Severe Thunderstorm Activities over India during SAARC STORM Project 2014-15: Study Based on Radar

Kamaljit Ray, B. A. M Kannan, Pradeep Sharma, Bikram Sen and A. H. Warsi
India Meteorological Department, Lodi Road, New Delhi
Regional Meteorological Centre, India Meteorological Department, Chennai
Email:raykamaljit@gmail.com

ABSTRACT

Severe thunderstorms create lot of damage to property and crops and human and animal fatalities through the strong surface wind squalls, large hail and occasional tornadoes accompanying them. Broad objectives of the Severe Thunderstorm Observation and Regional Modelling (STORM) programme were to understand the genesis, development and propagation of these systems for improved forecast skill for prediction of these severe thunderstorms. This paper reviews the status of convective activity over Indian region in 2014 and 2015 and discusses the two important severe thunderstorms that occurred on 30 May, 2014 in New Delhi and 21 April, 2015 in Purnia, Bihar. These two events caused lot of damage to life and property due to strong winds/gusts associated with the thunder squalls that affected these areas. Thunderstorm with squall was reported at Meteorological Office at Palam airport in New Delhi on 30 May, 2014 with wind speed in gust reaching 115 kmph .Similarly on 21 April, 2015 Doppler Weather Radar at Patna reported a micro burst signature at 1332UTC, 1352UTC, 1532UTC observations where the peaking winds of 48.2 m/s, 46.6 m/s, and 49.1 m/s were observed respectively, indicating severe wind damage potential at ground. In 2014, although the convective activity was less as compared to 2015 but a very widespread Hailstorm activity at the beginning of pre-monsoon period caused a lot of crop damage in Northwest and Central India.

Keywords: *Doppler Weather Radar (DWR), Reflectivity, Microburst and STORM Project.*

1. Introduction

During the pre-monsoon season of March, April and May, Gangetic West Bengal and surrounding areas get severe thunderstorms called Nor'westers, which are locally called as 'Kal-Baisaki'. The northwest India gets convective dust-storms called locally as 'Andhi'.Severe thunderstorms create lot of damage to property and crops and human and animal fatalities through the strong surface wind squalls, large hail and occasional tornadoes accompanying them.

Interest in tropical thunderstorm studies began in undivided India at the beginning of the 20 Century, more than 100 years ago. By the end of 1920's it was fairly well known that the most severe thunderstorms occur over eastern India and northeast India, which at that time included Bangladesh too as a part of undivided India. Hence, most of the scientific studies and field programmes organised by IMD between 1928 to dawn of freedom in India, were focussed on understanding the severe local thunderstorms in the pre-monsoon season over these parts of undivided India. Several important features about the development, movement, and synoptic tools for the prediction of thunderstorms were defined for over 50 years. Even after India's independence, synoptic data coverage and upper air soundings and introduction and application of atmospheric dynamics research using weather RADAR, focus remained in India over this region, although progressively, studies of thunderstorms of other regions was introduced. Several forecasting manuals of IMD, published during the period 1958-1964 addressed the problem of pre-monsoon thunderstorms over other regions of India too. As tremendous amount of observational and research infrastructure were developed in India between 1950 to 2000, atmospheric research community conceived a program called Severe Thunderstorm Observation and Regional Modelling (STORM) in 2005, to carry out intensive observational research and apply mesoscale dynamical models to understand and predict Norwesters (Das[1], et.al. 2013). The program was funded by the Department of Science and technology from 2006 to 2008, which was later supported by Ministry of Earth Sciences under the aegis of IMD. The Program received the attention of SAARC Meteorological Centre, Dhaka and with their effort a new program known as SAARC

STORM was adopted. The Phase-III of the Program since 2013 covers all SAARC countries.

Broad objectives of the programme were to understand the genesis, development and propagation of severe thunderstorms, to enhance the knowledge of dynamical and thermo-dynamical structure and the role of micro-physical processes on intensification of these severe storms, to study the behaviours of atmospheric electrification during intensification of these storms and their interaction with cloud microphysical processes, development/ customization of mesoscale prediction systems with improved forecast skill for prediction of these severe thunderstorms.

The Pre-monsoon thunderstorms are more hazardous, as they are accompanied with Squall and hailstorms. Koteswaram and Sriniwas (1958) have related the formation of severe thunderstorms over Gangetic West Bengal to low level synoptic conditions as well as passage of high level perturbations like jet stream/troughs of jets over the area. The frequency of thunderstorms in different months over India has been extensively discussed by Rao and Raman (1961). The study showed that the highest thunderstorm activity occurs over Assam, Bengal, Jharkhand and Odisha. Mukherjee (1964) studied thunderstorm activity around Guwahati airport and concluded that the frequency was maximum in May and it approached the station from west. Suresh and Bhatnagar (2004) have analysed unusual hailstorm over Chennai by using data from a single Doppler Weather Radar.Another radar study has been done by Sharma (1965) on hail storm over Guwahati, they concluded that the low over Nepal/North Bengal and its movement towards Guwahati was responsible for the occurrence of hook shaped perturbations. Chaudhury and Chattopadhyay (2002) studied Convective Inhibition Energy (CINE) in relation to Pre-monsoon convective activity over West Bengal. Hail storms are one of the greatest weather hazards to agriculture and aviation. Suresh and Bhatnagar (2004) have analysed unusual hailstorms around Chennai. H.R.Biswas et.al. (2010) have studied the severe hailstorm with hail size about 25 mm diameter over Guwahati airport and concluded that under favourable synoptic and instability conditions of thunderstorm occurrence, veering of winds over Guwahati between freezing level and 500 hPa level with vertical wind shear of horizontal winds exceeding 6.2m/s/km appears to be conducive for development of a hailstorm. Das et.al. (2010) have also done the climatological and synoptic aspects of hailstorms and squalls over Guwahati airport during Pre-monsoon season. They took 20 years data for the study and concluded that significant synoptic situation associated with the occurrence of hail were sea level trough from East U.P/Bihar to NE India and low level circulation over Bihar and neighbourhood.

Convective storm evolution and propagation of severe weather event is of utmost importance in nowcasting applications, owing to their higher frequency, fast dynamics and high damage potential. The primary tools for detecting convective storms are weather radar, lightning detectors, and satellite imagery. Very short period forecasting of the future location of convective storms has historically been based primarily on the extrapolation of radar reflectivity echoes. DWRs play a vital role not only in tracking the genesis and movement of thunderstorms and severe local storms but also to estimate the wind speed associated with the downdrafts of these storms. This article discusses the salient features of the STORM Project in 2014 and 2015 and analysis two important severe thunderstorm events that took place in these two years using Doppler Weather radar.

2. Data Used

The STORM Project monitoring period considered is from March to June.In addition to 0000 UTC RS/RW ascent at 35 locations over India, additional Radiosonde ascents at 0600 UTC in New Delhi, Mohanbari, Nagpur, Chennai and Kolkata on 20 days in April and May was undertaken. Observations from around 16 Doppler Weather radars (DWRs),half hourly satellite coverage, Integrated Precipitable Water (IPW) from GPS receivers installed in Chennai, New Delhi, Mumbai, Guwahati, real time transmission of data from 300 AWS stations, Synoptic observations from 350 Surface Observatories of India Meteorological Department (IMD) were some of the regular inputs collected and utilised for implementation of the Project. The total number of thunderstorm events recorded at a station in a particular day were categorised, based upon the time of occurrence and this was counted as the frequency of thunderstorm events in that particular time period. The day was divided into five time periods as defined by IMD i.e. Morning: 0400 to 0800hrs IST, Forenoon: 0800 to 1200hrs IST, Afternoon: 1200 to 1600hrs IST, Evening: 1600 to 2000hrs IST and Night: 2000 to 0400hrs IST.

3. Results

3.1 Salient features of STORM Project in the years 2014 and 2015

A total of 3620 thunderstorm events were recorded over the country during the Storm Period-2014 as compared to 5536 recorded in 2015(Table.1). Highest number of 473 thunderstorm events was recorded over West Bengal in 2014, as compared to 709 recorded over Karnataka in 2015. A number of thunderstorm events over the country were associated with squalls. According to World MeteorologicalOrganization (WMO) a squall is a sudden, sharp increase in wind speed by at least 8 m/s (16Kt) and reaching to at least 11m/s (22Kt) and lasting for at least one minute. A total of 44 thunder squalls were recorded over the country in 2014 and 53 in 2015 based on the Dines P.T anemometer observations of IMD network. 65 hailstorms were recorded over the country during the Pre-monsoon period in 2014 and 82 in 2015.The convective activity during the Pre-monsoon period was higher in 2015 as compared to 2014.

In 2014 and 2015, the thunderstorm activity was more or less same over Northwest India and central India but it was significantly high over Southern Peninsula in 2015 as compared to 2014 (Table.2) Highest number of Thunderstorm events were recorded over NW India in 2014, while in 2015, the highest TS events were recorded over Southern Peninsula. In 2014 Assam recorded 326 events while in 2015 Karnataka recorded highest 707 events during the STORM period. Thunderstorm activity was higher in all regions in 2015 as compared to 2014. Highest thunder squall events were recorded in East India followed by Northwest India in both years.16 thunder squalls were recorded over East India in 2014 as compared to 22 recorded in 2015. Hailstorm recorded in east India were 21 as compared to 15 in 2015. While they were 19 hailstorms in southern Peninsula in 2015 as compared to only 2 in 2014. The hailstorm activity was also higher over Central India in 2015 as compared to 2014 (Table.3). 47% of the total squalls had wind speed ranging between 22-30Kts followed by 31% in the range 31-40Kts.Only 3 % thunder squall events were within speed range 51-60Kts. The thunder squall with highest maximum wind speed of 115Kmph (62Kts) was recorded over Airport Met Office Palam, New Delhi on 30 May 2014 (case study) (Table.3). Highest number of hailstorm events were recorded over Northwest India (34) followed by East India (21). No hailstorm event was recorded over West India during the Storm Period-2014. West Bengal recorded maximum number of hailstorms (21) followed by Jammu & Kashmir (15). In 2015 Highest thunder squall events were recorded over East India closely followed by Northwest India.46% of the events recorded wind speed between 22-30Kts, followed by 28% in the range 31-40Kts. 2 % of the thunder squalls recorded wind speed between 61-70Kts. Highest maximum wind speed of 120Kmph (65Kts) was recorded over Deesa, Gujarat on 13 March, 2015. A total of 98 hailstorms were recorded over the country during the Storm Period-2015 i.e. period from 1 March to 30 June, 2015. The day with one or more thunderstorm over a station was considered as the thunderstorm day as per IMD convention. The all India distribution of TS days in 2014 and 2015 is shown in fig.1a&b

In 2014 highest numbers of thunderstorm events (114) were reported on 4 May and on 17 April due to the passage of western disturbance (WD) over northwest India. The WD led to an induced cyclonic circulation over Uttar Pradesh and adjoining areas in lower levels. The wind discontinuity over central India extended from this circulation uptocomorin area across Madhya Pradesh, Marathwada, interior Karnataka and Tamil Nadu. Widespread outbreaks of intense thunderstorms occured on many days affecting various regions of India during the STORM Period from 2013-2015. Some of the major events occurred on 17-18 April 2013, 6 June 2013, 20 April 2013,20 April 2014,30 May 2014,14 and 15 March 2015 and 21 April,2015. Details of all these events are given in Ray,et.al. (2013, 2014, 2015). In this paper we illustrate two case studies, 1) 30 May, 2014 over NW India 2) 21 April, 2015 over Purnia, Bihar.

3.2 Severe Thunderstorm activity in Delhi on 30 May 2014

A severe thunderstorm affected Delhi and adjoining region between 1630 Hrs IST and 1730 hrs IST of 30 May, crippling road traffic, metro services and flight operations and hitting power supply. At least nine people were killed in the NCR region, including six in Delhi, 13 were injured in various areas of the city in accidents like felling of trees, collapse of walls and electrocution following the storm which was accompanied by winds at a speed of over 90 kmph.

The micro-scale features of the severe thunderstorm that occurred on 30 May 2014 were very well captured by Doppler weather radar. The weather prevailed was that of a pre-monsoon hot dry weather. The maximum temperature hovered at 42.4 degrees. With the approach of the thunder-cells from NW, moisture discontinuity roughly NW oriented, extending 150km in length was captured by radar (Highlighted in brown dashes fig. 2). The storm gust front highlighted with blue dashes is also shown in fig.2.The cell was quite steep more than 15km in height. Fig 3a &b shows the cross section of the storm in reflectivity and velocity fields. The dryline front is also captured at 25km towards left.

As the storm approached towards the radar this moist layer of air (Gust front and the storm) started sliding over the dry boundary as well displacing it south-south west ward with time. This phenomenon is clearly visible in the rest of the time sequence radar images (fig 4& 5). By 1202 UTC the peak activity of the thunder cell is visible almost eliminating the dryline moisture discontinuity. The winds were peaking to the tune of 28 m/s after unfolding in PPI-velocity presentation in fig 6a. The derived product Volume velocity processing time series data is shown in fig. 6b.It covered a distance of around 100 kms in less than two hrs and crossed Delhi by 1730 hrs in the evening with a wind speed of 90-110 Kmph (Squall reported by IMD Observatory at Safdarjung airport). The temperatures plunged down to 26-28 °C, after the event. The duration of the squall associated with the thunderstorm was 1658-1703 hrs IST with wind direction from Northwest direction and wind speed 92 kmph recorded at observatory. A temperature fall of 13° C was reported from 1700 to 1730 hrs by the observatory (40°C to 27°C).

Thunderstorm with squall was also reported at Meteorological.Office at Palam airport in New Delhi. The duration of the squall associated with the thunderstorm was 1654-1656 hrs IST with wind direction from Northwest direction and wind speed 115 kmph .

3.3 Severe Thunderstorm activity over Bihar (Purnea on 21 April, 2015)

Bihar was affected by an intense thunderstorm activity from 1730 hrs IST to 2300 hrs IST of 21 April. Purnea, Araria, Kishanganj, Katihar, Madhepura, Supaul, Saharsa, Bhagalpur, Samastipur, Darbhanga and Madhubani districts in north and north eastern parts of the state were most affected. At least 44 people were killed and 100 others injured as a heavy storm with rain and hail swept through northern and north-eastern districts of Bihar on Tuesday night, destroying standing crops and property worth several crores of rupees. The storm uprooted thousands of trees, snapped power lines, blew away huts, and extensively destroyed crops of maize, wheat, pulses, mango and litchi. Road communication was also hit as uprooted trees blocked several stretches. The severe storm hit Purnea, Katihar, Madhepura and Saharsa from around 2115 to 2300 hrs IST of 21 April. The eastern and north eastern part of the country i.e. Bihar, Gangetic West Bengal, Jharkhand, Orissa, Assam and other states of NE India gets affected by severe thunderstorms during pre-monsoon months (March-May), in particular, during April & May. Nearly 28 severe thunderstorm episodes occur in this region during this period of two months. As compared to other states in East India, the thunderstorm activity is least over Bihar. In 2014 the thunderstorm activity over Bihar and Jharkhand was lowest as compared to West Bengal and Odisha. In an earlier study by Tyagi, et. al.(2012) ,the number of thunderstorm cells that originated over Bihar during 2007-2010, were only 5, as compared to 19 over Jharkhand, 22 over West Bengal and 37 over Odisha. Similarly, the number of cells that migrated over Bihar during the above period was only 6 in comparison to 22 over West Bengal and 16 over Odisha.

Around 1000 UTC in the surveillance scan of DWR Patna, significant weather signature (reflectivity 30 dBZ) centered at 28^0 N extending 83.7^0 to 88.7^0 E was noticed in DWR Patna (Fig.7). The weather echo started showing prominence at 1032 UTC with cloud height at 14km and reflectivity at 42-46bBZ moving in SE direction. The sequence of the events was studied between 1030 to 1800 UTC when the weather phenomenon persisted. The phenomenon was regeneration of cells and the transit was very rapid i.e. 400km in 4hrs, with an average speed of 100kmph. The maximum reflectivity on an average stood around 50dBZ peaking to 64dBZ at 1342 UTC (Fig.8). Throughout the period of study, the cloud top was hovering above 13km but the base could not be sensed; even during its closest approach (104.6km at 1432 UTC) the lowest beam of the volume scan was at a height of 1.1 km (Fig.9). A micro burst signature was observed in 1332UTC, 1352UTC, 1532UTC observations where the peaking winds of 48.2 m/s, 46.6 m/s, and 49.1 m/s were observed respectively. With absence of data near ground, this sensed wind (at 1.95km, 1.5km & 1.8km) is to be taken as an indicator of having severe wind damage potential at ground (Fig. 10).

The third micro burst at 1532 UTC later developed into meso-cyclonic-convective (MCC) storm signatures (1612 UTC), due to induced vorticity with a bean shape and with a possibility of hail/precipitation (Fig.11). The cloud top (signature of cloud strengthening and waning) estimated was at a maximum at 1652 UTC reaching 18.9km (Fig.12). This MCC persisted till 1732 UTC and divided into two, with opposite rotating MCCs causing the squall/tornado type destruction over Purnea. At later time, the event was observed only in surveillance scan with no much inference to offer except for its presence as the lowest beam height was 12.2km and 15.1km respectively.

Air Force Station, Chunar reported the squally winds from northwest (NW) direction and moving towards SE at about 1630 UTC ,the winds were around 115 km /hr (310/62 KT). As reported by officer on tour from MC Patna, some eyewitnesses told that there were circular type of winds which were blowing upwards and flew away asbestos and tin sheets. The residents were confined to their houses due to increase in the intensity of rain. The growth of the clouds was clear and sky was overcast around 1630 UTC. The south-easterly movement of strong winds further damaged the electric poles and caused power outage in the city. The funnel type structure of the clouds was not noticed by anybody, so the possibility of tornado can be ruled out.

4. Conclusions

Thunderstorms/lightning related incidents on an average claim more than 100 lives every year in India. In 2015 the severe thunderstorm on 21 April affected 8 northern districts of Bihar, Purnia district was one among the worst affected. It claimed 54 lives and over 75000 houses were partially/totally damaged. Hailstorms in Uttar Pradesh claimed 2 lives and 1000 hectares of land under wheat crop was destroyed. Apple orchards and banana plantations were destroyed in hailstorm in Himachal Pradesh and Karnataka.

Thunderstorm reporting by IMD stations was higher in 2015 as compared to 2014. In 2015 in the month of March, passage of active Western Disturbances (WDs) and their induced systems caused widespread precipitation and thunderstorm activity over western Himalayan region and adjoining plains. Their interaction with the troughs in tropical easterlies in the mid & upper tropospheric levels and wind discontinuity in the lower tropospheric levels, aided with the moisture influx from the tropical Seas, led to well distributed rainfall/hailstorms over west, northwest, north, central and adjoining peninsular India in the first fortnight. Third week witnessed a suppressed easterly wave activity on account of the convectively suppressed phase of Madden Julian Oscillation (MJO) over the Indian Seas. This along with clear skies, caused a sharp rise in the day temperatures leading to heat wave conditions over western parts of central India. The weather almost remained dry outside northeast and south peninsula. Thereafter, the passage of a series of WDs and perturbations in mid-latitude westerlies, and trough/wind discontinuity in the lower levels caused precipitation over north, northeast, central and Peninsular India. In April Passage of active WDs and cyclonic circulations induced by them once again caused isolated to scattered precipitation over north and northeast India almost all through the month. The presence of north-south troughs/wind discontinuity in the lower levels led to isolated to scattered thundershowers over south Peninsular India and central India during the month. In May WDs delayed the development of the 'Heat Low' over northwestern parts of India. Presence of cold and dry mid latitude air in the wake of slow moving deep amplitude westerly trough inhibited the vortices over Indian Seas to organize further. However, this cold and dry air and moisture incursion from the Sea due to low level cyclonic vorticity led to convective activity over most parts of India towards the later part of the second week of May.

In 2014, although the convective activity was less as compared to 2015 but at the beginning of pre-monsoon period, starting from 2nd fortnight of February to 1st fortnight of March, there was widespread rainfall/hailstorm activity over major parts of the country. The passage of western disturbances and its induced systems and the presence of warm and moist tropical air in the lower tropospheric levels over the Peninsular India created conducive conditions for the development of convective cells leading to widespread hailstorm activity over NW and central India.This continuous precipitation over major parts of the country kept day temperatures below normal over most parts of the country. Some of the questions need to be answered through further studies in this field like a) What was the reason for less convective activity during 2014 as compared to 2015 b) What made the Storms of 30 May 2014 and 21 April 2015 so severe as compared to other events during the year? c) What caused the splitting of the MCC in 2 parts with opposite rotation of the wind fields?

The STORM Project Pilot Phases from 2006-2013, strengthened the observation network, monitoring and assimilations in NWP models. Operational nowcast Services for around 180 locations were started in 2013 in order to reduce the impacts of these severe thunderstorms in society, using IMD Network of DWRs, Satellite data and Automatic weather stations network.

Acknowledgements

The report was prepared with valuable inputs from various regional sub-offices of India Meteorological Department (IMD).We acknowledge guidance, support and facilities provided by DGM, India Meteorological Department in carrying out this work.

References

Biswas H.R., Chakrabarti D., Kore P.A., Das G. K., 2010:A Severe Hailstorm over Guwahati Airport and its Vicinity on 2nd April, 2006: Synoptic and Thermodynamic Perspective. *Mausam*, 61, 3,391-400.

Chaudhuri S. and Chattopadhyay S., 2002: Multi layer perceptron model in pattern recognition of surface parameters during pre-monsoon thunderstorms. *Mausam*, 53, 4, 417-424.

Das Someshwar, Mohanty U. C., Tyagi, A., Sikka D. R., Joseph P. V., Rathore L. S., Habib A., Baidya S, Sonam K., and Sarkar A., 2015: The SAARC STORM - A Coordinated Field Experiment on Severe Thunderstorm Observations and Regional Modelling over the South Asian Region, *Bull. Amer. Meteor. Soc.,95(4)*,603-617,DOI: http://dx.doi.org/10.1175/BAMS-D-12-00237.1

Das G.K., Samui R. P., Kore P.A., Siddique L. A., Biswas H. R., Barman B.,2010: Climatological and Synoptic Aspects of Hailstorm and Squall over Guwahati Airport during Pre-monsoon Seasons. *Mausam,* 61, 3, 383-390.

Koteshwaram P. and Srinivasan V., 1958: Thunderstorms over Gangetic West Bengal in the pre-monsoon season & the Synoptic Factors favourable for their formation. *India J. Met. &Geophys*. 10, 275-286.

Mukherjee A.K., 1964: Study of Thunderstorms around Guwahati Airport. *India J. Met. & Geophys.*15, 425-430.

Rao K.N. and Raman P.K.1961: Frequency of days of Thunder in India. *India J. Met. & Geophys.*,12, 103-108.

Ray Kamaljit, Mohapatra M., Bandopadhyay B.K., Sikka D.R, ChakravarthyKalyan, SenBikram, Debnath G.C., Stella S., Das Sunit, Duraisamy M., SaiKrishnan K.C, Kannan B., GoyalSuman, Jordar D., Saxena Rahul, Bhan S.C., TyagiAjit, Mohanty U.C., Das Someshwar and Rathore L.S., 2013: Report on Pre-monsoon Season 2013 Thunderstorm over India, IMD *Report No. SMRC STORM PROJECT-2013/2/2013.*

Ray Kamaljit, Bandopadhyay B.K., Sen Bikram, Sharma Pradeep, Warsi A. H., Mohapatra M., Yadav B.P., Debnath G.C., Stella S., Das Sunit, Duraisamy M., Rajeev V. K., Barapatre V., Paul Surender, Singh Himanshu, SaiKrishnan K.C., Goyal Suman, Das A.K., Bhan S.C., Sikka D.R , ChakravarthyKalyan, TyagiAjit, Das Someshwar and Rathore L.S., 2014: Pre-Monsoon Thunderstorms 2014: A Report', *IMD Report No. ESSO/IMD/SMRC STORM PROJECT-2014/01(2014)/03.*

Ray Kamaljit, Bandopadhyay B.K., Sen Bikram, Sharma Pradeep, Warsi A. H., Mohapatra M., Yadav B.P., Debnath G.C., Stella S., Das Sunit, Duraisamy M., Rajeev V. K., Barapatre V., Paul Surender, Shukla P., MadanRanju, GoyalSuman, Das A.K., Bhan S.C., ChakravarthyKalyan and Rathore L.S., 2015: Pre-Monsoon Thunderstorms 2015: A Report, *IMD Report No. ESSO/IMD/SAARC STORM PROJECT-2015/(01)(2015)/4.*

Sharma B.L., 1965: Radar Study of Hailstorm over Guwahati on 17 April, 1962. *India J. Meteor. Geophys.*, 16,3, 459-466.

Suresh R. & Bhatnagar a. K., 2004: Unusual Hailstorms during May, 2002 in Chennai & its suburbs-A Study using data from a single Doppler Weather Radar, *Mausam* 55, 4, 655-670.

TyagiAjit, Sikka D.R., GoyalSuman and BhowmickMansi, 2012: A Satellite Based Study of Pre-Monsoon Thunderstorms (Nor'westers) over Eastern India and their organization into Mesoscale Convective Complexes, *Mausam*, 63, 1, 29-54.

Table1.Thunderstorm Activity during 2014 and 2015 STORM Period

Year	Total TS Events	Thundersquall Events	Hailstorm Events	Region with highest TS Events	State with Highest TS Events	Amount (events) & day of highest TS activity
2014	**3620**	44	65	NW India (1469)	West Bengal (473)	114, 4 May 2014, 113 on 17 April, 2014
2015	**5536**	53	82	SP India (1854)	Karnataka (709)	131, 16 May, 2015, 119 on 11 May & 1 June, 2015

Table 2.Thunderstorm Activities during 2014 and 2015 STORM Project

TS Events		2014	2015	TS Events		2014	2015
Central India	Chhattisgarh	131	152	**East India**	BIHAR	22	105
	Madhya Pradesh	116	119		JHARKHAND	12	72
	Vidharba	60	69		ODISHA	184	255
	Total	**307**	**340**		SIKKIM	78	96
NW India	Delhi	48	55		WEST BENGAL	395	466
	Haryana	165	91		**Total**	**691**	**994**
	HP	100	118	**SP India**	ANDHRA PRADESH	194	406
	J & K	369	427		KARNATAKA	157	707
	PJB	212	82		KERALA	168	423
	RAJ	322	240		TAMILNADU	44	318
	UP	209	298		**Total**	**563**	**1854**
	UTKD	44	114	**West India**	Goa	16	7
	Total	**1469**	**1425**		Gujarat	11	27
NE India	ARUNACHAL PRADESH	20	33		Maharashtra	7	26
	ASSAM	326	510		**Total**	**34**	**60**
	MANIPUR	19	29				
	MEGHALAYA	66	151				
	MIZORAM	29	37				
	TRIPURA	70	129				
	Total	**530**	**889**				

Table 3.Monthwise Details of Squall, Hails and Thunderstorm Days during STORM Project 2014 and 2015(15 March to 15 June)

Region		Squall				Hail		TS Days			
		2014	Max Speed	2015	Max Speed	2014	2015	2014	Max	2015	Max
Central India	March		35Kts(65kmph) from W, Gwalior, 31 May evening hours		44kmph(24KT) from NW, Satna, 19 May, night hours	0	4	4	Nagpur-30, Jagdalpur-29	8	Ambikapur-27, Pendra Road-26, Nagpur-25
	April	2		0		1	1	22		20	
	May	2		2		0	1	24		24	
	June					0	0	15		14	
	Total	**4**		**2**		**1**	**6**	**65**		**66**	
Northwest India	March	0	115kmph(62KT) from N, Palam, 30 May evening hours	0	93kmph(50KT), Palam from NW, 13 June, forenoon hours	5	8	13	Sundernagar-30, Pahalgam-29	9	Bhadrarwah-38, Batote-37
	April	3		7		7	18	21		26	
	May	10		3		19	8	31		28	
	June	1		4		3	0	14		15	
	Total	**14**		**14**		**34**	**34**	**79**		**78**	
Northeast India	March	1	69kmph(37KT), Agartala from SW, 22 March, night hours	0	78kmph(42KT), Agartala from N, 22 April, night hours	3	2	14	Silchar, &Chabua(IAF)-33, Tezpur(IAF)-30	9	Guwahati-54, Silchar-45
	April	2		6		3	3	25		28	
	May	2		2		1	0	28		31	
	June	0		0		0	0	13		15	
	Total	**5**		**8**		**7**	**5**	**80**		**83**	
East India	March	1	76kmph(41KT) from NW, Digha, 12 April evening hours	1	92kmph(50KT) from SW, Gaya, 24 April, afternoon hours	6	1	12	Gangtok-37, Hashimar(IAF), Kumbhigram (IAF)-34, Keonjgarh-24	12	Gangtok-36, Keonjgarh-35
	April	3		12		6	9	25		30	
	May	5		7		9	4	30		31	
	June	7		2		0	1	15		15	
	Total	**16**		**22**		**21**	**15**	**82**		**88**	
South Peninsular India	March	0	115kmph(62KT) from NE, Vishakhapatnam, 22 May, evening	0	106kmph(57KT) from E, Bengaluru 23April evening	0	3	3	Thiruvananthapuram-30, Hakimpet(IAF)-27	10	Thiruvananthapuram -55, Bengaluru-41
	April	0		1		1	10	29		30	
	May	1		1		1	6	30		30	
	June	0		4		0	0	14		15	
	Total	**1**		**6**		**2**	**19**	**76**		**85**	
West India (15 April to 15 June)	March	No Data	68kmph(37KT) from SW, Ahmedabad, 6 May, evening hours	1*	82kmph(44KT) from SSW, Ahmedabad, 13May evening hours	No Data	**0**	No Data	Pune(IAF)-15, Ahmedabad-7		Panjim-11, Ahmedabad-3
	April	0		0		0	1	6		0	
	May	3		1		0	1	15		10	
	June	1		0		0	1	9		8	
	Total	**4**		**1**		**0**	**3**	**30**		**18**	

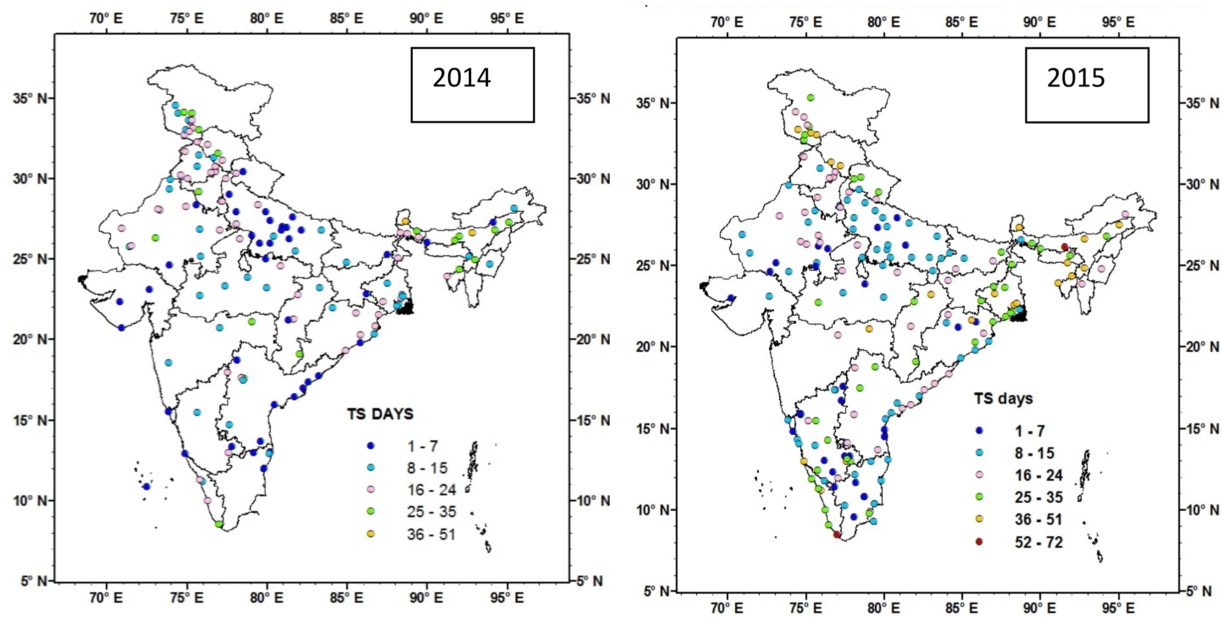

Figure 1: Spatial Distribution of Thunderstorm Days over India during Storm Period-2014 & 2015

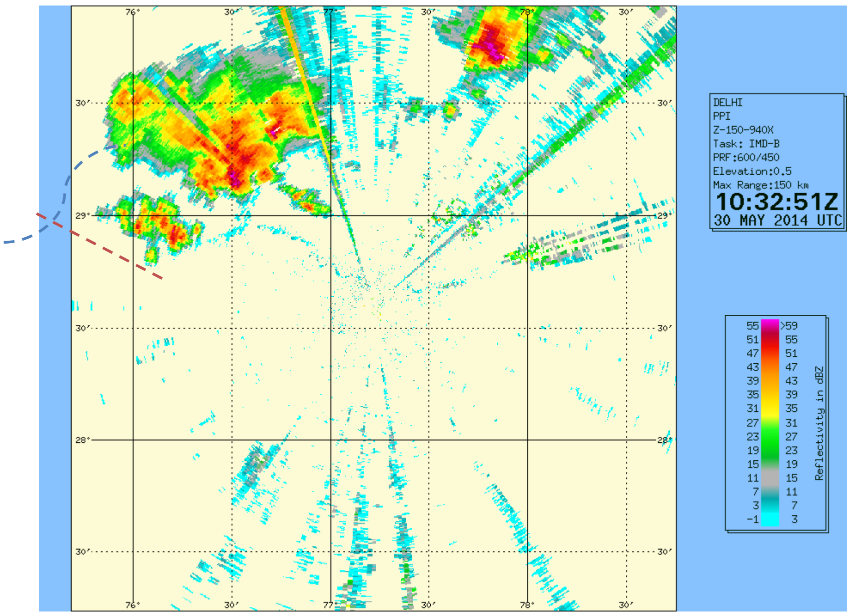

Figure 2: DWR-Delhi, PPI- Total Reflectivity with Highlighted Moist Gust front (Blue dashes) and Dry Moisture Discontinuity (Brown dashes)

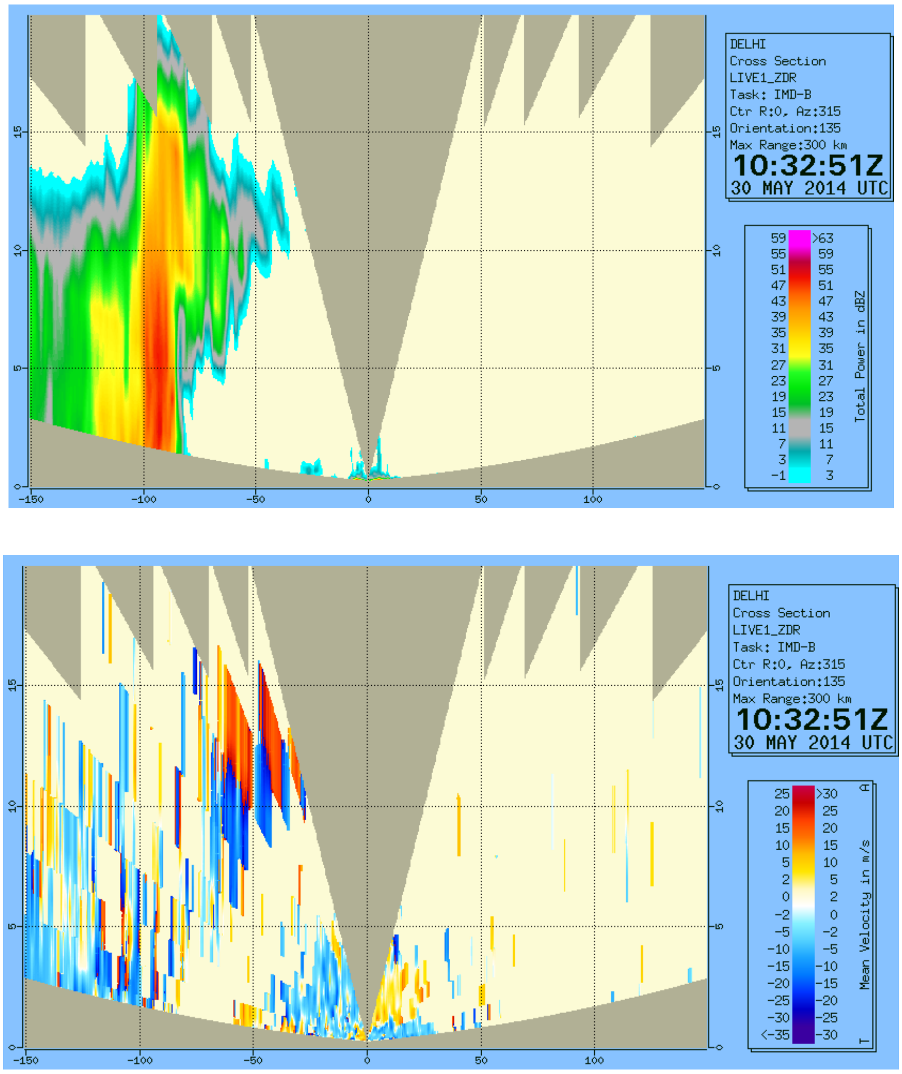

Figure 3(a & 3b): DWR-Delhi, X-Z Cross Section of the Storm in Reflectivity and Velocity Fields

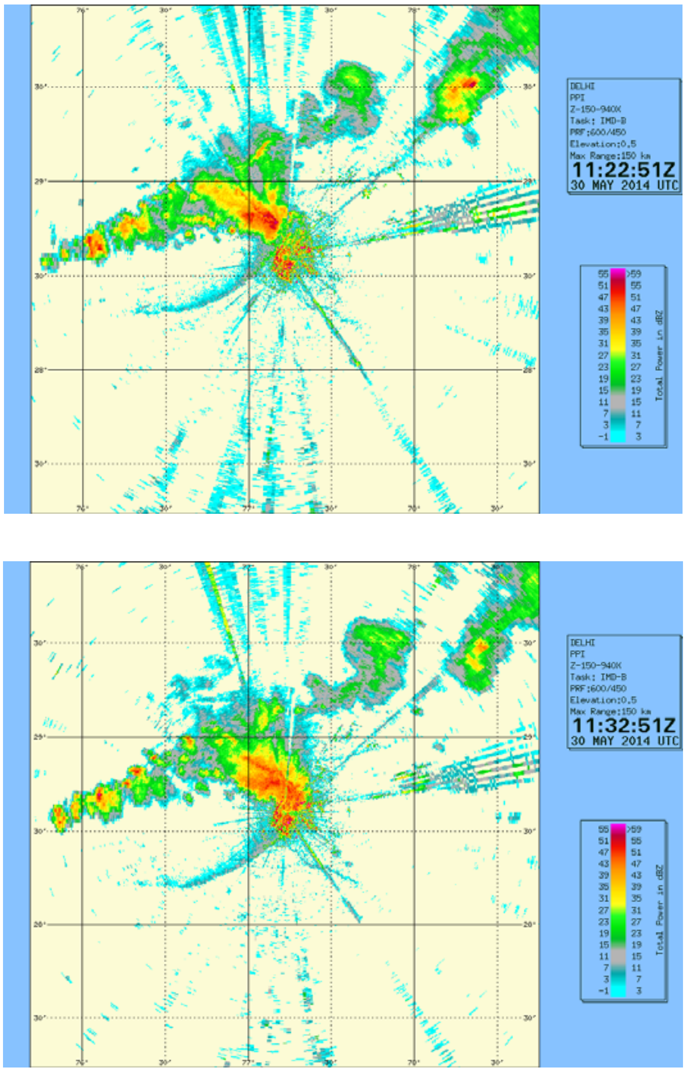

Figure 4: DWR-Delhi, Thunder Cells organized into a Squall Line Pattern, the Gust Front Pushing the Moisture Discontinuity below 28.5 deg Latitude

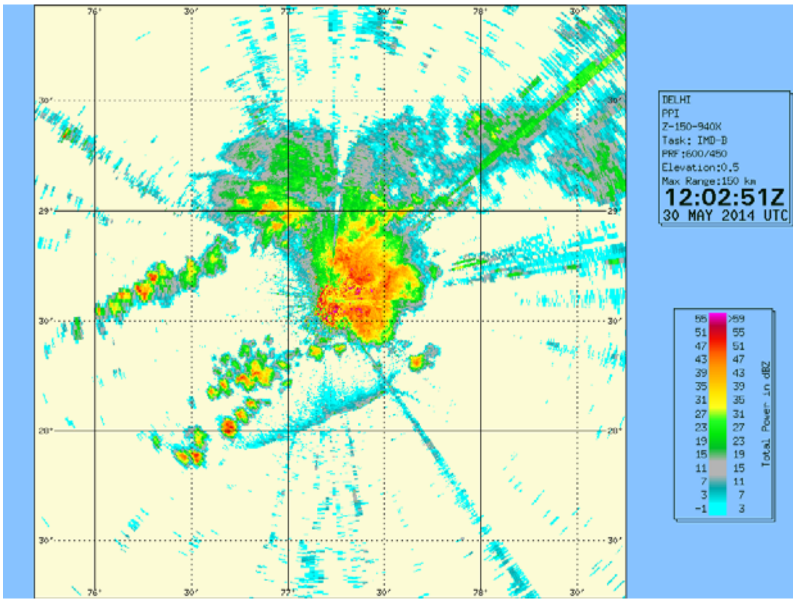

Figure 5: DWR-Delhi, Active Dominance of Thunder Cell almost Weeding off the Moisture Discontinuity Delhi

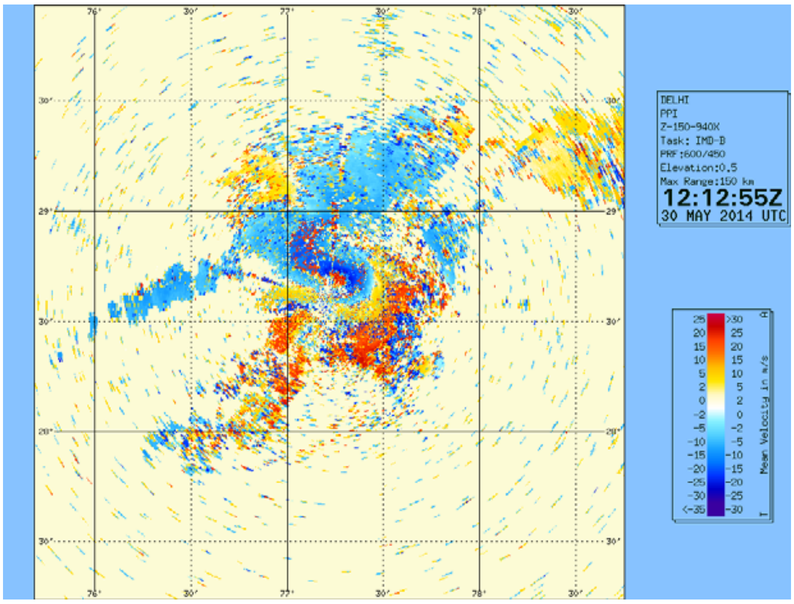

Figure 6(a): DWR-Delhi, PPI-Velocity showing Higher Winds near Surface 28 m/s

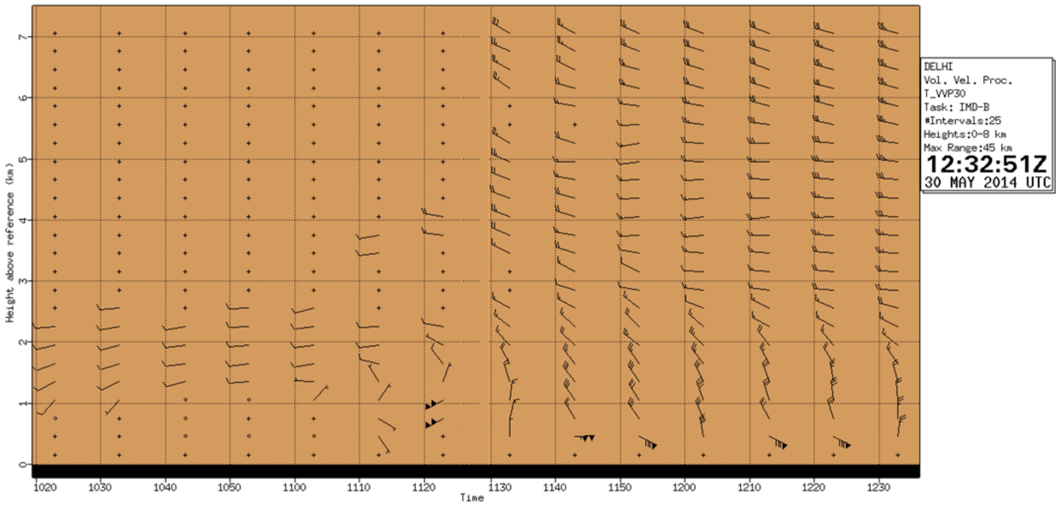

Figure 6(b): DWR-Delhi, VolumeVertical Processing –Time Scale Image showing Radar Derived Vertical Wind Profile

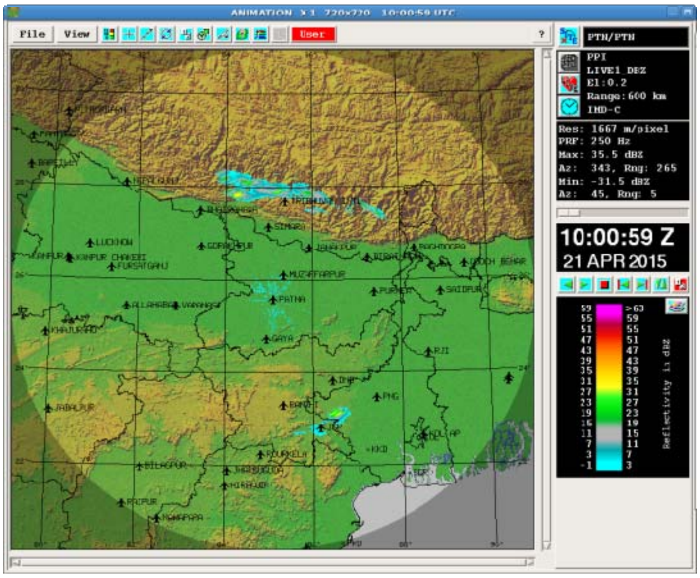

Figure 7: DWR-Patna PPI/MAX Z Imagery Showing the Surveillance Scan Coverage of 500km

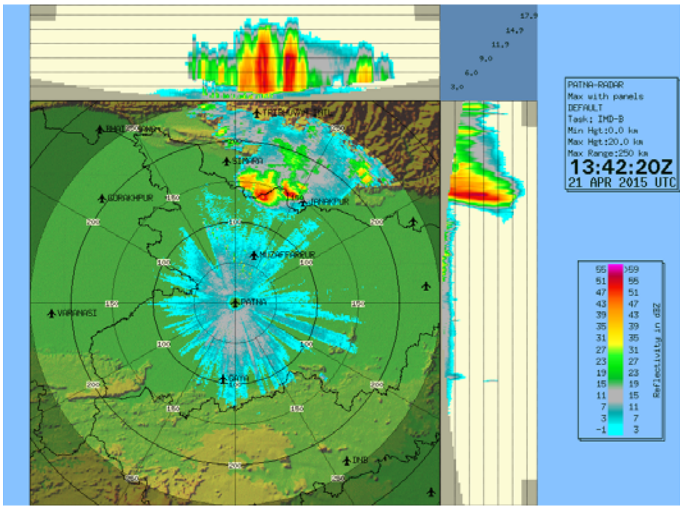

Figure 8: DWR-Patna PPI/MAX Z Imagery showing Cells with Highest Reflectivity of 64dBZ reached at 1342 UTC

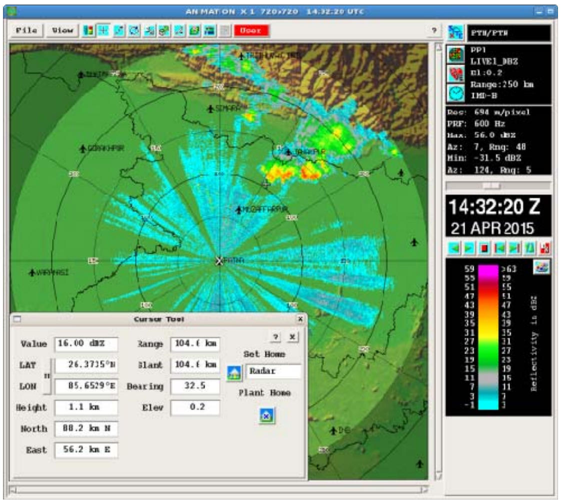

Figure 9: DWR-Patna PPI/MAX Z Imagery showing Cells with high dBZ during the Closest Approach to the Radar

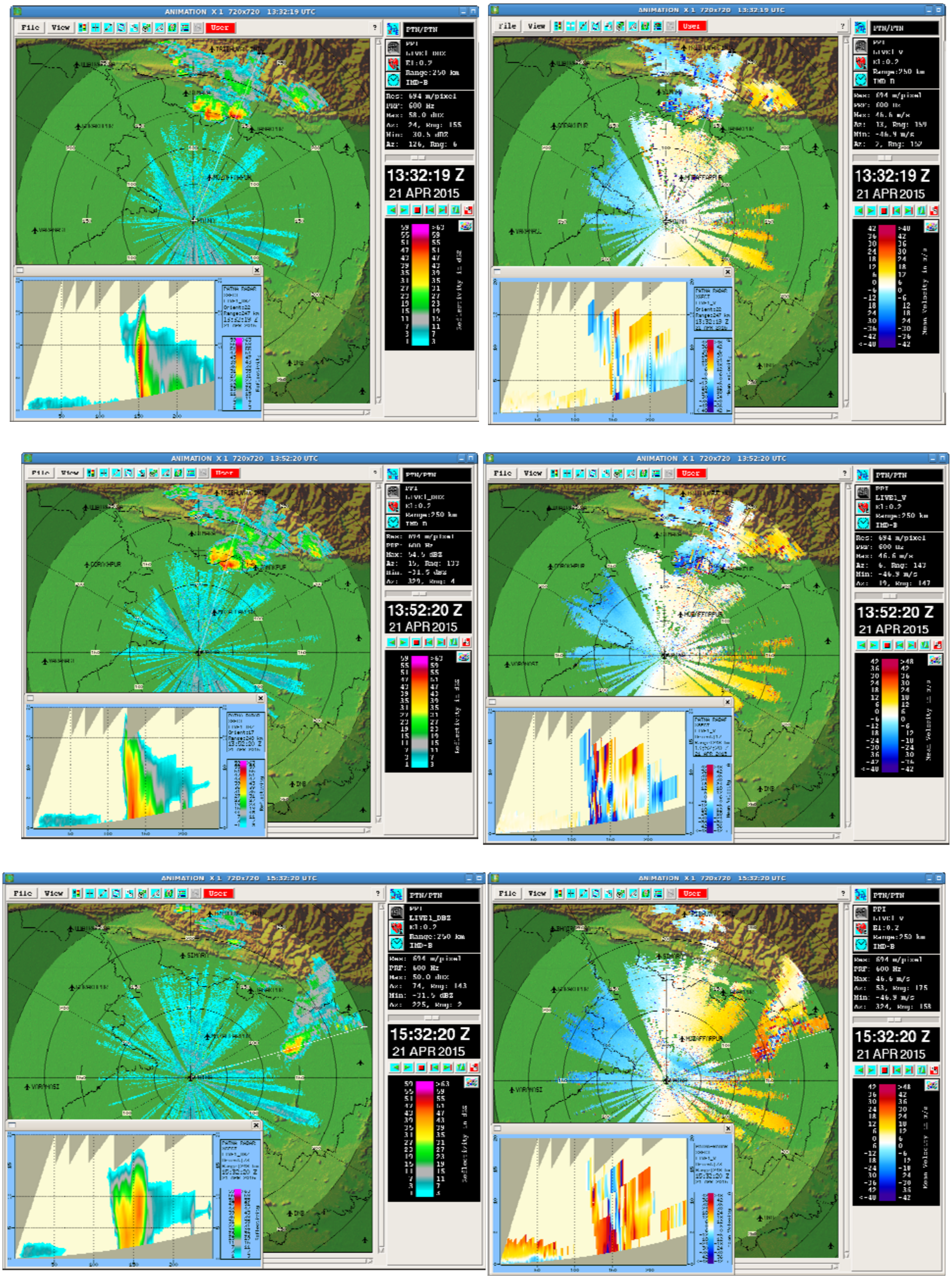

Figure 10: PPI/RHI Z and PPI/RHI V at 1332 1352 and 1532 UTC of 21 April showing Microburst Signatures

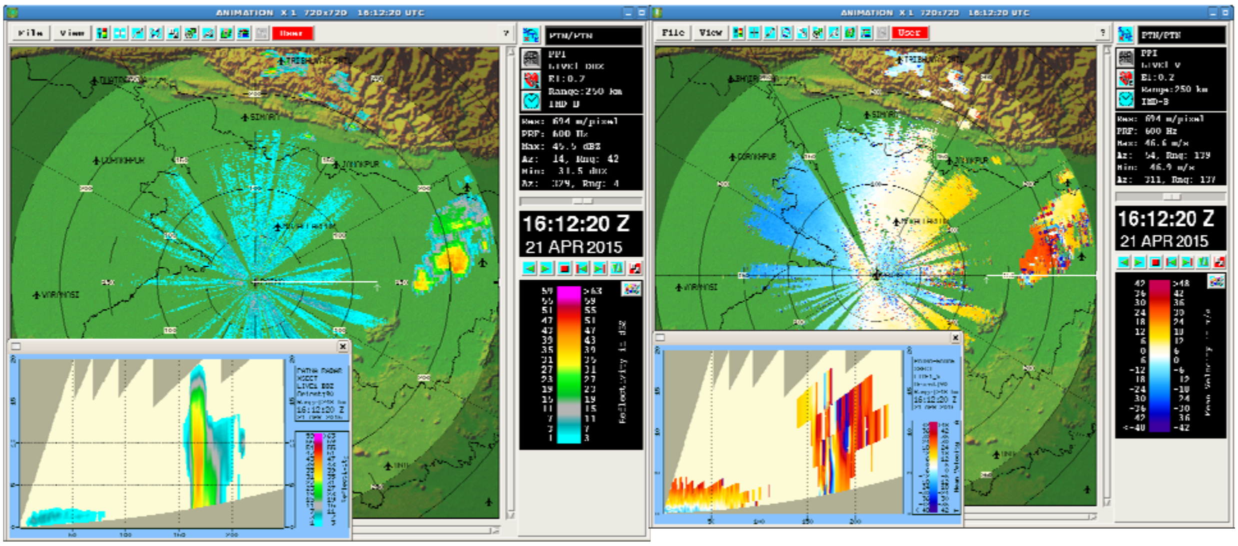

Figure 11: PPI/RHI Z and PPI/RHI V at 16.12 UTC of 21 April showing Characteristics of Meso Cyclonic Circulation (MCC)

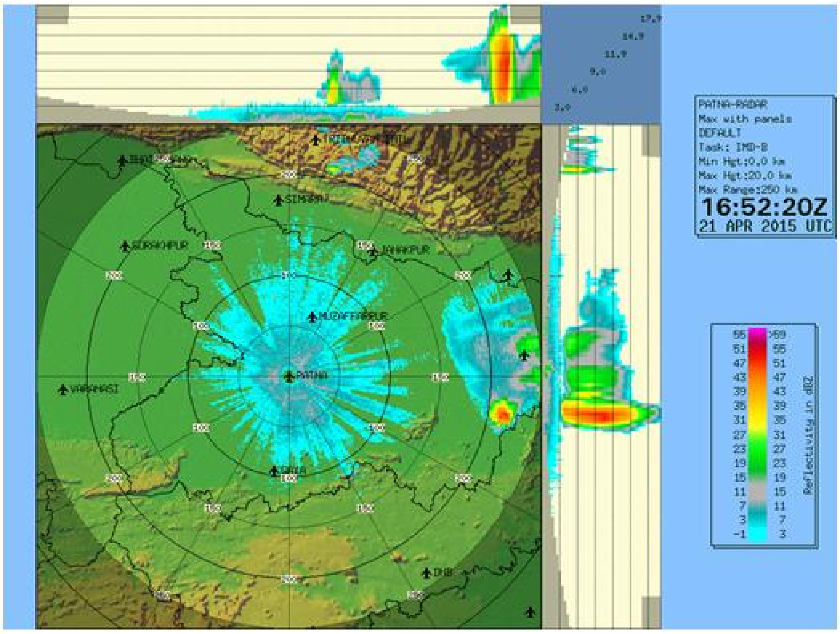

Figure 12: Radar reflectivity Imagery of Highest Cloud top of 18.9 km reached at 1652 UTC, near Purnia