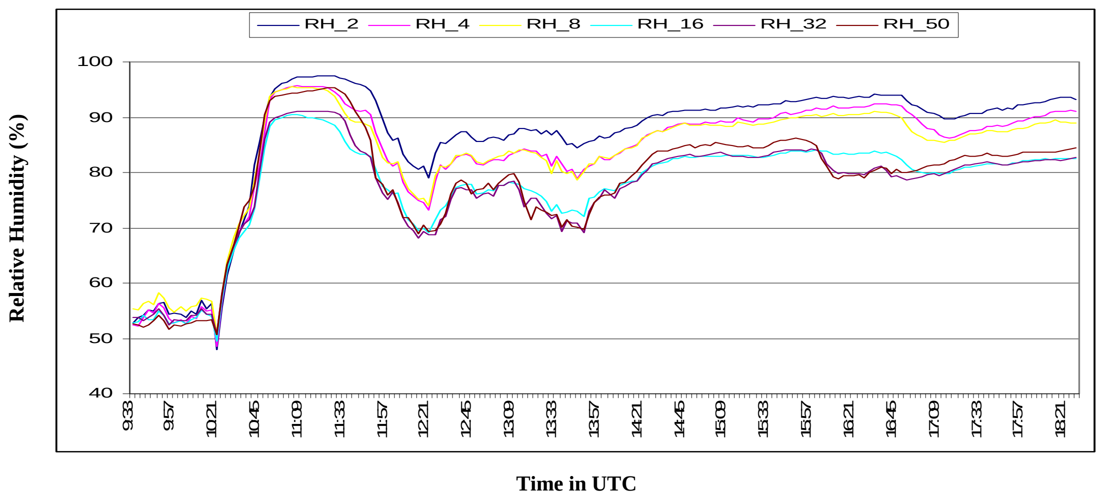
There were no reports from or near the position of origin of the MCS. The first report came from Bareilly, which reported dust raising wind and lightning between 1500 to 2100 UTC of 6 May. It was followed by thunder, rain, and lightning at Bahraich between 2100 UTC of 6 May and 0000 UTC of 7 May. Even though the two stations are not very close to the centroid of the MCS, the observations agree with the time of passage of the MCS close to the stations.

In the development stage of the MCS, we have observations from 6 observatories between 0000 and 0300 UTC of 7 May. All stations have reported thundery weather. The weather was highly disturbed over stations Jaunpur, Varanasi and Ballia which is supported by the report of the inspecting officer. Perhaps the reports of wind speed as given in the report of the inspecting officer by the local people, reaching 200-250 kmph and 150-200 kmph at Jaunpur-Varanasi and Ballia are exaggerated. However these reports are in agreement with the satellite observations discussed in Section 4 as the MCS was growing in size and intensity (Low CTT) at this phase and

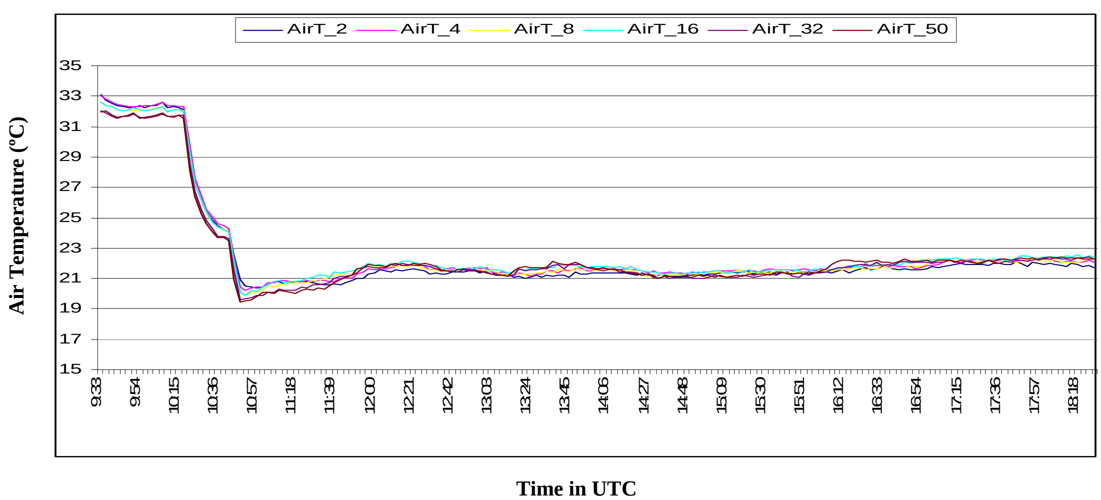
(a) Wind speed



(b) Relative humidity



(c) Air Temperature



Figs. 9 (a-c). Observations from surface layer Tower data of IIT Kharagpur on 7 May 2010 hence the expected weather was squally with gusty winds. Note that this development occurred at early morning hours (0000-0300 UTC) and hence dynamic forcing rather than diurnal heating was responsible for the development stage. The MCS might have slightly weakened between 0300-0600 UTC as analysed from satellite observations. Hence several synoptic stations (6 stations) have reported thunderstorm with rain and even squally weather development noticed between 0420-0710 UTC at station Gaya. The MCS appears to have regained its intensity by 0600 UTC of 7 May and reached its most intense stage at about 1100 UTC over and near Kolkata (Observation from Kalaikunda, Barrackpur, Dum Dum and Alipore). These observations are in agreement with the satellite data discussed in Section 4. We discuss the weather radar data of Kolkata in a separate section.

5.2. *Autographic instrumental data*

In the initial stage data from Bareilly & Bahraich show that the dry bulb temperature fell by 2 °C to 4 °C when the MCS passed close to these stations. In the barographic trace for Bahraich the pressure fell at the time of thunderstorm and rose after it. The thunderstorm occurred there between 2045-2115 UTC of 6 May. The developing stage shows temperature fall at several stations exceeding 6 °C and the maximum fall of 13 °C was recorded at station Gaya. All these observations refer to the day hours before noon and hence there could be contribution by diurnal heating and water bodies of river Ganges in the re-intensification of the MCS. Maximum pressure rise of 5 hPa is recorded after the thunderstorm in the barograph of Gaya. Sudden increase in rainfall (about 8.5 mm) occurred at Sriniketan between 0900 to 0930 UTC then slow rainfall continued between 0930 hrs to 1130 UTC. Total rain has occurred about 11.7 mm and in the other case 8 mm rain occurred at Jharsuguda between 2215 to 2230 UTC and 2 mm rain between 2230 to 2245 UTC of 7^{th} May, 2010. Appendix 4 shows the TRMM estimated rainfall accumulated on 3 hourly basis in different stages of the MCS development. Rainfall is derived from TRMM 3 hourly average for 0.25° × 0.25° grid and interpolated to the observatory stations. At the initial and development stages collectively the 3 hourly average rainfall is estimated to be 14 mm but at the mature stage it has become double (27 mm). So the rain increased in intensity as the system re-intensified and moved over Bihar and West Bengal at its mature stage. This occurred at 0600-0900, 0900-1200, 1200-1500 UTC of 7 May (noon to afternoon hours). Thus diurnal heating must have lead to the maturity of the MCS hence increased in rainfall. At these hours the MCS was also lying close to the North Bay of Bengal which was providing moisture inflow to the system.

5.3. *Analysis of dense network of AWS observatories of West Bengal*

Observations from 7 AWS network operated by Jadavpur University were obtained for the mature stage of the MCS is shown in Appendix 5. Weather remained disturbed at these networks between 0736 to 0900 UTC and each station remained under its grip for about 20-40 minutes only. Maximum sustained wind (not squall) remained rather moderate between 10 to 16 m/sec for the stations Puabagan and Bishnupur, where the sustained wind was between 15 to 16 m/sec. It was not possible to estimate the squally instantaneous winds as the data were available for only 3 minute average basis. However, the fall in temperature was quite large and at several stations it exceeded 12 °C. There was rise in relative humidity by about 40%. The maximum intensity of the system as estimated from wind and pressure data happened at the station Puabagan between 0912 to 0942 UTC of 7 May. This was about 1-2 hour earlier than when the MCS affected Kolkata area (between 1000 to 1100 UTC of 7 May). Thus the system remained intense between 0800 and 1100 UTC and then began to dissipate thereafter. At the intense and most developed stage of the MCC, the pressure fall and rise (about 3 hPa to 5 hPa), the dry bulb temperature fall (more than 10 °C) and the increase in relative humidity (about 40%) were very large and perhaps a typical of a typical Norwester. All these changes point out that this Nor'wester (MCC) was of great intensity. So the system not only lasted for about 24 hours, travelled all across the Gangetic Plain but was also of great intensity at mature stage.

5.4. *Dissipation stage*

The MCS, as estimated from satellite and conventional meteorological data, began to dissipate as its deep convective zone passed close to Kolkata. This was at about 1200 UTC of 7 May and during the evening hours over the region. Satellite imagery showed that at the dissipation stage the system split into two convective clusters – one moving over Bangladesh and the other over Odisha. The second active stage had lasted for 6 hrs (between 0600 UTC to 1200 UTC of 7 May). The MCS had completely dissipated by 1800 UTC of 7 May and the dissipation stage took for about 2-3 hours. At the dissipation stage gusty and squally winds were reported at stations over Bangladesh as well as Odisha. All in all the MCS was extra-ordinary long lasting and its life history covered nearly 30 hours (from about 1300 UTC of 6 May to 1800 UTC of 7 May). In spite of its long lifetime it could not be predicted from either the operational mesoscale model or the operational global model. As the MCS is a long lasting one and occurred under rather weak large scale forcing, except that in the second active stage it

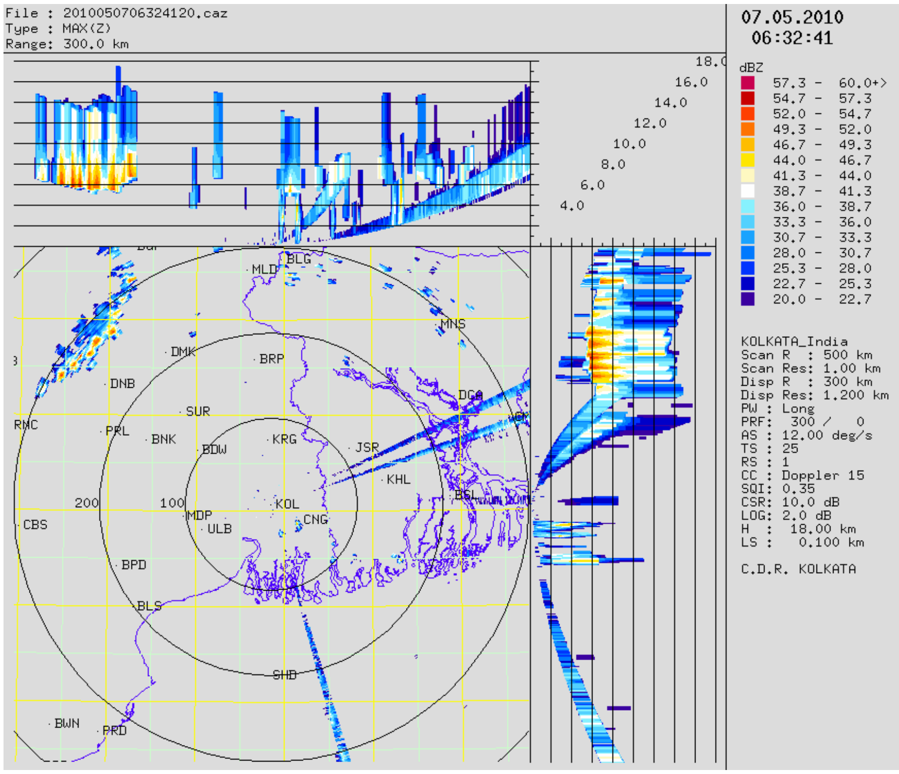


Fig. 10. Kolkata Doppler radar picture when the MCS was located at about 300 km from the station

was passing over a high CAPE region of favourable thermodynamical environmental over Bihar Jharkhand & West Bengal. Special effort is needed to simulate it using a mesoscale model. This work is left for future study by the modeling group.

6. Analysis of the mature stage using surface layer tower data from Kharagpur and Doppler weather radar data of Kolkata

6.1. *Analysis of data from IIT Kharagpur surface layer tower data*

A surface layer instrumented tower was operating during the period in the campus of IIT Kharagpur. The tower had functional instruments / measurement for wind direction & speed, temperature and moisture profile at 6 levels (2, 4, 8, 16, 32 and 50 m heights above ground level. Figs. 9(a-c) provide the response of slow response (3 minute average) instruments at 12 minute interval. Wind speed began to increase between 1009 and 1021 UTC and reached a maximum strength of 15 m/sec at 1030 UTC at 32 and 50 meters height. (Lower level winds also increased but the maximum strength was recorded at 32 and 50 meter above ground). The wind dropped at different times in between but remained gusty with 4 maximum of wind strength reaching between 6-9 m/sec between 1057 to 1257 UTC. The gustiness decreased thereafter as the convective activity decreased over the station with the moving away of the MCS. Note that at all levels the wind speed increased and decreased almost simultaneously indicating the coherence of updraft and downdrafts recorded at the tower. There was sharp drop of the air temperature from 33 °C between 0957-1009 UTC to 20 °C followed by slow rise to 21.5 °C at 1200 UTC. Temperatures fall was also coherent at all levels. The relative humidity profile data [Fig. 9(b)] shows sharp increase between 1021 to 1033 UTC from about 50% to the maximum of 90-95% recorded between 1109 to 1145 UTC. We note that the maximum wind occurred between 1045-1057 UTC, Maximum fall in air temperature was recorded between 0957-1009 UTC and maximum relative humidity between 1109-1145 UTC. Thus we note that the wind speed increased first (1009 to 1021 UTC). After that air temperature began to fall and the minimum was reached when the first wind maximum began (major downdraft must have occurred in this time interval). At the same time R.H. also sharply rose between 1021-1033 UTC. Thus the peak of the downdraft was accompanied with recording of minimum temperature and the sharp rise in R.H began thereafter. The duration of the sharp increase in wind and R.H. as well as decrease in air

TABLE 3

Significant changes in meteorological parameters at different heights of surface layer tower data of Kharagpur at different times on 7 May 2010

Height (m)	Temp. fall (°C)	Time (UTC)	RH rise (%)	Time (UTC)	Max wind (mps)	Time UTC)
2	2.0	1021-1024	48	1021-1057	3.9	1021
	1.6	1045-1048			7.1	1045
4	2.1	1021-1048	46	1021-1057	4.3	1021
	1.6	1045-1048			7.9	1045
8	1.5	1021-1024	44	1021-1057	5.6	1021
	2.0	1045-1048			9.3	1045
16	2.0	1021-1024	40	1021-1057	7.8	1021
	2.1	1045-1048			11.2	1045
32	1.8	1021-1024	40	1021-1057	10.5	1024
	2.0	1045-1048			14.9	1045
50	1.7	1021-1024	43	1021-1057	8.9	1024
	1.5	1045-1048			14.0	1045

TABLE 4

Summary of Kolkata weather radar data as the MCS approached and moved away from the station

Date 7 May 2010 Time (UTC)	Approximate distance from Kolkata (km)	Maximum reflectivity (dBZ)	Approximate cloud top (km)	Approximate arc length of convection (km)
(a) MCS moving towards the station in mature stage				
0527	350	25 – 29	6-8	70
0737	190	49 – 52	8-10	250
0842	130	47 – 49	8-10	325
0855	130	49 – 52	10-12	350
0908	105	49 – 52	10-12	360
0934	85	49 – 52	12-14	380
1013	50	49 – 52	14-16	375
1026	20	49 – 52	12-14	450
(b) MCS moving away from the station and dissipating				
1053	0	44 – 47	-	300
1157	50	44 – 47	6-8	200

temperature lasted for about 12 minutes for each parameter. These features are characteristic of the squalls accompanied with downdrafts in a severe tropical thunderstorm. As prior to the onset of the convective weather the air temperature was close to 33 °C, the role of diurnal heating in the activation of the thunderstorm is quite evident. Also as characteristic of a Nor'wester, the event affected the Kharagpur region in the afternoon (1000-1300 UTC). The station Kharagpur remained under the influence of the MCS (Nor'wester locally) for a period of about 3 hrs during which winds remained highly gusty at all levels of the surface layer tower. Table 3 provides

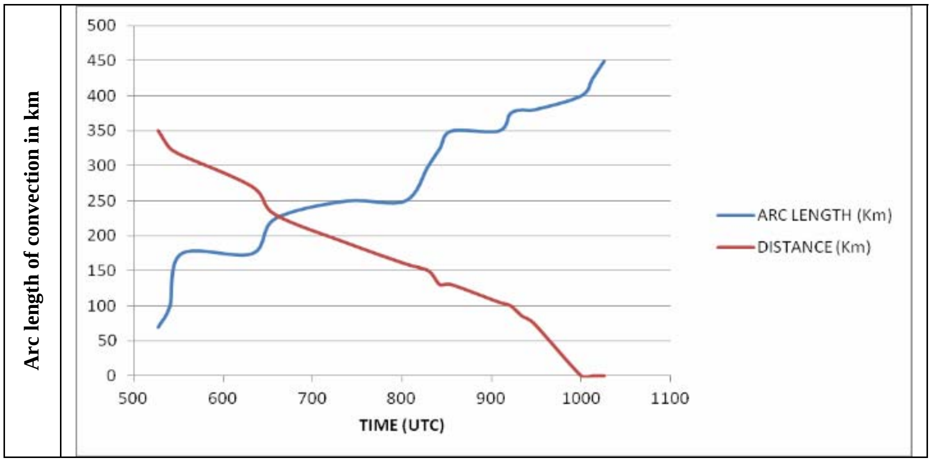


Fig. 11. Time variation of the arc length (km) of the MCS as estimated from Kolkata radar on 7 May 2010

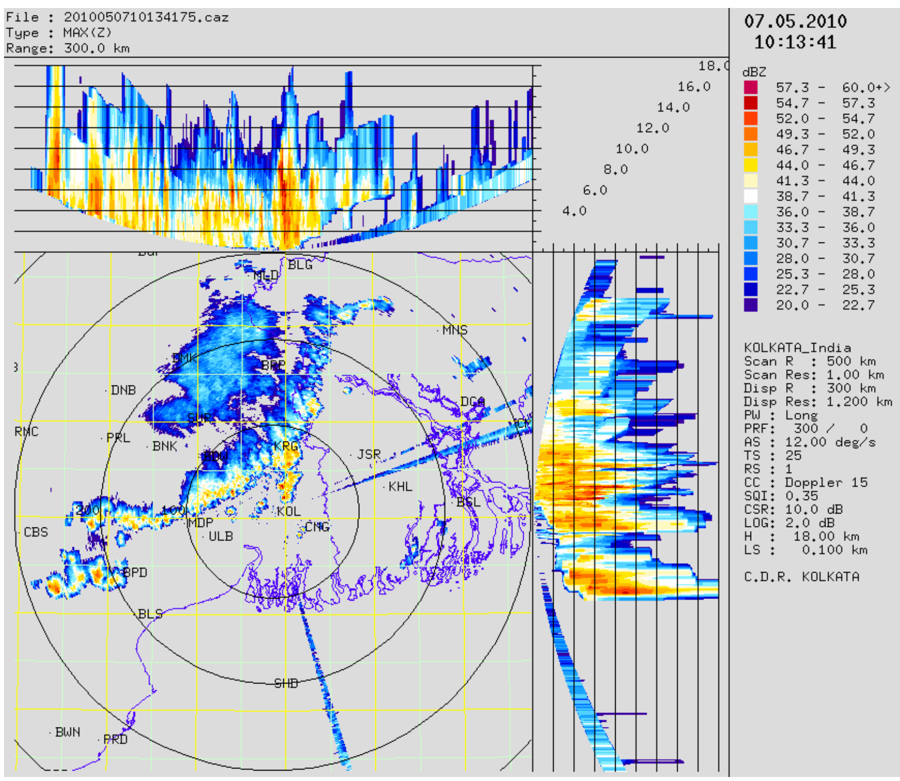
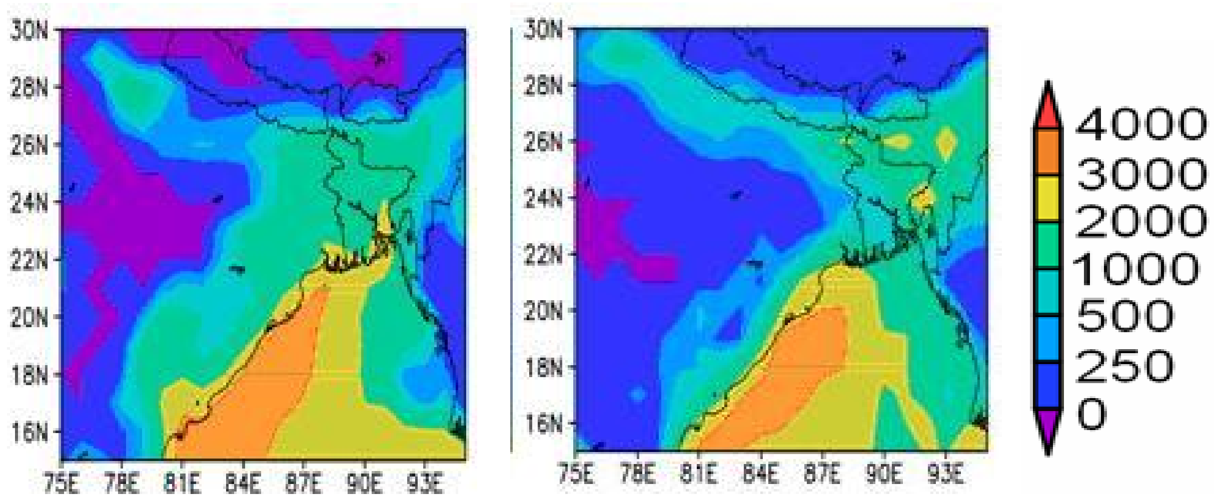


Fig. 12. Kolkata radar picture at 10:13:14 UTC on 7 May when the MCS was very closed to radar station

important information derived from the tower data for different tower levels at different times when the event was happening over the station.

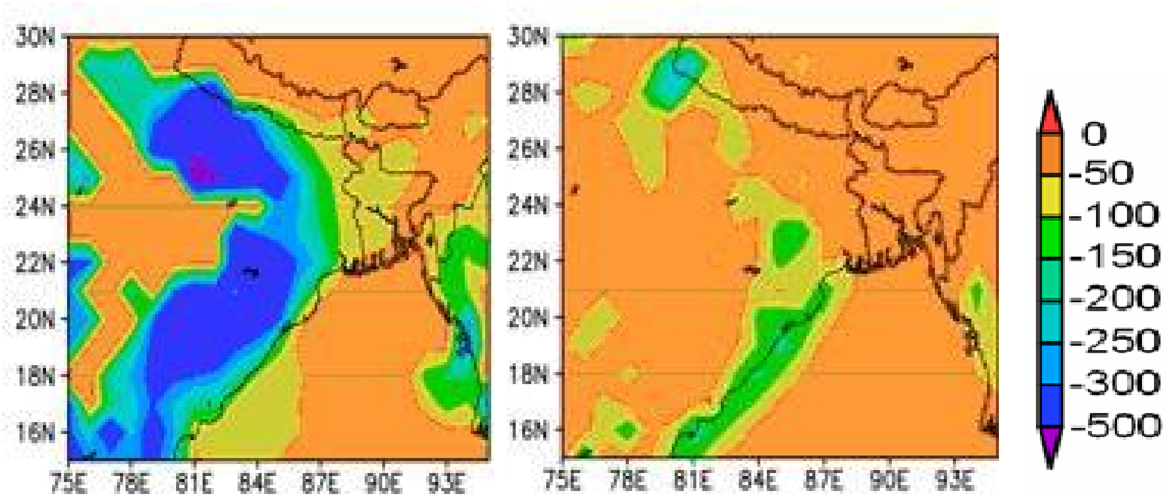
6.2. *Analysis of Kolkata Doppler Weather Radar (DWR) data*

The MCS came under the surveillance of Kolkata DWR at 0527 UTC when it was at a distance of about 350 km from the radar site. Repeated radar information at 10-15 minutes interval was obtained when the MCS convection was at a distance of 300 km from radar site. The maximum reflectance value of 48 dBZ and was achieved the cloud top reached about 8 km height at that stage as the radar station was at a distance of 300 km of the site of intense convection (Fig. 10). Convection continued to intensify and move southeastward as given in Table 4.



0000 UTC 1200 UTC Legend

Fig. 13. CAPE values on 7 May 2010 based on NCEP data



0000 UTC 1200 UTC Legend

Fig. 14. CINE values on 7 May based on NCEP data

Thus, when the developing MCS was far away from the radar station, cloud top height, its dBZ and arc lengths were of lesser magnitude. As it approaches closer to the radar station all these parameters increased. At mature stage the MCS was composed of severe thunderstorms in the form of a well-defined squall line of 300-450 km length of deep convective cluster. As the convection was growing MCS increased in intensity. We have estimated the arc lengths and the maximum reflectivity at different times in UTC. Fig. 11 shows the information from radar on arc length. The size of the arc length increased from nearly 70 km to 450 km between 0527 to 1026 hrs UTC and reflectivity increased from 25-29 dBZ to 49-52 dBZ. Thus, as the MCS reached mature stage with time and the maximum arc length occurred at about 1000 UTC. As the most mature stage was reached before the MCS passed over Kharagpur and had become a MCC.

Fig. 12 shows the radar picture at 10:13:41 UTC when the MCS was within about 25-50 km of radar site. Maximum reflectivity was about 50 dBZ and the cloud tops could give upto 14-16 km height indicating the high intensity of MCS and areal coverage (arc length) during the mature stage when it was very close to the radar station.

6.3. *Thermodynamic environment of the MCS during its life cycle*

Even though there are a good number of radiosonde stations along the track of the MCS (Delhi, Lucknow, Allahabad, Patna, Ranchi, Kolkata, Bhubaneshwar) data from several stations for 0000 UTC were not available upto upper troposphere to calculate thermodynamical parameters like CAPE & CINE. Hence we have to depend upon the model-generated analysis from the NCEP reanalysis. Fig. 13 & 14 show the CAPE & CINE values at 0000 & 1200 UTC of 7 May over and along the track followed by the MCS. The figure shows that region was covered by high CAPE (1000-2000 Joules/kg) along the region and the values increased between 0000 to 1200 UTC of 7 May. Similarly the CINE also remained small. Thus the environment through which the MCS travelled remained supportive of conditional instability, which helped in not only sustaining the convective configurations but also in further intensifying it from morning hours to the late afternoon hours. This has been the characteristic of the environment over the eastern part of the Indo-Gangetic Plains over which Nor'westers are generated and cause destructive convective weather.

7. Summary and concluding remarks

The study is focused on the description of the development history of a MCS, which formed under weakly forced synoptic condition but was exceptionally long lasting one. It originated in the afternoon hours of 6 May, 2010 over the vegetative hilly region of Uttarakhand in Western Indian Himalayas ahead of a western disturbance affecting Pakistan. Under the influence of the western disturbance easterly low level flow prevailed along the foothills of Central Himalayas & adjoining Northern parts of the Indo-Gangetic Plain. The region is the seat of conditional instability. The initial small cloud cluster increased in intensity, formed into a MCS, which gradually increased in size between 1200 UTC of 6 May, 2010 and 0000 UTC of 7 May and can become a MCC. The system continued to develop during the morning and early day hours of 7 May and the first outbreak of the severe weather occurred over central and eastern Uttar Pradesh (over Lucknow, Allahabad Jaunpur and Varanasi sector) when local people reported whirling high speed winds (though perhaps exaggerated in their estimates) with thunder and rain. The system appeared to have somewhat weakened for 2-3 hours and then began to develop further between 0600 to 1200 UTC of 7 May, 2010. It reached maturity between 1000 to 1200 UTC of the day over the Gangetic West Bengal between Kharagpur and Kolkata. It began to split into two parts - one going towards Odisha and other across Kolkata to Bangladesh and finally dissipated over these areas. Synoptic, hourly METAR, Self-recording instrumental data, Surface layer tower data, satellite observations, at hourly interval and radar surveillance by Kolkata DWR are deployed to trace different stages in the development history of the system. Our analysis suggests the following:

(*i*) System originated as a small cloud cluster in late day hours over hilly and vegetated region of Uttarakhand ahead of a western disturbance affecting Pakistan.

(*ii*) Mid and upper tropospheric northwesterly flow advected the system southeastward towards western and central Uttar Pradesh and the weak dynamic forcing with prevailing conditional instability sustained the system during the night hours to early morning hours of 7 May.

(*iii*) As the day advanced the system continued to grow in size (areal coverage of satellite IR data) and intensity (CTT of satellite IR data), which resulted in severe weather outbreak over eastern Uttar Pradesh. Thereafter the system appeared to have somewhat weakened but again started intensifying over Bihar and Gangetic West Bengal.

(*iv*) It reached maturity between 0900 to 1200 UTC of 07 May between Kharagpur and Kolkata. At the mature stage it reached the status of MCC (Maximum Areal coverage over 100000 km^2). At the most mature stage the radar surveillance showed maximum reflectivity of above 50 dBZ and the cloud top reached 14-16 km in height. Diurnal heating and the land surface processes (vegetated landmass and nearness of water bodies of the river Ganges and its tributaries) must have contributed to rapid intensification between 0900 to 1200 UTC of 7 May. The strong downdrafts accompanied with squalls in the severe thunderstorms during the evening hours lead to the weakening of the mature MCC (Nor'wester system) and to the dissipation of the system between 1200 to 1500 UTC of 7 May. On the whole the system could be tracked for over 27 hours – An unusually long duration. The maturity was reached over the traditionally well known in Bihar, Gangetic West Bengal (Tyagi *et al*. 2012).

We admit that due to lack of dense network of surface observatories and relative absence of upper air sounding and radar network over the region during the life history of the system, more details of the system could not be examined. We consider that in order to fully understand the structure and development of severe thunderstorms (Nor'westers) during the pre-monsoon season, the region between Ranchi-Kharagpur-Raipur and Bhubaneshwar (Jharkhand, Gangetic West Bengal, Odisha, Chattisgarh) are required to be covered by Mesoscale surface and upper air networks as well as up-gradation of DWRs. Without mesoscale surface and upper air data, it would be less possible to predict the evolution of such systems through dynamical models as was the case in this system. A special effort, which is beyond the scope of this work, is required to simulate this system by very high-resolution models, particularly its mature stage using Kolkata DWR data. Till operational modeling of severe convective systems achieve high reliability, it would be of advantage if nowcasting system 3-6 hrs in advance, are developed for which satellite observations and radar data could be combined judiciously and objectively.

Acknowledgement

The authors acknowledge the help provided by Regional Meteorological Centres New Delhi and Kolkata, IAF Met Branch, Birla Institute of Technology, Ranchi and IIT Kharagpur surface layer towers, Satellite Meteorology Branch of IMD, New Delhi, DWR Kolkata and the NWP Branch of IMD, New Delhi, and Dr. Krishna Kishore of IIT Delhi for providing the variety of data used in the study. It took considerable effort to collect these data from different sources. The study originated during the group meeting at IMD New Delhi organized in 2010 STORM campaign which were facilitated by the Director General of Meteorology and the support provided by him during the study period is also acknowledged.

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APPENDIX 1

List of data used in the study

1. Satellite (Kalpana-1) imageries:

   (i) Hourly Infrared Images from 1200 UTC to 2300 UTC of 6th May 2010 & 0000 UTC to 1800 UTC of 7th May 2010.

   (ii) Hourly visible images from 0100 to 1100 UTC of 7th May.

2. TRMM derived 3 hourly Rainfall data.

3. Radar Data : Doppler Radar images of Kolkata from 0527 hrs to 1157 hrs (UTC) of 7th May.

4. Tower Data : IIT Kharagpur Surface Tower Data of Wind speed, Relative Humidity, Air temperature and Air Pressure at the interval of three minutes at six different levels 2, 4, 8, 16, 32 and 50 m.

5. AWS data from Purulia, Raghunathpur, Saldiha, Khatra, Puabagan, Bishnupur and Santiniketan of three minute interval collected from Jadavpur University.

6. Current weather data of Hindon, Sarsawa, Bareilly, Agra, Allahabad, Kanpur, Lucknow, Gorakhpur, Bagdogra, Panagarh, Barrackpore and Kalaikunda collected from Air force stations.

7. Autographic charts of the following stations:

   Thermograph : Bareilly, Bahraich, Gorakhpur, Varanasi, Patna, Gaya, Sriniketan, Dum Dum, Alipore, Jharsuguda and Balasore.

Barograph : Bahraich, Gorakhpur, Varanasi, Patna, Gaya, Dum Dum, Alipore, Jharsugda and Balasore.

Hygragraph : Patna, Gaya and Sriniketan.

SRRG: Sriniketan & Jharsuguda.

8. Weather data of Rajshahi Dhaka Chittagong of Bangladesh.

9. Daily Meteorological Report published by DDGM (WF) Pune has been taken into consideration

APPENDIX 2

Weather associated with MCS at different stations along its track

Station	Time (UTC)	Weather	24 hrs rainfall ending at 0300 UTC of 7 May 2010 (mm)	Remarks
Initial Stage (1300 UTC of 6th May to 2300 UTC of 6th May				
Bareilly	1500-2100	Dust raising wind & lightning	0.0	-
Bahraich	2100-0000	Thunder, Rain, Lightning	3.2	-
Developing Stage (2300 UTC of 6th May to 0300 UTC of 7th May)				
Gorakhpur	0000-0300	Thundershower	10.3	-
Jaunpur	0100-0130	Whirling wind with speed 200-250 kmph. Clouds blackish like hooks, thunderstorm accompanied with squall	0.0	Affected area very narrow strip. 9 person died due to Duststorm / Thunderstorm by collapsing trees walls etc
Varanasi	0030-0100	Whirling wind with speed 200-250 kmph, Clouds blackish like hooks, thunderstorm accompanied with squall	48.8	Affected area very narrow strip. 1 person died due to Duststorm / Thunderstorm by collapsing wall
Varanasi (Ozone unit)	0100-0430	Thunder with rain	4.2	
Ballia	0200-0300	Wind speed 150-200 kmph. Duststorm, Thunderstorm accompanied with squall, sometimes it appears as tornado. Height of CB clouds : 16-18 km	7.1	4 person died in Balllia district due to lightning
Lucknow	0130-0200	Wind speed 78 kmph. Heavy thundershower with hail storm	2.7	-

Station	Time (UTC)	Weather	24 hrs rainfall ending at 0300 UTC of 8 May 2010 (mm)	Remarks
Mature Stage (0300 UTC of 7th May to 1100 UTC of 7th May)				
Patna	0420-0710	Thundershower with rain	19.6	-
Gaya	0420-0710	A Squall passed over Gaya at 0415 UTC with wind speed 108 kmph lasted for 1 minute. Rainfall 2 cm	17.0	-
Bhagalpur	0730-0915	Thunderstorm with rain	2.9	-
Chapra	0430-0600	Rain	36.6	-
Sabaur	0300-1200	Rain	4.6	-

APPENDIX 2 (*Contd.*)

Station	Time (UTC)	Weather	24 hrs rainfall ending at 0300 UTC of 8 May 2010 (mm)	Remarks
Muzaffarpur	0450-0740	Rain	18.8	-
Dum Dum (GWB)	1030	A Squall passed over Dum Dum at 1030 UTC of 7th May with wind speed 71 kmph lasted for 1 minute	32.1	-
Alipore	1045	A Squall passed over Alipore at 1045 UTC of 7th May with wind speed 52 kmph lasted for 3 minutes	31.0	-
Barrackpur	1000-1100	Thundershower, Wind speed reaching to 28 kmph	1.8	-
Kalaikunda	1030-1100	Thunder shower, Wind speed reaching to 66 kmph	31.7	-
		Dissipating Stage (1100 UTC of 7th to last stage)		
Balasore	1130-1315	Thundershower	2.3	-
Jharsuguda	1820-1930	Thunderstorm	9.8	-
Rajshahi (Bangladesh)	0900-0930	Squall, wind speed reaching to 33 kmph	0.0	-
Dhaka (Bangladesh)	1305	Gusty wind, Wind speed 48 kmph	0.0	-
Chittagong (Bangladesh)	1543-1558	Gusty wind , Wind speed reaching to 41 kmph	Trace	-

APPENDIX 3

Detail of the meteorological parameters as measured from autographic charts of different stations and at different intensity stages of the MCS

Station	Fall in Thermograph Temperature (Between hrs UTC)	Fall/rise in Barograph Pressure (hPa) (Between hrs UTC)	Increase in Hygrograph Relative Humidity (%) (Between hrs UTC)	Rainfall recorded by the self recording rain gauge (mm) (Between hrs UTC)
		Initial Stage (1300 UTC of 6th May to 2300 UTC of 6th May)		
Bareilly	2.0 °C (1700-1800)	–	–	–
Bahraich	4.0 °C (2030-2130)	Fall 1.0 hPa (1945-2045) Rise 2.0 hPa (2045-2115)	–	–
		Developing Stage (2300 UTC of 6th May to 0300 UTC of 7th May)		
Gorakhpur	4.0 °C (2330-0000)	Fall 1.0 hPa (2200-2215) Rise 1.0 hPa(2215-2230) Fall 2.0 hPa (0030-0045)	–	–
Varanasi	6.0 °C (0100-0130)	Fall 2.0 hPa (0145-0200)	–	–
		Mature Stage (0300 UTC of 7th May to 1100 UTC of 7th May)		
Patna	9.0 °C (0400-0500)	Rise 1.5 hPa (0330-0400)	25% (0330-0400)	
Gaya	13.0 °C (0400-0430)	Rise 5.0 hPa (0400-0445)	25% (0300-0430)	
Sriniketan			22% (0845-0900)	11.7 mm (0845-1100)
Dum Dum (GWB)	10.0 °C (1030-1130)	Rise 3.5 hPa (1030-1130)	–	–
Alipore	9.5 °C (1045-1230)	Fall 1.5 hPa (1100-1145) Rise 1.0 hPa (1145-1230)	–	–

APPENDIX 3 (*Contd.*)

Station	Fall in Thermograph Temperature (Between hrs UTC)	Fall/rise in Barograph Pressure (hPa) (Between hrs UTC)	Increase in Hygrograph Relative Humidity (%) (Between hrs UTC)	Rainfall recorded by the self recording rain gauge (mm) (Between hrs UTC)
		Dissipating Stage (1100 UTC of 7th to last stage)		
Jharsuguda	7.0 °C (2130-2230)	Fall 0.5 hPa (2230-2330)	–	9.8 mm (2200-2245)
Balasore	13.0 °C (1115-1230)	Fall 1.0 hPa (1330-1415) Rise 2.0 hPa (1415-1430)	–	–

APPENDIX 4

3 hourly TRMM rainfall (mm) at different stages (as interpolated to stations) on 6 and 7 May 2010

Date	Time (UTC)	Lat.	Long.	Rainfall (mm)	Nearby IMD station	24 hrs rainfall (mm) on 7 May 2010
			(a) Initial stage			
6 May 2010	12-15	30.00	79.50	11.5	Mukteshwar (Uttrakhand)	8.4
6 May 2010	12-15	29.50	78.75	12.0		-
6 May 2010	12-15	29.75	80.00	30.0	Askot (Uttrakhand)	-
6 May 2010	15-18	29.00	79.50	27.0	Pantnagar (Uttrakhand))	7.4
6 May 2010	18-21	28.75	81.50	7.0		
6 May 2010	21-00	27.75	81.50	43.0	Kheri (UP)	0.0
6 May 2010	21-00	27.30	80.65	17.0	Bahraich (UP)	3.2
			(b) Developing stage			
7 May 2010	00-03	27.50	82.90	10.0	Gonda (UP)	-
7 May 2010	00-03	27.50	82.25	5.0	Gonda(UP)	-
7 May 2010	00-03	26.25	82.50	19.0	Gorakhpur (UP)	10.3
7 May 2010	00-03	25.75	82.00	13.0	Allahabad (UP)	0.0
7 May 2010	00-03	26.25	82.50	19.0	Gorakhpur (UP)	10.3

Date	Time (UTC)	Lat.	Long.	Rainfall (mm)	Nearby IMD station	24 hrs rainfall (mm) on 8 May 2010
			(c) Mature stage			
7 May 2010	03-06	25.80	83.75	7.0	Near Varanasi (UP)	48.8
7 May 2010	03-06	25.30	83.75	10.0	Varanasi (UP)	48.8
7 May 2010	06-09	24.75	86.00	39.0	Gaya (Bihar)	17.0
7 May 2010	06-09	24.50	87.25	8.0	Dumka (Jharkhand)	-
7 May 2010	06-09	24.50	85.25	6.0	Hazaribagh (Jharkhand)	-
7 May 2010	06-09	24.25	87.00	61.0	Asansol (WB)	29.6
7 May 2010	09-12	22.75	87.00	6.0	Bankura (WB)	13.1

Appendix 4 (*Contd.*)

Date	Time	Lat.	Long.	Rainfall (mm)	Nearby IMD stations	24 hrs rainfall (mm) on 8 May 2010
			(d) Dissipation stage			
7 May 2010	12-15	21.85	87.00	14.0	Baripada (Odisha)	13.4
7 May 2010	12-15	21.10	85.75	33.0	Keonjhar (Odisha)	0.0
7 May 2010	12-15	22.85	89.00	37.0	Kolkata (WB)	31.0
7 May 2010	12-15	22.85	88.75	31.0	Near Kolkata (WB)	31.0
7 May 2010	12-15	22.33	88.50	32.0	Near Kolkata (WB)	31.0
7 May 2010	15-18	20.90	86.45	12.0	Chandbali (Odisha)	8.8

At initial & developing stage TRMM rainfall is greater than IMD. In dissipation stage the TRMM & IMD rainfall are nearly equal

APPENDIX 5

Meteorological parameters as measured from AWS (obtained from Jadavpur University) for the mature stage of the MCS on 7 May 2010

Station	Lat. (N)	Long. (E)	Disturbed weather (Time in UTC)	Max wind reached (mps) (Time in UTC)			Rise in RH (%) (Time in UTC)		Fall in Temperature (deg C) (Time in UTC)		Pressure Fall/Rise (hPa) (Time in UTC)		Accumulated R/F(mm) from 0000 UTC of 7 May 2010 to 1800 UTC of 7 May 2010
				Mature Stage (0300 UTC of 7th May to 1100 UTC of 7th May)									
Purulia	23.33	86.38	0736-0810	1	13.3	0736	43	0724-0827	16.1	0724-0748	Fall 0.50	0736-0742	
				2	10.5	0748					Rise 1.66	0742-0754	25.9
				3	10.6	0806							
Raghunathpur	23.55	86.67	0740-0805	1	10.7	0748	35	0745-0806	12.0	0727-0757	Fall 0.31	0733-0739	
											Rise 1.81	0739-0745	00.0
Saldiha	23.20	86.72	0821-0842	1	14.7	0821	41	0821-0857	9.8	0818-0848	Fall 0.07	0809-0812	
				2	8.2	0924					Rise 2.61	0812-0830	06.7
Khatra	22.98	86.85	0836-0900	1	13.3	0842	30	0839-0909	6.0	0842-0848	Fall 0.67	0851-0857	
					11.7	0857					Rise 3.20	0857-0909	08.3
Puabagan	23.23	87.07	0824-0906	1	15.8	0827	43	0803-0939	16.1	0748-0857	Fall 0.20	0809-0821	
				2	13.4	0903					Rise 3.01	0821-0845	00.2
Bishnupur	23.08	87.32	0906-0930	1	15.4	0912	39	0912-0942	11.8	0906-0933	Fall 0.20	0851-0903	
				2	12.0	0927					Rise 2.20	0903-0912	12.1
Santiniketan	23.72	87.70	0840-0900	1	14.8	0845	34	0845-0900	10.5	0842-0854	Fall 2.26	0724-0730	
					17.1	0851					Rise 3.12	0730-0854	00.0
					9.4	0909							