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A Study of hailstorm of 19th April 2010 over Delhi using Doppler Weather Radar observations

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सार – पालम पर स्थापित किए गए डॉप्लर मौसम रेडार से प्राप्त प्रेक्षणों के उपयोग से 19 अप्रैल 2010 को दिल्ली में हुई ओलावृष्टि का अध्ययन किया गया है। डॉप्लर मौसम रेडार से लिए प्रेक्षणों के आँकड़ों को मौसम विज्ञान विभाग के मुख्यालय में लगाए गए केन्द्रीय सर्वर में ग्रहण किया जाता है। केन्द्रीय सर्वर में स्थापित आइरिस सॉफ्टवेयर (मै. सिगमैट, फिनलैण्ड) की सहायता से इन आँकड़ों का विश्लेषण किया गया। इन विश्लेषण से यह पता चला है कि 45 डी.वि.जेड. परावर्तकता का स्तर हिमांक स्तर से 6.3 कि. मी. की उँचाई तक विद्यमान था जो कि विट्ट आदि (1998 ए.) के द्वारा किए गए संभावित फंक्शन आरेख से प्राप्त ओलावृष्टि की 100 प्रतिशत संभाव्यता के बराबर है। 1110 यू.टी.सी. तथा 1120 यू.टी.सी. पर परावर्तकता क्रमशः 10 कि. मी. तथा 7 कि. मी. की उँचाई तक 55 डी.वी.जेड. से अधिक पाई गई। 1110 यू.टी.सी. पर 62 डी.वी.जेड. 3 कि. मी. पर तथा 1120 यू. टी.सी. पर 64 डी.वी.जेड. 3.5 कि. मी. पर अधिकतम परावर्तकता थी। परावर्तकता के ये मान एन.ई.एक्स.आर.ए.डी. (यू.एस.ए.) में प्रयुक्त प्रचालानात्मक प्रभाव सीमा से अधिक है। 1040 यू.टी.सी. तथा 1120 यू.टी.सी. के दौरान ऊर्ध्वाधर समाकलित द्रव की मात्रा 58.7 कि.मी. प्रति मी.^{2} तथा 64.1 कि.मी. प्रति मी.^{2} के बीच थी जो कि ओलावृष्टि की पहचान करने के लिए प्रयुक्त प्रचालानात्मक मान 43 कि.ग्रा. प्रति मी.^{2} अधिक है। विट्ट आदि (1998 ए.) द्वारा विकसित सवंर्धित ओला संसूचन एल्गोरिथ्म के भारतीय परिस्थितयों में प्रयोग करने की संभावना का पता लगाने के लिए एल्गोरिथ्म में प्रयुक्त, भीषण ओला सूचकांक (एस.एच.आई.) भीषण ओला की संभाव्यता (पी.ओ.एस.एच.) तथा अधिकतम संभावित ओला आकार (एम.ई.एच.एस.) के मान ज्ञात किए गए। डॉप्लर मौसम रेडार के आँकड़ों के प्रयोग से की गई गणना के आधार पर अधिकतम संभावित ओला आकार के मान, 1050 यू.टी.सी., 1100 यू.टी.सी, 1110यू.टी.सी, तथा 1120यू.टी.सी, पर क्रमशः 1.6 से. मी., 2.5 से. मी., 2.6 से. मी. तथा 2.0 से. मी. थे जो कि ओलावृष्टि की सूचनाओं में दिए गए ओला आकार से पूरी तरह से मिलते है। इस अध्ययन से यह निष्कर्ष निकलता है कि एन.ई.एक्स. आर.डी.ए. (यू.एस.ए.) में प्रयुक्त संवर्धित ओला संसूचन एल्गोरिथ्म परावर्तकता एवं ऊर्ध्वाधर समाकलित द्रव के प्रचालनात्मक मानो को भारतीय परिस्थियों में भी ओलावृष्टि की पहचान तथा चेतावनी के लिए प्रयोग किया जा सकता है।

ABSTRACT. Hailstorm of 19th April 2010 over Delhi has been studied using observations from Doppler Weather Radar (DWR) installed at Palam. The data was analysed at Central Server located at India Meteorological Department HQ using IRIS software (of M/s SIGMET-VAISALA, Finland) installed in the server. Reflectivity of 45 dBZ level was found to be 6.3 km above freezing level at the time of hailstorm which corresponds to 100% (obtained from probability function diagram of Witt *et al*. (1998)) probability of hail. Reflectivity was more than 55 dBZ upto 10 km and 7 km at 1110 UTC and 1120 UTC respectively which exceeds the hail threshold limit adopted in NEXRAD (USA). Maximum of 62 dBZ was observed at about 3 km at 1110 UTC and 64 dBZ at 3.5 km at 1120 UTC in Radar Data. Very high values of Vertical Integrated Liquid (VIL) ranging from 58.7 kg/m^2 to 64.1 kg/m^2 were observed between 1040 UTC and 1120 UTC which is higher than 43 kg/m^2, the threshold value for occurrence of hail. Severe Hail Index (SHI), Probability of Severe Hail (POSH) and Maximum Expected Hail Size (MEHS) were computed to verify the applicability of enhanced Hail Detection Algorithm (HDA) outlined by Witt *et al*. (1998) to Indian conditions. The Maximum Expected Hail Size (MEHS) computed using Doppler Weather Radar observations were 2.5 cm, 2.6 cm and 2.0 cm respectively at 1050 UTC, 1100 UTC and 1110 UTC which are in close agreement with the reported hail size. The study confirms that HDA and other thresholds of reflectivity and VIL used for hail detection and warnings in NEXRAD (USA) can be used in Indian conditions also.

Key words – Doppler weather radars, Vertical integrated liquid, Plan position indicator, Hailstorm, Max display, Range height indicator.

1. Introduction

Hails, the solid form of precipitation, form when updrafts in thunderstorms carry the raindrops in colder areas above freezing level. When the hails begin to fall because of gravity, they are swept back into the top of the cloud formation over and over again by the updrafts. A new layer of frozen water droplets is added to the hailstone during each trip and grow in size. Size of the hailstones depends on how many times it has been tossed up into the upper levels of the storm before they finally fall on the ground. Hailstorms are hazardous to aircrafts, buildings and structures, horticulture and cars and can be deadly to livestock and people.

Delhi experiences a good number of thunderstorms throughout the year with maximum in July. The cloud tops reach upto 14 to 15 kms. Thunderstorm clouds with their top extending upto 20 Kms. are also observed during June, July and August (Chatterjee and Prakash, 1986). All thunderstorms do not produce hails. Though annual frequency of occurrence of thunderstorm around Delhi is 42, frequency of hail occurrence is very less [0.8 for Palam and 1.6 for Safdarjung (India Meteorological Department, 1999)]. Following reasons have been attributed to this [Suresh and Bhatnagar (2004); Witt *et al.* (1998)] : (a) as the freezing level in tropical regions is high (about 5 km), the hails melt before reaching the ground after crossing the freezing level (b) as the duration and area of the hailstorm is very small, it remains unrecorded if the occurrence is not near the vicinity of meteorological observatory. Therefore, hail reports from public, electronic and print media are to be relied upon regardless of its uncertainty in size and timeliness. It is a fact that, due to practical difficulties and limitations, the hail reports have much less objectivity, precision and standardisation (Asnani, 1993).

Occurrences of hailstorms in North and North-Eastern India have been analysed using analogue radar observations by many researchers (Rakshit, 1962; Shravan Kumar and Sen Sharma, 1970; Mukherjee and Bhattacharya, 1972; Gupta and Ghosh, 1980). Suresh and Bhatanagar (2004) studied the hailstorms of May 2002 using observations from Doppler Weather Radar installed at Chennai which became operational w.e.f. 20th February 2002. They concluded that the hail warning conditions / thresholds used in extra-tropics, such as echo-top of 45 dBZ level 1.4 km above freezing level, vertically integrated liquid (VIL) of 43 kg/m^2 or more, VIL density of 3.5 kg/m^3 and reflectivity of more than 55 dBZ at 3 km height for hail detection and hail warning are applicable in tropical regions also. They documented the applicability of Severe Hail Index (SHI), Probability of Severe hail (POSH) and Maximum Expected Hail Size (MEHS) of the enhanced Hail Detection Algorithms (Witt *et al*., 1998) and suggested that more cases of hailstorms need to be studied for operational purposes.

On 19th April 2010, TV channels reported that Delhites had a sigh of relief from scorching heat because of occurrence of hailstorm in the evening in parts of east Delhi and NOIDA (Uttar Pradesh, areas adjacent to Delhi). Print media (Times of India, 20 April 2010) also confirmed the same on 20th April 2010. The details of intensity of hailstorm and size of hailstones and exact timing was not reported by both electronic and print media. However, it was mentioned that medium pebble size hailstones were observed between 1630 and 1700 IST on 19th April 2010.

In the present paper, data from Doppler Weather Radar, which has been installed at Palam airport recently, have been analysed on offline mode to study various parameters like Vertical reflectivity profile, vertical integrated liquid, etc associated with the hailstorm to further verify the results of Suresh and Bhatnagar (2004). Severe Hail Index (SHI), Probability of Severe Hail (POSH) and Maximum Expected Hail Size (MEHS) were computed and compared with approximate size of hail reported by electronic/print media to verify the applicability of HDA outlined by Witt *et al.* (1998) for tropical (Indian) conditions.

2. Doppler Weather Radar - Delhi

Under modernisation programme, India Meteorological Department has procured 12 Doppler Weather Radars from M/s Beijing Metstar Radar Co. Ltd. China, one of which has been installed at Palam airport (Lat. 28° 33′ 00″ N and Long. 77° 04′ 12″ E). Factory Acceptance Test and Site Acceptance of this system were conducted during 27-29 March 2010 and 1-3 April 2010 respectively. Radar was calibrated and receiver linearity was checked during these tests. The radar was put under endurance test of 14 days continuous operation from 3rd April 2010.

2.1. *Technical Details of DWR - Delhi*

Transmitter

Type	: Klystron Amplifier
Peak power	: 750 k Watts
Frequency	: 2875 to 2878 MHz
Pulse width	: 1 µs(short pulse) and 2 µs (long pulse)
Pulse Repetition Frequency (PRF) (Hz)	: 250-1200 in short pulse & 250-550 in long pulse
Receiver Noise figure	: better than 1.5 dB
Minimum Digitally Detectable Signal	: –114 dBm in long pulse and –112 dBm in short pulse

Digital part of the receiver

Band width	: 1 MHz in reflectivity & 0.5 MHz in velocity mode
Dynamic range	: Better than 95 dB

Antenna

Reflector type and diameter	: Prime focus feed, 8.5 m
Polarisation	: Linear, Horizontal
Scan rate	: 3 to 36°/sec (0.5 – 6 rpm)
Beam width	: ~1°
Gain	: 44.5 dBi

The DWR system has been provided with 6 no. of computers two of which have identical features (one main and other as hot standby) for control and operations involved in data acquisition, product generation, display and archival. Other three are used for (*i*) radar calibration and maintenance, (*ii*) simultaneous real time display of reflectivity, radial velocity and spectral width and (iii) remote display and passive monitoring of system performance respectively. The sixth computer with 42″ plasma monitor is used for display and demonstration of various products.

The Doppler Weather Radar system employs dual PRF technique (3:2; 4:3; and 5:4 ratio of PRFs) for velocity unfolding. The system has frequency agility and second trip recovery facilities.

Apart from installation of Doppler Weather Radar at Palam airport, a central server with IRIS [Interactive Radar Information System] software (of M/s SIGMET) has also been installed in Telecom Division of India Meteorological Department HQ, New Delhi. All Doppler Weather Radars have been connected with central server with 256 kbps VPN circuit. The central server has been configured to receive and process the data from all existing Doppler Weather Radars including Gematronik GmbH make radars which generate data in proprietary Rainbow format and 11 others to be installed by M/s Beijing Metstar Radar Co. Ltd., China. The IRIS software is capable of generating products including composite of all Doppler Weather Radar images. IRIS software also converts data in universally used formats like NetCDF, HDF5 required for assimilation in Numerical Weather Prediction models.

2.2. *Data*

Radar reflectivity, radial velocity and spectral width data collected at 10 minutes interval for 10 elevations from 0.2° to 21° on a regular basis on 19th April 2010 have been utilised in this study. The generated binary data file was interactively accessed through the inbuilt software feature of IRIS to arrive at the analysis data values rather than simple extrapolation from imageries. The 0000 UTC upper air sounding data (RS/RW) of Ayanagar, Delhi which is located 10 km away from the radar site has been used to get the height of freezing level and -20 °C height.

3. Hail Detection Algorithm

Petrocchi (1982) developed hail detection algorithm based on cell structure but, its utility was found inadequate as it did not reveal the size of hails to assess the damage potential of hailstorm. To address this problem, Witt *et al*. (1998) developed an enhanced Hail Detection Algorithm (HDA) for operational use in NEXRAD. In the HDA, Witt *et al*. (1998), adopted the concepts of Waldvogel *et al*. (1979) in detecting hail of any size by using 45 dBZ reflectivity heights above the freezing level.

Witt *et al.* (1998) also developed empirical relationships using Digital Weather Radar observations to compute Severe Hail Index (SHI), Probability of Severe Hail (POSH), Warning Threshold (WT) and Maximum Expected Hail Size (MEHS) in the enhanced Hail Detection Algorithm (HDA), which has been used extensively for the present study.

4 Result and discussions

Surface temperatures in April 2010 has been exceptionally high (6-7 °C above normal) since the beginning of the month in N-W India. The occurrence of rain accompanied by hail on 19th April 2010 became important news for electronic and print media, as it had brought down the temperature. Times of India (English daily newspaper) Delhi edition reported eye witness accounts of people on 20th April 2010 with headline "Hailstorm, rain bring relief but heat wave to continue". According to the report, rain commenced at about 1045 UTC and hailstorm started little later. It is a fact that public usually report the size of hailstone in comparison with size of the objects like pea, pebble, ping pong ball etc and hence exact size is not known. Size of hails which occurred on 19th April was reported as medium pebble size. The event lasted for about 45 minutes, *i.e*., upto 1130 UTC.

4.1. *Storm genesis and movement*

The storm developed at a distance of about 40 km WNW of radar site around 1000 UTC and moved in ESE direction. As the system moved ESE direction, it moved towards the radar and it was closest to the radar site at about 1040 UTC. Though, it was tracked from its origin to the time it produced hail and beyond by the Doppler Weather Radar, the observations had its own limitations in view of nearness to the radar. As such, the parameters (SHI, POSH, MEHS) of the enhanced Advance Hail

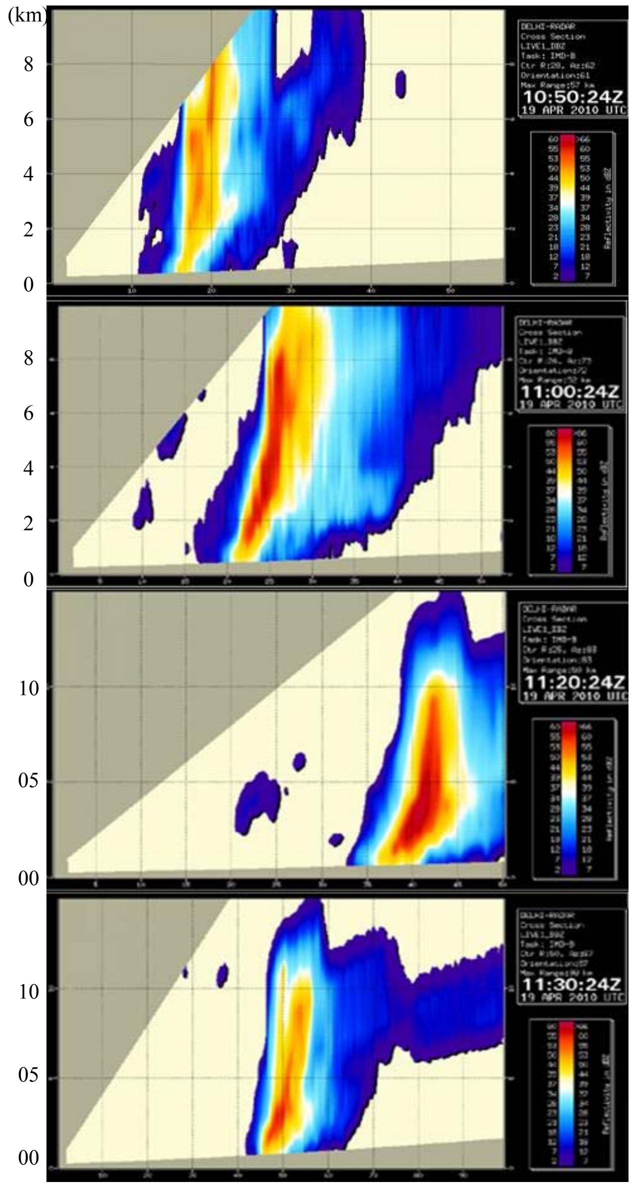

Fig. 1. VCUT products generated through IRIS software for 1050 UTC, 1100 UTC, 1120 UTC and 1130 UTC. It is clearly seen that core high reflectivity extend upto 8 km from 1100 UTC to 1120 UTC when hailstorm occurred. At 1130 UTC reflectivity has reduced in the vertical column and is confined in lower levels only

Detection could not be computed accurately. However, at the time of occurrence of hail, the storm was at a distance of about 30 to 35 km and the values of these parameters provide valuable information about presence of hail and the expected size.

4.2. *Test for presence of hail of any size*

Most of the algorithm use height of 45 dBZ echo top above environment freezing level for probabilistic hail detection. Height of freezing level (H_0) at 0000 UTC on 19th April 2010 as revealed by RS / RW ascent from Ayanagar Observatory, New Delhi was 4.261 km. To determine the 45 dBZ height levels above freezing level, the vertical cut (VCUT) product from volume scan data has been used. The VCUT products provide information about distribution of any chosen parameter measured/derived by DWRs in vertical plane passing through any two points of interest. VCUTs through the radar station and the storm cell were generated and the raw product files were interactively accessed to determine the height of 45 dBZ reflectivity of the storm cell at different times. VCUT product imageries for specific period of interest: 1050 UTC to 1130 UTC at 10 minutes interval are shown in Fig. 1.

TABLE 1

Probability of hail occurrence at different times obtained from probability function diagram of Witt et al (1998) for each H_{45}–H_0

Time in UTC	Heght of 45dBZ reflectivity above freezing level (H_{45}–H_0)	Probability of hail occurrence (%)
1020	3.9	80
1110	6.3	100
1120	5.4	90
1130	5.3	90
1140	4.1	80

Height of 45dBZ reflectivity above freezing level (H_{45} – H_0) and Probability of hail occurrence at different time periods are given in Table 1 which confirms the reported hail between 1045 and 1130 UTC. As the cloud was too near to the radar to probe the cloud to the top, probability for other timings could not be obtained.

4.3. *Vertical Reflectivity Profile*

To determine maximum reflectivity present in the storm at different times, from its genesis, Max Products were generated from volume data by the IRIS software. The Maximum Product takes a polar volume raw data set, converts it to a Cartesian volume, generates three partial images and combines them to the displayed image. The partial images are (*i*) a top view of the highest measured values in *Z* direction. (*ii*) a north-south view of the highest measured values in Y direction. (*iii*) an east-west view of the highest measured values in *X* direction. Maximum values of reflectivity and their corresponding heights were picked up from Max displays and PPI products generated for each elevation for each observation. Max product for 1050 UTC, 1100 UTC, 1110 UTC and 1120 UTC are given in Fig. 2.

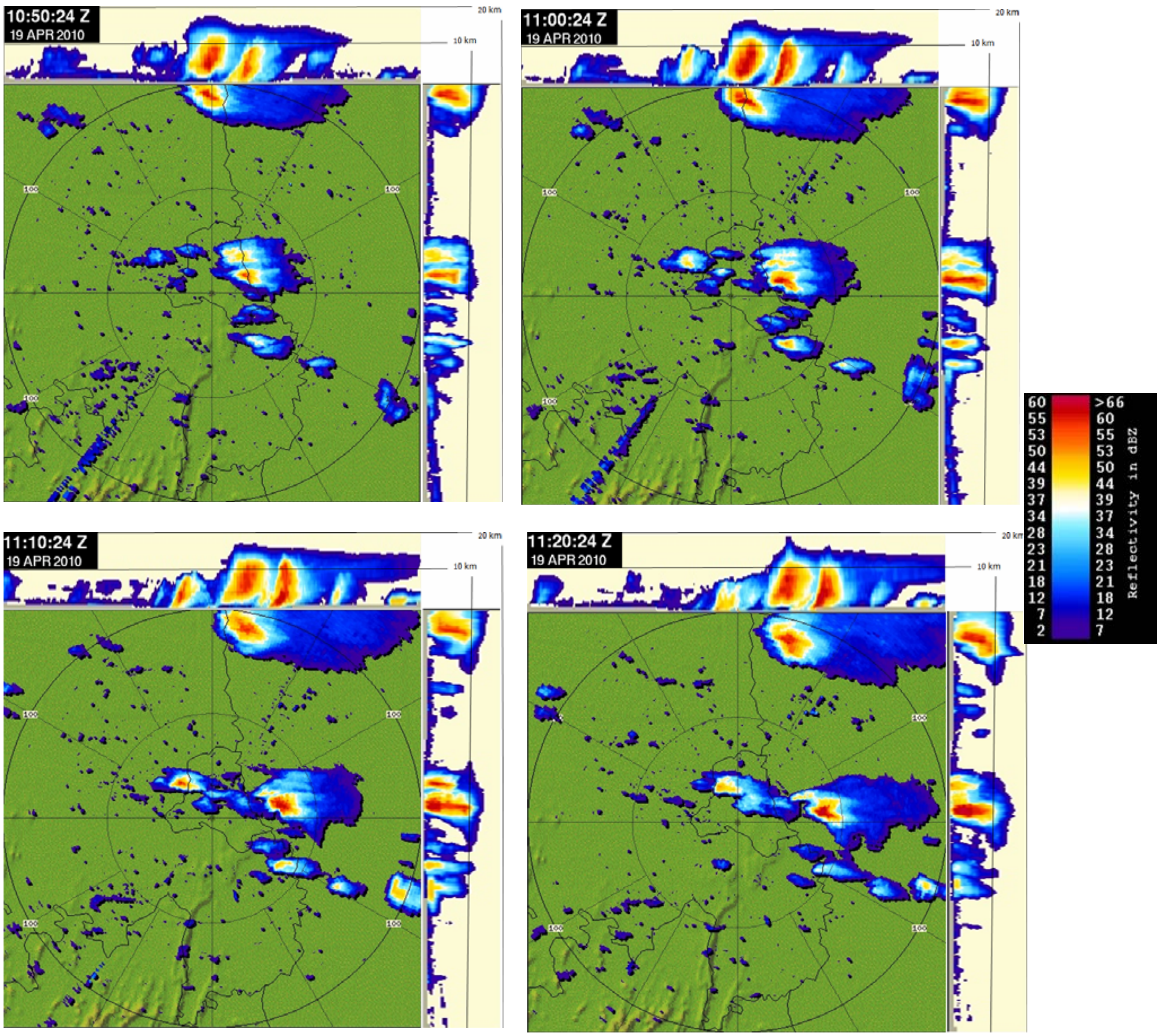

Fig. 2. Maximum display of reflectivity. The side panels show the cross-section height of 20 km and the range rings are spaced 50 km. It can be seen that reflectivity was more than 55 dBZ upto 10 km at 1110 UTC and upto 7 km at 1120 UTC. Cloud tops are reaching upto about 13 km

It was observed that upto 1030 UTC, when storm was in NNW direction of radar at a distance of more than 20 - 25 km, observed reflectivity was less than 50 dBZ. At 1040 UTC maximum reflectivity core of only 50.5 dBZ was seen between 2 and 3 km. At 1050 UTC reflectivity further increased and it was between 45 dBZ and 55 dBZ from 0.5 km to 7.5 km (observations are available upto this height only because the storm was at a distance of less than 20 km). At 1100 UTC reflectivity was more than 55 dBZ from about 1 km to 8 km (Fig. 1). Maximum reflectivity of 60 dBZ was also observed at about 3 km.

It was seen from vertical reflectivity profile (as seen from Fig. 1 that reflectivity was more than 55 dBZ upto 10 km and 7 km at 1110 UTC and 1120 UTC respectively. Maximum of 62 dBZ at about 3 km at 1110 UTC and 64 dBZ at 3.5 km at 1120 UTC was observed. At this time the storm was located at a distance of about 30 to 35 km away in the east of the radar site, the areas where the hails have been reported.

Various authors have suggested different reflectivity threshold to differentiate between hail and heavy rainfall. According to Atlas (1990), Rinehart (1999), Holleman

TABLE 2

Time (UTC)	VIL (kg/m^2)	SHI	POSH (%)	MEHS (mm)
1010	6	0	0	1
1020	5	0	0	1
1030	7	0	-	0
1040	59	0	0	1
1050	64	41	18	16
1100	64	98	43	25
1110	63	102	44	26
1120	64	61	29	20
1130	28	28	7	13
1140	24	20	0	11

(2001), thunderstorms with reflectivity factor >55 dBZ at about 1 km, ≥ 50 dBZ at 3 km and 45 dBZ between 5 and 9 km suggest presence of hail in the thunder clouds. Studies of hailstorms by Wilson and Wilk (1982) revealed that hails are possible in the regions of thunderstorms where reflectivity is more than 55 dBZ while Auer(1994) suggested that the thunderstorm with reflectivity more than 54 dBZ can produce hails of size 10 mm. According to Baeck and Smith (1998) and Fulton *et al*. (1998) reflectivity threshold for hails is 55 dBZ.

It is clear from literature survey that there are no fixed reflectivity criteria to distinguish between rain and hail. However, it can be concluded that there is good probability of hail occurrence when reflectivity is more than 55 dBZ. The Doppler Weather Radar observations from 1100 UTC to 1120 UTC on 19th April 2010 clearly show that reflectivity conditions are fully met. From this, one can conclude that hailstones occurred for very short duration of nearly 20 minutes from around 1100 UTC to 1120 UTC.

4.4. *Vertical Integrated Liquid (VIL)*

Greene and Clark (1972) introduced use of Vertical Integrated Liquid (VIL) for severe storm and hydrological applications. High values of VIL correlate well with the occurrence of severe thunderstorms and hail. In stratiform clouds, VIL is generally less than 10 kg/m^2 while in convective clouds VIL can be more than 40 kg/m^2 (Holleman, 2001). However, there is no warning threshold of VIL to detect hails. In United States, threshold value of VIL for the day is either derived from the temperatures at 400 and 500 hPa by means of an empirical equation or take the VIL value corresponding to the first hailstorm of that day (Lenning *et al*., 1998). Amburn and Wolf (1997) used VIL density (VIL normalized by using echo top heights of certain reflectivity threshold). They used a universal threshold of 3.5 kg/m^3. However, use of universal VIL density over VIL is not acceptable to researchers. Edwards and Thompson (1998) found that results obtained by taking VIL density of 3.5 kg/m^3 and VIL threshold as 38 kg/m^2 are same on the data of Amburn and Wolf (1997). They also found that hail was always observed when VIL values exceed 43 kg/m^2.

VIL values were computed through IRIS software for vertical depth of 0 km (surface) to 15 km using $Z = 20000\ M^{1.8}$ which is similar to one used by Suresh and Bhatnagar (2004) while studying unusual hailstorms over Chennai during 2002. Maximum values of VIL observed at different times are given in Table 2. It can be seen from the Table 2 that VIL values from 1010 UTC to 1030 UTC were below 10 kg/m^2 and from 1130 UTC onward it was less than 30 kg/m^2. The values of VIL from 1040 UTC to 1120 UTC were quite high (ranging from 58.7 kg/m^2 to 64.1 kg/m^2). At 1050 UTC the storm was very close to the radar and could be probed by the radar upto 10 km only because of scan limitations. Had it been at more distance and probed upto the top, the VIL values would have been much more than the estimated value. It is clear from the table that VIL values are more than the threshold of 43 kg/m^2 which have been used by many researchers at extra tropical regions and Suresh and Bhatnagar (2004) in tropics for detection of hail. These observations clearly suggest that hails were present during this period.

4.5. *Maximum Expected Hail Size*

Values of Severe Hail Index (SHI), Probability of Severe Hail Detection (POSH) and Maximum Expected Hail Size (MEHS) calculated using HDA of Witt *et al.* (1998) described in Section 2 are given in Table 2. Threshold values Z_L and Z_U are the same as proposed by Witt *et al.* (1998) and also used by Suresh and Bhatnagar (2004). Warning threshold (WT) computed for 19th April 2010 taking H_0 = 4.621 km based on 0000 UTC RS/RW observation of Ayanagar, is 124. It is observed from the table that SHI is zero upto 1040 UTC and increased to 102 at 1110 UTC and decreased rapidly thereafter. It is clear from the Table 2 that SHI has never exceeded the Warning Threshold of the day (*i.e.*, 124). Maximum Expected Hail Size (MEHS) from 1040 UTC to 1140 UTC ranged from 1.1 cm to 2.6 cm while the print media reported size was similar to medium size pebble which can be taken as 1.5 cm or 2 cm. Though there is no meteorological observation regarding the hailstorm and the exact size of hailstone, it can be concluded based on algorithm that there is a close agreement between estimated and media reported hailstone size. Hails of larger expected size of 2.6 cm might have also occurred but could not be verified for want of meteorological observations in the area of hailstorm. Probability of Severe Hail (POSH) was maximum (0.44) at 1110 UTC. The high values of SHI, POSH, MEHS clearly suggest that hail occurred for a very short duration of 10 to 15 minutes between 1100 UTC and 1120 UTC.

5. Summary

Study of hailstorm of 19th April 2010 over Delhi using observations from Doppler Weather Radar confirms the conclusions of Suresh and Bhatnagar (2004) drawn from their study of unusual hail storms during May 2002 in Chennai that Hail Detection Algorithm developed by Witt *et al.* (1998) can be used in tropics regions to detect and predict hailstorms. The predictability of hail of any size based on the height of 45 dBZ reflectivity above freezing level (H_{45}-H_0) is found to be quite good. Maximum Expected Hail Size calculated for the storm ranged from 1.1 cm to 2.6 cm which is in good agreement with the size reported in media. The study has also revealed that Vertical Integrated Liquid (VIL) was observed to be more than threshold value of 43 kg/m^2 given by Amburn and Wolf (1997). Reflectivity threshold of more than 55dBz was also observed upto 10 km and upto 7 km during the hailstorm. Analysis of Doppler Weather Radar observations for more cases of hail occurrence is required to use the Hail Detection Algorithm of Witt *et al.* (1998) into operational use. Cases of thunderstorms which do not produce hails are also to be analysed to finalise different threshold and to avoid false alarm of hail occurrence.

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