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Unusual hail storms during May 2002 in Chennai and its suburbs – A study using data from a single Doppler Weather Radar

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सार – जलवायवी तौर पर पूरे वर्ष के दौरान चेन्नई ओर इसके निकटवर्ती क्षेत्रों में ओलावृष्टि की परिघटना बहुत कम पाई गई है। तथापि वर्ष 2002 में दो बार ओलावृष्टि की सूचनाएं प्राप्त हुई, पहली सूचना चेन्नई में 29 मई को छपी हुई सामग्री/इलैक्ट्रॉनिक माध्यम से तथा दूसरी सूचना 30 मई 2002 को शहर से बाहर स्थित अरकोणम में भारतीय नौसेना द्वारा अनुरक्षित मौसम विज्ञान वेधशाला से प्राप्त हुई। चेन्नई के चक्रवात संसूचन रेडार केन्द्र पर हाल ही में लगाए गए डॉपलर मौसम रेडार से प्राप्त किए गए आँकडों के आधार पर इन दोनों ओलावृष्टियों का विश्लेषण किया गया। इस विश्लेषण से यह पता चला है कि ओलावृष्टियों की उर्ध्वाधर सीमा 20 कि.मी. से अधिक थी और इसकी परावर्तकता 18.5 कि.मी. पर भी अधिकतम 45 डी.बी.जेड. देखी गई। 3 कि.मी. की ऊँचाई पर यह परावर्तकता 58 डी.बी.जेड. से अधिक थी जो एन.इ.एक्स.आर.ए.डी., संयुक्त राज्य अमेरिका (मानचित्रावली, 1990) द्वारा अपनाई गई 3 कि.मी पर 50 डी.बी.जेड. नामक ओलावृष्टि चेतावनी के लिए प्रचालनात्मक प्रभाव सीमा से अधिक है। ओलावृष्टि के मार्ग में 5 और 10 कि.मी. की ऊँचाई के मध्य 55 डी.बी.जेड. से भी अधिक की परावर्तकता मापी गई है। इसके अतिरिक्त ओलावृष्टि की विभिन्न अवस्थाओं में 45 डी.बी.जेड. का स्तर हिमांक स्तर से कम से कम 4.5 कि.मी. ऊपर था जिसके कारण 10 कि.मी. की ऊँचाई ए.जी.एल. तक और इससे अधिक ओले गिरे। धरातल पर प्रेक्षित किए गए ओलावृष्टि के लगभग 1 घंटा पूर्व उर्ध्वाधर समाकलित द्रव 43 कि.ग्रा.एम$^{-2}$ (कभी कभी 50 कि.ग्रा.एम$^{-2}$) से भी अधिक था और यह प्रत्यक्ष रूप से प्रेक्षित किए गए ठीक ओलावृष्टि के समय 58.7 ओर 64.7 कि.ग्रा.एम$^{-2}$ था। 18 कि.मी. ऊँचाई पर ओलावृष्टि के क्षेत्र में 46 एम.पी.एस. के वेग अपसरण से इस बात की पुष्टि होती है कि 0.80 संभाव्यता के साथ 19 एम.एम. के ओले गिरने की अधिक संभावना थी। अधिकतम ओला सूचकांक (एस.एच.आई.) अधिकतम ओलों की संभावना (पी.ओ.एस.एच.) और अधिकतम संभावित ओला आकार (एम.ई.एच.एस.) परिकलनों के लिए एन.ई.एक्स.आर.ए.डी.. के संवर्धित ओला संसूचन एल्गोरिथ्म (9 के आकार का) की जाँच की गई और इनसे इन दो स्थानों पर और इन दोनों तारीखों को ओलावृष्टि के मार्ग में स्थित कुछ और स्थानों पर ओलावृष्टि की संभावना की पुष्टि हुई है।

ABSTRACT. Climatologically, hail storm phenomena over Chennai and its neighbourhood is extremely rare throughout the year. However two hail storm were reported during the year 2002, one by print / electronic media on 29 May within the city limits and the other on 30 May 2002 by a meteorological observatory maintained by Indian Navy at Arakonam located at the outskirts of city. These two storms were analysed based on the data received from the newly installed Doppler Weather Radar at Cyclone Detection Radar station, Chennai. The analysis reveals that the vertical extent of the hailstorms was well beyond 20 km and reflectivity as high as 45 dBZ was seen even at 18.5 km. The reflectivity at 3 km height was exceeding 58 dBZ which is well above the operational threshold limit for hail warning, *viz*., 50 dBZ at 3 km adopted by NEXRAD, USA (Atlas, 1990). More than 55 dBZ reflectivity was measured between 5 and 10 km altitude during the passage of hail storm. Moreover the 45 dBZ level at different stages of the storm was atleast 4.5 km above the freezing level permitting the growth of hail stones upto and beyond 10 km height a.g.l. The vertically integrated liquid (VIL) was more than 43 kg m^{-2} (at times more than 50 kg m^{-2}) about an hour before the hails were observed at surface and it was between 58.7 and 64.7 kg m^{-2} just at the time of the hailstorm physically observed. Velocity divergence of 46 mps over the storm area at 18 km altitude confirms that hails of 19 mm was more probable with 0.80 probability. The enhanced hail detection algorithm (build 9) of NEXRAD has been verified for the severe hail index (SHI), probability of severe hail (POSH) and maximum expected hail size (MEHS) calculations and these confirmed the possibility of hail over these two locations and some more locations in the passage of the storm on these two dates.

Key words – Doppler weather radar, Hail storm, Vertically integrated liquid, Wind shear, Divergence, Sea breeze, Surface inversion.

1. Introduction

Though Chennai has a fairly good frequency of thunderstorms (3 to 10 days during May to October) and the thunder cloud tops reaching 16 km are not at all uncommon based on radar studies (Venkateswara Rao *et al*., 1961; Lakshmanaswamy and Sundaresa Rao, 1974), the incidence of hail storm is extremely rare in this region,

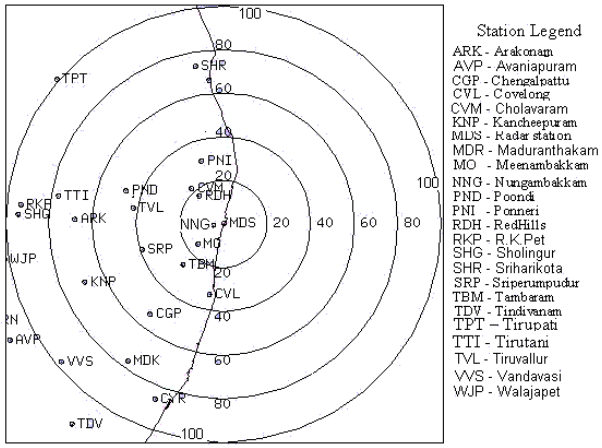


Fig. 1. Location map of meteorological observatories and a few selected raingauge stations within 100 km radius from Doppler Weather Radar, Chennai

as per the meteorological record (IMD,1999). This is presumably because the hail leaving the freezing level (around 5000 m throughout the year) melts during its long travel before reaching the ground. Another possible reason for the lack of detection of hail at ground level could be that the duration and area of the hail fall is very much smaller than that of the rainfall and hence there might have been incidence(s) of hail fall in some part of the city but not in the vicinity of the meteorological observatories. Chennai has two meteorological observatories, one at Nungambakkam (NNG - 13° 04.092′ N / 80° 14.776′ E) and the other at Meenambakkam airport (MO - 12° 59.61′ N / 80° 10.62′ E), maintained by the India Meteorological Department (IMD). In addition to the above, one meteorological observatory is maintained by Indian Air Force at Tambaram (TBM) and one more observatory is functioning at Indian Navy, Arakonam (ARK) in the outskirts of the city. The locations of these observatories are shown in Fig. 1. It has been universally accepted that due to practical difficulties and limitations, the hail reports have much less objectivity, precision and standardisation (Asnani, 1993). On two occasions, one on 29 May and the other on 30 May, hail was reported in Chennai and its suburbs during 2002. These two severe weather events were analysed with the radar data obtained from the recently commissioned Doppler Weather Radar (DWR) at Cyclone Detection Radar (CDR) station (13° 05.031′ N / 80° 17.400′ E) at Chennai. The results are discussed in this paper.

TABLE 1

Important features of Doppler Weather Radar, Chennai

Transmitter	
Type	Klystron Amplifier
Peak power	750 k Watts
Frequency	2875 to 2878 MHz
Pulse width	1μs (short pulse) and 2μs (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 r.p.m)
Beam width	~1°
Gain	44.5 dBi
Computers and peripherals	
Work station	Two SUN ULTRA10 systems
Data archival 4mm DAT drive	4 mm DAT drive –1; DLT drive – 1;
Facilities	
Dual PRF (for Velocity unfolding)	3:2; 4:3; and 5:4 ratio of PRFs.
Second trip recovery	
Frequency agility	

2. Data

A state-of-the art DWR from M/s Gematronik, Germany has been on continuous trial mode operation from 31 October 2001 and pressed into IMD radar network, after successful site acceptance testing for catering to the local weather needs besides cyclone tracking purposes *w.e.f.* 21 February 2002 (Bhatnagar *et al*., 2003). The radar has been well calibrated and the receiver linearity is being checked every month as part of periodical maintenance. The receiver is quite sensitive and detects signal as low as –114 dBm in long pulse (2 μsec) and –112 dBm in short pulse (1 μsec) mode. The dynamic range is better than 95 dB. A few important technical details of the radar have been given in Table 1. The radar is operated 24 hrs a day by adopting different volume scan strategies. Volume scans with 12 elevation steps from 0.2° to 19.8° elevation in 8 to 12 minutes had been made during May 2002, using different scan strategies. The digital data comprising reflectivity, radial velocity and velocity spectrum width have been used in this study for the period 29 May and 30 May 2002 for diagnostically analyzing the rare / unusual hail storm over Chennai and its surroundings. The 0000 and 1200 UTC upper air (RS/RW) data of Chennai observatory for the said period have also been used for thermodynamical analysis of the storm. The meteorological observations recorded during the storm period by the naval meteorological observatory at INS Rajali, Arakonam have been obtained and considered for evaluating the information derived from DWR.

3. Methodology

The hail storm frequency in tropical plains is very much lower than that over the extra-tropical plains. In view of its very small extent and limited duration of fall, the hail is considered as a minor product of thunderstorm though its catastrophic effect is very much high in agricultural (horticulture) and aviation applications. Since most of the hail melts away either partially or fully before reaching the ground, the information collected at surface suffers error due to observation limitations (observatories are located wider apart and/or lack of training in reporting the precise and accurate hail information etc.). As such, the reports received from the public and thereupon through print and electronic media have to be taken as a general information about the incidence rather than the accuracy part of it in terms of the size of the hail stone and time at which the hail storm was observed.

The reflectivity (Z), radial velocity (V) data received from volume scan of 0.2° to 19.8° elevations have been analysed for each range bin and the analysed results are presented in the usual plan position indicator (PPI), Constant altitude PPI (CAPPI) and top projection type displays. It is well known that the CAPPI type of display does not show the echoes close to the radar site (above the maximum elevation) as well as farther away from the radar (below the lowest elevation) due to scan limitations. For example, a CAPPI of 1 / 3 / 8 / 10 / 12 km from a typical scan with elevation angles from 0.2° to 19.8° will cover a range from 3 / 8 / 22.0 / 27.5 / 33.0 km to 141.5 km. The elevation limits of these scans form a 'cone of silence' or no data region around the radar. To get data over the cone of silence, one should have adopted scan strategies with higher elevation angles such as 40-50° which is normally not practiced in operational mode unless specific weather situation warrants so. Hence the 'no data' region close to the radar is filled with data from the available highest elevation for the nearer range and the type of display thus obtained is called Pseudo CAPPI (PCAPPI). As the reflectivity does not appreciably vary with height in the lowest atmosphere say upto 1.0 km or so, during intense convection (Szoke *et al*., 1986; Atlas, 1990), by filling up the data void region of 5-8 km range from radar with the highest available elevation data helps us to have a fairly good idea about the precipitating clouds at a height very close to the surface in a region close to radar. This PCAPPI display will be close to reality when the height chosen is very low, say less than 1 km. However, when any higher height exceeding 4 km is chosen, one may keep in mind that what is depicted in closer range of radar is nothing but the projection from the upper most elevation data which may be far below the height chosen for the display.

Since the upper level divergent outflow gives an idea about the vertical velocity, the difference between radial velocities of opposite direction at higher level was considered as a tool to identify hails in convective storms (Burgess and Devore, 1979; Snapp, 1979; Witt and Nelson, 1991). This technique is, however, applicable only for storms which are at a distance reasonably far away from the radar due to scan limitations. In the present study, spectrum width did not give any useful indication about the presence of hail. As there are many factors other than the hail itself contribute to the velocity spectrum width and because of the constraint of viewing at nearly vertical elevation angles, the spectrum width is not considered as a hail warning tool in general (Abshaev, 1982; Witt and Nelson, 1991). Hence further analysis based on spectrum width is not discussed in this paper.

4. Hail storm over Villivakkam on 29 May 2002

On 29 May 2002 afternoon, hail storm was reported over Villivakkam, a suburb of Chennai (10 km west of radar) by local daily newspaper ("The Hindu", English daily news paper, Chennai edition, dated 30 May 2002). Television channels did telecast this information on 29th itself and the public reported that hails of 0.5 to 1.0 cm were observed during hail storm over Villivakkam. Though the time of observation of hail stones by the local residents at Villivakkam was between 0830 and 0915 UTC, the newspaper reported the occurrence of hail at 0800 UTC. But the occurrence could not be recorded by the regular meteorological observatories [Fig. 1; Nungambakkam (NNG), Meenambakkam (MO) and Tambaram (TBM)] located at a distance of 5 to 22 km away from Villivakkam. According to newspaper report, the gusty winds have uprooted many trees, electric lamp posts besides damaging many hoardings in Chennai suburbs.

4.1. *Maximum reflectivity factor (Z)*

The storm started its origin from 70 km NW of radar at 0700 UTC and moved ESE initially and thereafter SSW to southward. The data obtained from a volume scan with 0.2° to 19.8° elevations have been analysed bin by bin for all elevations and the maximum reflectivity (Z) is worked out for each bin at various heights for all elevations for each scan from 0704 UTC to 1215 UTC. The maximum

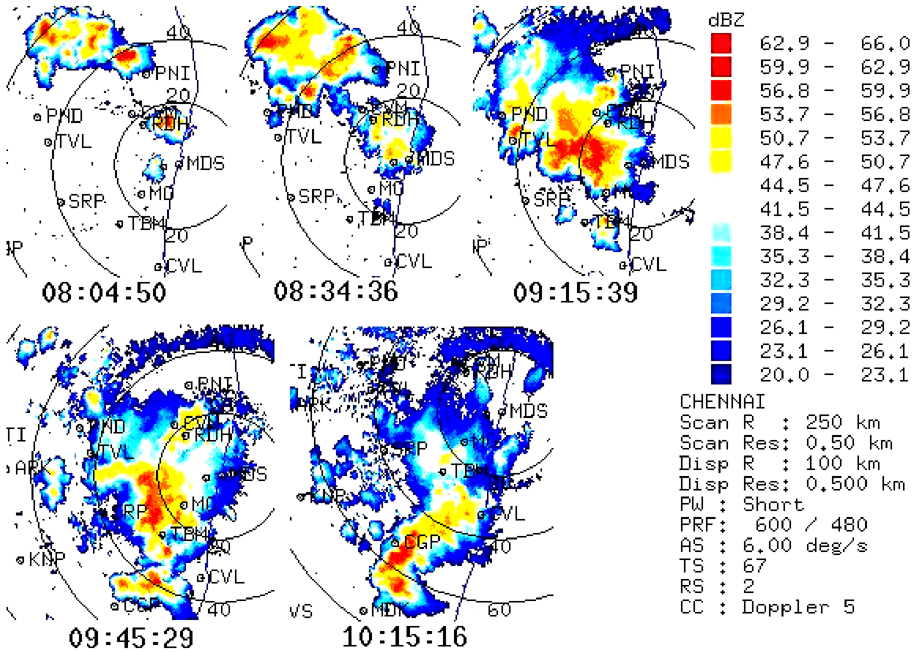


Fig. 2(a). Display of maximum reflectivity (*Z*) from the storm on 29 May 2002. Note that the maximum *Z* at 10 km range has been obtained from surface upto 3.5 km only with 19.8° elevation whereas at ranges between 40 and 50 km, the maximum *Z* have been obtained from surface to 13-18 km altitude. Range circles are 20 km apart

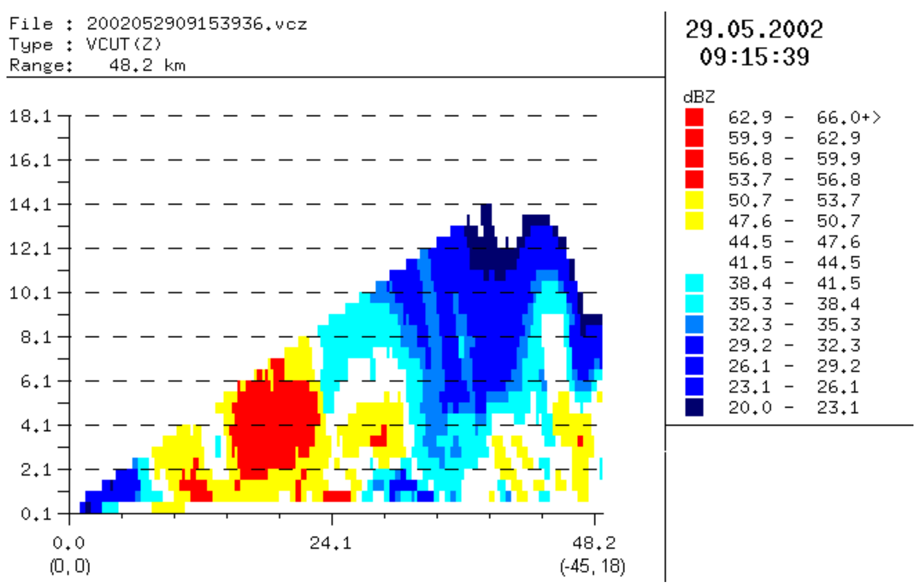


Fig. 2(b). Display of vertical profile of reflectivity of the storm at 0915 UTC. The vertical cut of the storm is from the radar, marked as (0,0) in Cartesian coordinate. The step ladder is due to scan limitations and the nearness of the storm to the radar (cone of silence)

value thus obtained for each bin is projected over a top projection type display from 0804 to 0945UTC and shown in Fig. 2(a). It can be seen that maximum *Z* (from surface to 17 km altitude) was more than 58 dBZ at 0804 UTC (NW of Ponneri marked as PNI in the figure) between 40 and 60 km range from the radar and also at 0915 UTC at a

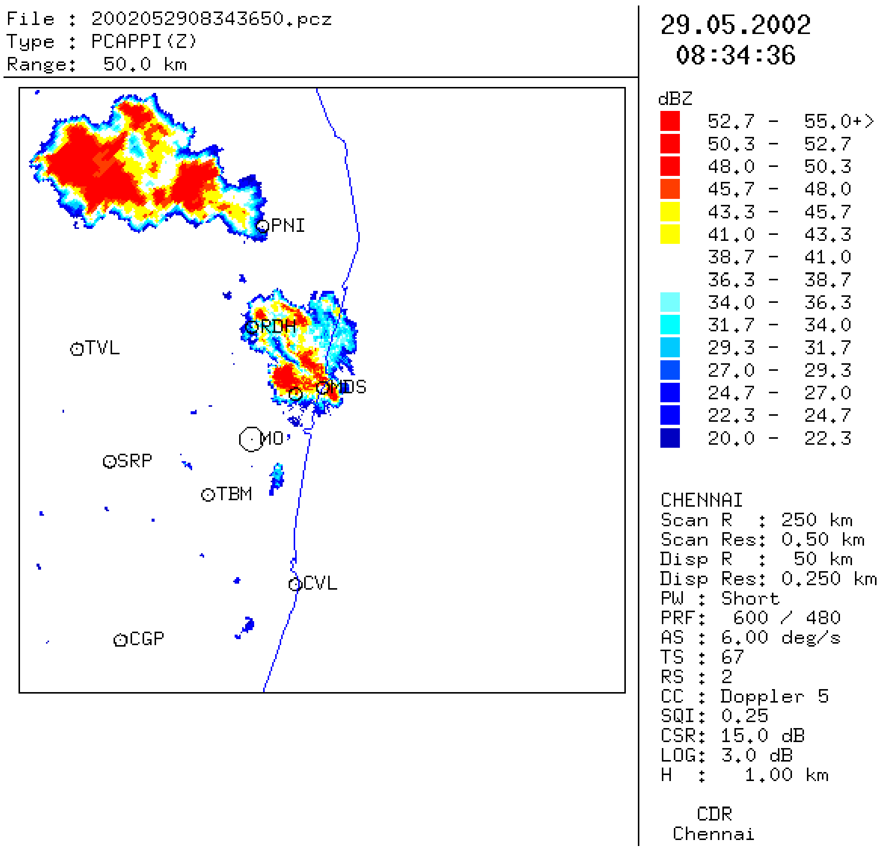


Fig. 2(c). Pseudo CAPPI of reflectivity at 1.0 km height

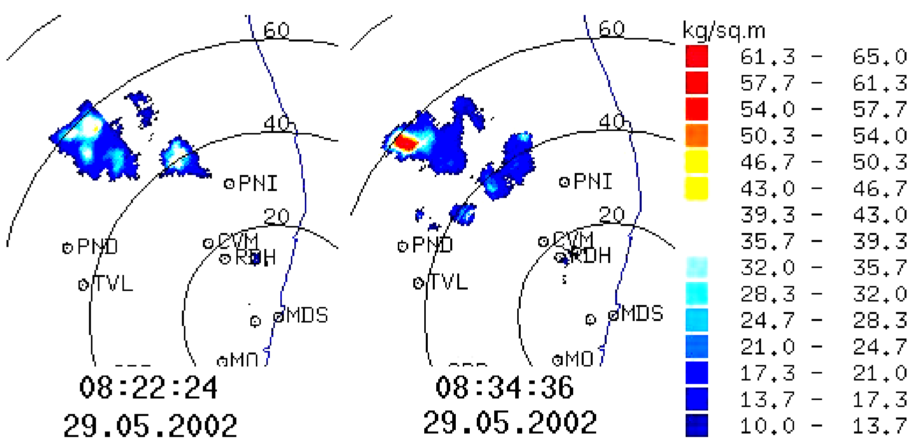


Fig. 2(d). Vertically integrated liquid (kg/m^2) based on Greene and Clark (1972)

range of 18 km from radar (SSW to south of Red Hills marked as RDH in the figure) but this maximum is between surface and 6 km altitude.

While Mason (1971) considered a threshold value of 55 dBZ to distinguish between severe rain and hail, Wilson and Wilk (1982) considered echoes in excess of

55 dBZ as possible hail regions. It has been suggested by Auer (1994) that radar reflectivity of more than 54 dBZ produce hails of size 10 mm. Baeck and Smith (1998) and Fulton *et al*. (1998) have also labeled 55 dBZ as the hail threshold limit. Witt *et al.* (1998a) in their latest hail detection algorithm (build 9.0) applicable to NEXRAD used 55 dBZ as the lower threshold for severe hail (size exceeding 19 mm). Other hail detection algorithms based on reflectivity include minimum 50 dBZ at 3 km height and the presence of 50 dBZ or higher between 5 and 12 km altitude, probability of hail when the echo top of 45 dBZ exceeding freezing level etc. (Waldvogel *et al.*, 1979; Foote, 1984; Burgess and Lemon, 1990; Atlas, 1990 and Rinehart, 1999). Though there are varying thresholds of Z in identifying hail, based on the available results one may reasonably conclude that when $Z > 55$ dBZ there are fairly good chances of hail, if not severe hail, over tropics and extra-tropics. Hence based on the observations from 0804 to 0945 UTC, one may have reasons to believe that there could have been hails fallen at different locations from NW to west of DWR during this period albeit the only ground truth information was reported at Villivakkam located 10 km west of DWR.

4.2. *Vertical profile/height of maximum reflectivity factor*

The height of the maximum reflectivity at various heights within the clouds have been worked out from the volume data for a distance upto 50 km from the radar centre when the clouds pass from northwest to southsouthwest of DWR during 0804-1045 UTC. Amburn and Wolf (1997) have used a threshold of 7 dBZ to identify the cloud top. The lower threshold to identify the cloud region has been fixed in this study as 10 dBZ without loss of generality since this limit has been used by many research workers. It can be seen from Fig. 2(b) that the maximum Z of 62 dBZ was seen from 2.5 to 4.1 km and $Z > 56$ dBZ was measured from 2.1 to 6.5 km and above at 15-18 km range from the radar. Due to scan limitations and nearness of the storm the data has been restricted to 6.6 km only which can be seen from the step ladder type display. Reflectivity of more than 58 dBZ was seen from 0804 to 1015 UTC. The presence of a reflectivity core of more than 50 dBZ somewhere between 5 and 8 km altitude, the presence of radar echo tops beyond 8 km altitude and the mid-level overhang of more than 4 km are some of the important conditions used in NEXRAD and NSSL (National Severe Storms Laboratory) hail detection algorithms (Smart and Alberty, (1985) and Kessinger *et al*. (1995)) for hail detection. In the present study, all these conditions have been fully satisfied. Hence, the possibility of hail during these periods at different places can not be ruled out though there is no supporting evidence of hail storm reported by public or in print/electronic media but for a report from Villivakkam.

Literature survey reveals that more than 55 dBZ at 0.8-1.0 km height, 50 dBZ or more at 3 km height and 45 dBZ at mid-level between 5 and 9 km etc. have been used by various weather services as the potential indictors of hail storms (Atlas, 1990; Rinehart, 1999; Holleman, 2001). Reflectivity of more than 49 dBZ at 0.8 km CAPPI layer has been adjudged as the best critical success indicator of hail detection by Holleman (2001). Fig. 2(c) shows PCAPPI (Z) of 1.0 km height at 0834 UTC on 29th. It has been observed from PCAPPI (Z) of 1.0 km height that the Z was more than 54 dBZ and it was more than 58 dBZ at 0915 UTC (figure not shown) over Villivakkam. The time of occurrence of hail as reported in the newspaper was at 0800 UTC during which period the Z was less than 50 dBZ. This sort of time difference in reporting hail by public is not at all uncommon as reported by Witt *et al*. (1998b) and Edwards and Thomson (1998) when they analysed 'Storm Data' prepared by National Climatic Data Centre, NC, USA in detail for validating hail. As such, in the absence of data beyond 3.5 km altitude over Villivakkam (in view of its closer proximity to radar), based on available data from surface to 3.5 km over this place, one can conclude that hail could have been probable between 0834 and 0915 UTC and not at 0800 UTC.

Reflectivity exceeding 50 dBZ at 3 km constant altitude is a pre-requisite condition for identifying hail stones (Atlas, 1990). Reflectivity at 3 km was more than 45 dBZ throughout the storm travel and it was more than 58 dBZ at 0915 UTC. The Z values were found to be more than 53 dBZ at 9 km height above ground level at 0804 UTC when the storm was NW of Ponneri. Combining all this information, one may conclude that hail could have been possible at 0804 UTC over NW of Ponneri and between 0834 and 0915 UTC over Villivakkam.

4.3. *Echo top of 45 dBZ above freezing level*

The height of 45 dBZ at 0804 UTC was more than 11.5 km when the storm was NW of Ponneri. The 45 dBZ height at 0915 UTC was more than 10 km at a range 25 km west of radar (15 km away from Villivakkam). Considering the reflectivity at lowest elevations over Villivakkam and comparing these values with that obtained during 0804-0834 UTC at farther locations, one may have reasons to conclude that the maximum height of 45 dBZ at Villivakkam at 0915 UTC (had there been higher elevation scans to probe the atmosphere) could have been very well above 11 km height. Climatological normal of freezing levels at 0000 and 1200 UTC during

TABLE 2

Freezing level (m) over Chennai during 28 May to 2 June, 2002
[Climatological normal has been adopted from IMD (1999)]

Time	Height	Climatological normal	28 May	29 May	30 May	31 May	1 June	2 June
0000	hPa	575	604	595	585	581	588	565
	Height (gpm)	4730	4293	4460	4621	4665	4558	4879
1200	hPa	565	542	510	566	570	569	541
	Height (gpm)	4870	5265	5794	4886	4814	4838	5262

May and the freezing levels on 29 May have been tabulated in Table 2. It can be seen from Table 2 that the 45 dBZ contour was atleast 5000 m higher than the 1200 UTC freezing level. According to Witt *et al*. (1998a) when the height of 45 dBZ is above the freezing level by more than 4.5 km (6.0 km), the probability of hail at the ground is 0.90 (1.00). As such we can conclude that hail was almost certain (though there were no report from the public) NW of Ponneri at 0804 UTC and hail was most probable at Villivakkam between 0834 and 0915 UTC.

4.4. *Vertically integrated liquid (VIL) and VIL density*

Douglas (1964) proposed a method to estimate the liquid water content in a cloud from the radar reflectivity factor. Greene and Clark (1972) introduced VIL as a tool to analyse severe storms and for its use in hydrological applications. It has been well documented by many researchers that VIL rarely exceeds 10 kg/m^2 in stratiform precipitations and VIL of more than 40 kg/m^2 is quite common in convective precipitation (Holleman, 2001). Edwards and Thompson (1998) proposed VIL of 38 kg/m^2 as threshold level for hail warning and hail is possible when VIL is 43 kg/m^2 and more. In the absence of precise values of 'c' and 'D' applicable for Indian sub-continent [in the radar reflectivity factor (z) and liquid water content (M) relationship proposed by Douglas (1964) and Greene and Clark (1972), *viz*., $z = c\,M^D$ where z is in mm^6 m^{-3} and M is in gm^{-3}], we have used the original relationship coined by them as it is and integrated to get VIL in kg m^{-2}. (*i.e.*,) VIL = $\int_{base}^{top} M\,dh$. Douglas method (*viz*., $z = 23900\,M^{1.82}$) estimates somewhat lower values of VIL than Greene and Clark method (*viz*., $M = 3.44 \times 10^{-3}\,z^{4/7}$, *i.e.*, $z = 20465\,M^{1.75}$). Though there are some variations in the values between these methods when the reflectivity is more than 50 dBZ, the variability is not appreciable when the reflectivity is less than 45 dBZ. Hence we have used Greene and Clark method for further analysis, since this method has been used by many researchers. VIL was more than 50 kg/m^2 from 0804 UTC at different spots in the storm. The peak value 52 kg/m^2 was found at 0804 and 0834 UTC north of Poondi (PND) and at 0804 UTC it was 54 kg/m^2 over a spot 15 km WNW of Ponneri (PNI). VIL of 43 to 47 kg/m^2 was generally found during the rest of the period over the area of passage of the storm. Fig. 2(d) depicts the VIL at different time periods based on Greene and Clark. Very low value of VIL is seen over Villivakkam due to the fact that the vertical integration of liquid water was limited upto 3 km only in view of its proximity to the radar.

Amburn and Wolf (1997) proposed a method to normalize the VIL value by dividing the VIL by the height of echo top of 7 dBZ. The resultant value is called as VIL density (unit : g/m^3). VIL density of more than 3.5 g/m^3 has been considered by them as potential indicator for hail warning. This method has been slightly modified to suite to Indian conditions by taking the cloud top as the height of 15/20 dBZ echo top. This is quite logical since the cloud top in the case of extra-tropics with 7 dBZ echo top is normally confined to less than 10 km and in tropics cloud tops with 15/20 dBZ itself exceeds beyond 16 km. The computed VIL density was 3.5 g/m^3 at 0804 UTC by considering 16 km as the echo top height. The values of VIL and VIL density confirm the applicability of method suggested by Amburn and Wolf (1997) to issue hail warning when VIL exceeds 38 kg/m^2 and VIL density exceeding 3.5 g/m^3.

4.5. *Genesis and propagation of storm*

The storm had its origin 70 km NW of radar around 0700 UTC. The storm was moving initially towards ESE and came within 50 km radius from DWR at 0734 UTC. The vergence based on volume velocity processing (VVP) method suggested by Waldteufel and Corbin (1979) has been computed from 100 to 1700 m a.g.l. for radius circles

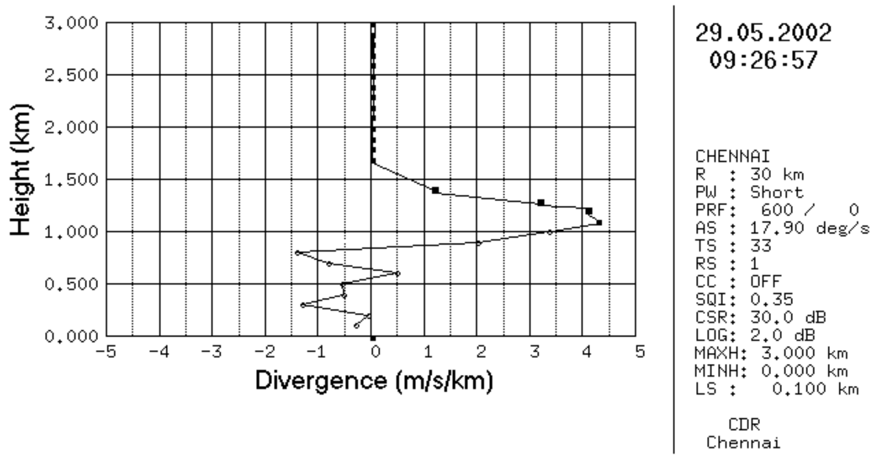


Fig. 3. Divergence within 30 km radius from DWR, Chennai at 0926 UTC on 29 May 2002

30 km and 20 km around the radar. Convergence and upward movement in the lowest layers upto 1.0 km or so preceded the storm (upto 0915 UTC with peak value –2.4 × 10^{-3} s^{-1} at 0846 UTC) and divergence or downdraft followed the storm track (with values 1.90 and + 3.00 × 10^{-3} s^{-1} between 400 and 900 m at 0946 UTC). This is in conformity with the earlier results of Browning and Foote (1976) and quoted in Asnani (1993). Elevation shear (ELS) and three dimensional shear (3DS) have been computed and found that these shears were in excess of 20 m/s/km from 0730 UTC over the areas wherein the convective clouds were observed from 0804 UTC. Convergence within 30 km radius from DWR in the lower atmosphere could be seen even from 0616 UTC. Sea breeze front was advancing inland from 0705 UTC [figure not shown; however, advancement from 0804 UTC can be seen from Fig 2(a)]. The strong convergence from 0616 UTC together with moisture feed from the sea breeze was favouring the development of convective clouds between 0700 and 1000 UTC close to radar.

It is an established fact that a fully developed storm causes the gust front which moves ahead of storm. In the present case, using the gust front detection algorithm of Eilts (1987), it has been noticed that the gust front was seen atleast 20 km ahead of the storm (Fig. not shown). Thus the gust front also caused the convergence ahead of the storm track and this also contributed to the development of thunderstorm cells between 0800 and 1000 UTC. When the storm crossed the radar (*i.e.*, when it moved south of radar between 0846 and 0915 UTC), strong downdraft was observed. Meenambakkam airport meteorological office recorded 25 kts at 0930 UTC. On an analysis of VVP, strong divergence of 4.3 × 10^{-3} s^{-1} was seen at 1.1 km a.g.l at 0926 UTC (Fig. 3). This sort of strong divergence (4.0 × 10^{-3} s^{-1}) was observed at surface by Fankhauser (1976) in Raymer, Colorado, USA hail storm on 9 July, 1973.

The precipitation accumulation by integrating the surface rain rate has been made. In practice rain rate is estimated at 1.0 km CAPPI layer based on Marshall – Palmer *Z-R* relationship (Marshall and Palmer, 1948) and then integrated over a period of time to compare with ground truth - rain gauge recorded rainfall - within 100 km range from the radar. The rain rate has been estimated through the *Z-R* relationship as applicable for Chennai, *viz*., $Z = 267\ R^{1.345}$. The accumulated precipitation almost tallied with ground truth recorded by five raingauges located in the storm area (Nungambakkam 3mm; Meenambakkam 13 mm; Red Hills 25 mm; Cholavaram 19 mm and Tamarapakkam 15 mm). Fig. 4 shows the precipitation accumulation from 0605 to 1144 UTC. The accumulated precipitation over the area of high rainfall could not be validated in the absence of rain gauges over these locations. Rain rate of 90 mm/hr was seen in all the scans at different time periods as well as over different locations from 0834 to 0915 UTC and in some locations it was even more than 90 mm/hr. This sort of high rain rate is due to the fact that since the rain rate algorithm, in the present set-up, does not have any upper cut-off value of reflectivity (to distinguish between rain and hail, otherwise called as 'hail cap' by NEXRAD), reflectivity *Z* in excess of 53 dBZ at 1.0 km height over places wherein hailstorm was observed had caused the enhanced rain rate. This also indirectly supports that wherever $Z > 53$ dBZ was observed at lower heights and the reflectivity core

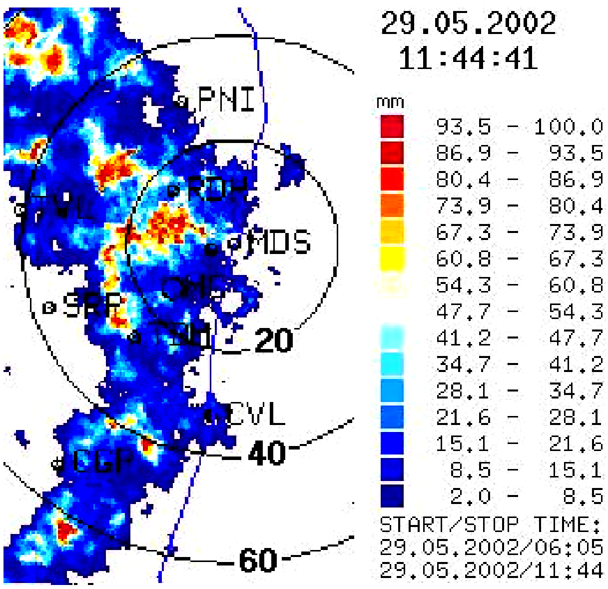


Fig. 4. Accumulated precipitation during storm period (0600-1200 UTC) on 29 May 2002

with more than 55 dBZ were seen atop 3 km, hail was the probable contributory mechanism of this sort of enhanced *Z*. Interested readers may see Fulton *et al*. (1998) and Baeck and Smith (1998), for hail cap threshold adopted by NEXRAD while estimating rain rate. Fanhauser (1976) reported rain rate of 100 mm/hr in Raymer, Colorado, USA hail storm on 9 July, 1973 wherein hail stone of size 15 mm was observed. This perhaps confirms the public report of hail size of 10-15 mm observed at Villivakkam since the rain rate was more than 100 mm/hr between 0834 and 0915 UTC over Villivakkam and its adjoining area wherein hail was observed.

4.6. *Estimated size of the hails*

In a few case studies of hail storms over north and northeast Indian region using conventional / analogue radars, the size of the hail was estimated using temperature – entropy (T - φ) gram (Mull and Kulshrestha, 1962; Sharma, 1965). In this paper, we adopted the enhanced hail detection algorithm (which uses both radar and upper air sounding information) which is operationally used by NEXRAD. The algorithm as outlined in Witt *et al*. (1998a) is briefly summarised below. The severe hail index (SHI) is defined as

$$\mathrm{SHI} = 0.1 \int_{H_o}^{H_T} W_T(H)\, E \; dH$$

where H_o is the environmental melting level and H_T is the height of the top of the storm cell. The temperature based weighting function $W_T\,(H)$ is defined by

$$W_T\,(H) = (H - H_o) \,/\, (H_{m20} - H_o)$$

where H_{m20} is the height of –20° C environmental temperature. When the height $H \le H_o$, $W_T\,(H) = 0$. When $H \ge H_{m20}$, $W_T\,(H) = 1$. The hail kinetic energy flux E (Waldvogel *et al*., 1978) which is a function of reflectivity in dBZ and a weighting factor $W(Z)$ is given by

$$E = 5 \times 10^{-6} \times 10^{0.084Z}\, W(Z)$$

where $W(Z) = (Z - Z_L) / (Z_U - Z_L)$, Z_L = 40 dBZ and Z_U = 50 dBZ. The maximum expected hail size (MEHS) in mm is determined by MEHS = 2.54 $(\mathrm{SHI})^{0.5}$. The probability of severe hail (POSH), usually expressed in %, is given by POSH = 29 ln [SHI / (57.5H_o – 121)] + 50. Severe hail is considered as hail of size more than 19 mm.

Since, Villivakkam is very near to the radar, reflectivity beyond 3 km could not be obtained due to scan elevation (max. 19.8° elevation) limitations. Hence the above method was applied to cells which were observed northwest of Ponneri (about 50 – 55 km NW of radar) at 0834 UTC. The SHI thus computed over the storm area (approximately 25 sq.km) ranges from 40 to 370 and the corresponding maximum hail size could be in the range 16 – 48 mm. The lower value of the maximum hail size (*viz*., 16 mm) obtained over Villivakkam area agrees reasonably with the public report. The maximum hail size (20 to 48 mm) estimated from the measured reflectivities of 60-64 dBZ at 0834 UTC could not be verified for want of hail report from the sparsely populated areas (about 20 km NW of Ponneri). Hail over the areas with more than 60 dBZ from 3 to 9 km (with 64 dBZ between 7 and 8 km) could have been quite probable despite lack of reports and the maximum size estimated in this study is fairly correct according to Witt (personal communication). The probability of severe hail (POSH) over the entire storm cell area has ranged from 12 to 77%.

5. Hail storm over Arakonam on 30 May 2002

Unlike the Villivakkam hail storm on 29 May 2002 which skirted the Meteorological observatories, this hail storm was recorded by the Meteorological Office at Indian Navy, Arakonam situated 65 km west of DWR, Chennai. Relevant information for the present study have been extracted from the log book of meteorological office, Arakonam. Thunderstorm is not an uncommon phenomenon during the pre-monsoon season over the interior Tamilnadu. The convective instability is favourable for development of convective clouds upto a

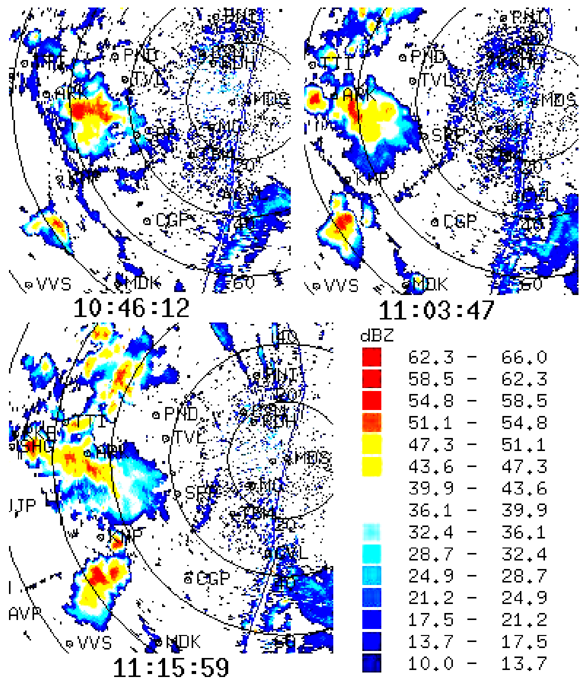


Fig. 5(a). PPI (Z) at 0.2° elevation from 1046 UTC on 30 May 2002

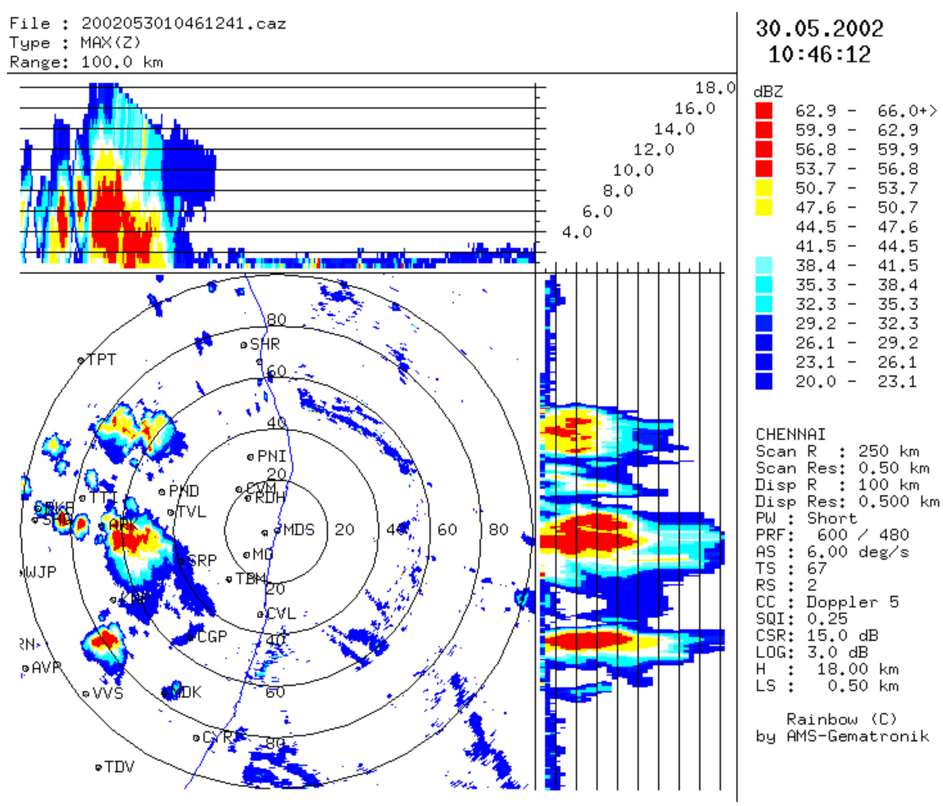


Fig. 5(b). Display of maximum reflectivity over each bin at 1046 UTC / 30 May 2002. The top (right hand side) display refers to the height corresponding to maximum reflectivity when the storm is viewed from south to north (west to east)

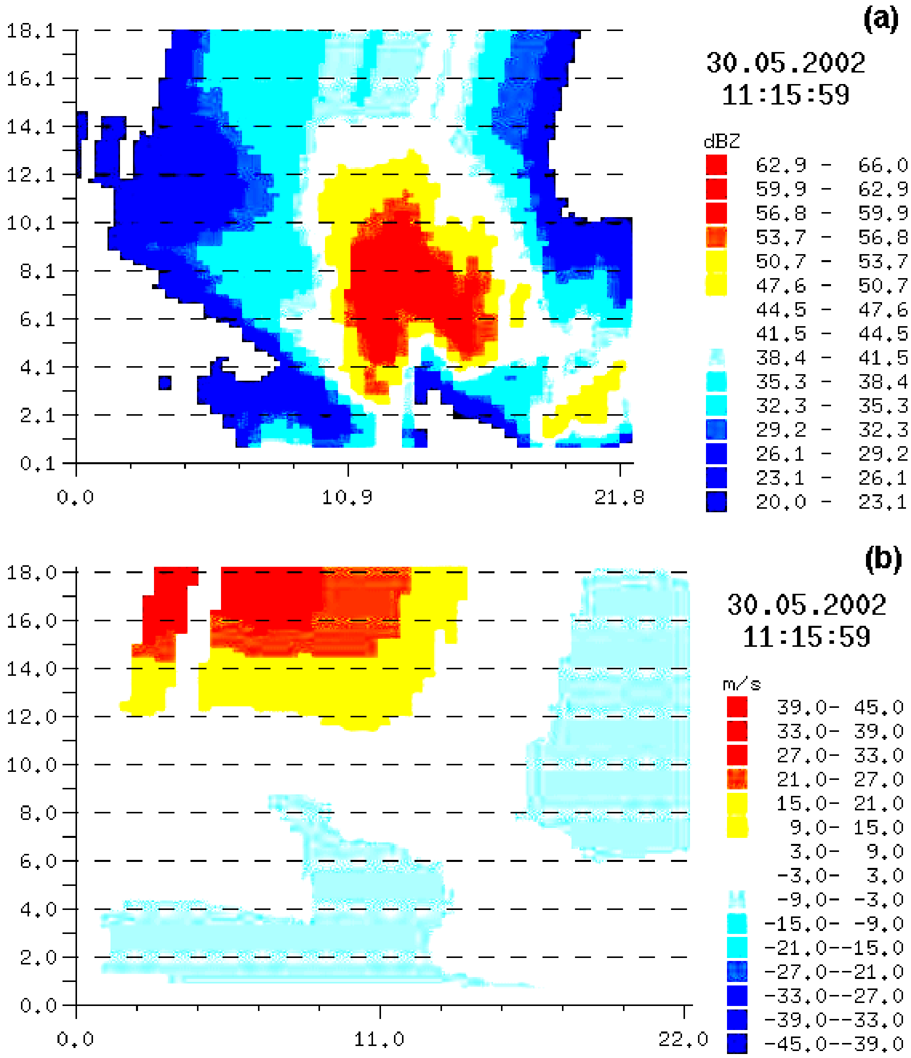


Fig. 5(c). Vertical cut of volume data of reflectivity and radial velocity of the storm close to Kancheepuram at 1115 UTC on 30 May 2002. The cut has been made from the (x,y) coordinate (-75, -41) to (-55, -31) with reference to the radar (0, 0)

greater height as has been established by many researchers and operational meteorologists. Isolated thunderstorm activity in and around Chennai was forecast by Area Cyclone Warning Centre, Nungambakkam, Chennai. This storm was giving copious rainfall upto 100 km west of radar and unauthorized reports indicated hail storm was experienced from Arakonam to Tirutani (marked as TTI in Fig. 1) located 80 km west of radar.

5.1. *Genesis of storm*

The storm had its origin 30 and 40 km north to NNE of Arakonam around 0847 UTC. With the moisture incursion from sea breeze front from 1016 UTC and due to low level convective instability at 1046 UTC as revealed by the three dimensional shear (3DS) of more than 28×10^{-3} s^{-1}, intense thunderstorm clouds developed during this period close to Arakonam. Elevation shear at 0.2° and 0.7° elevation was more than 28×10^{-3} s^{-1} from 0930 UTC in the areas where clouds developed from 0946 UTC. The time evolution of storm as probed by the DWR, Chennai at the lowest elevation (0.2°) from 1046 UTC to 1115 UTC has been displayed in Fig. 5(a). Gust front was observed 4-8 km east of Arakonam at 1046 UTC. Thus, the sea breeze penetration, high shear values and the gust front movement at and around 1046 UTC favoured the development of intense thunderstorm which produced hail between 1105 and 1115 UTC over Arakonam.

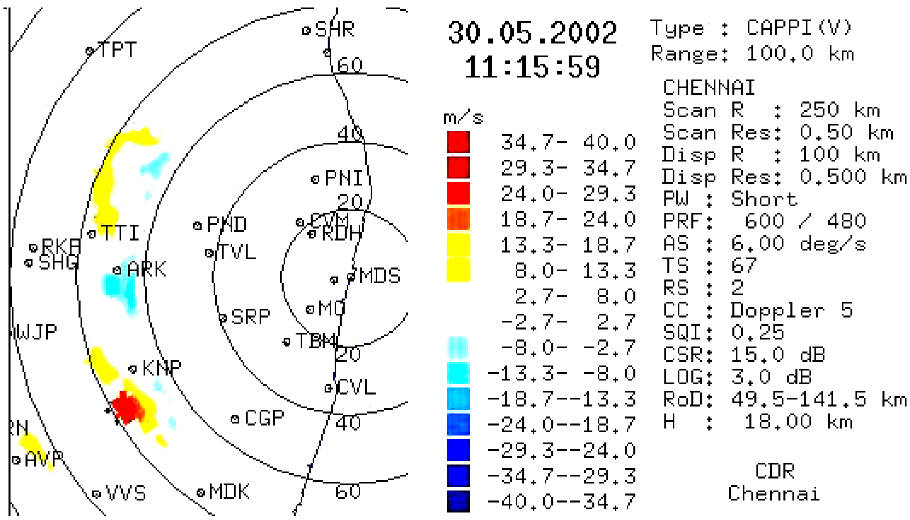


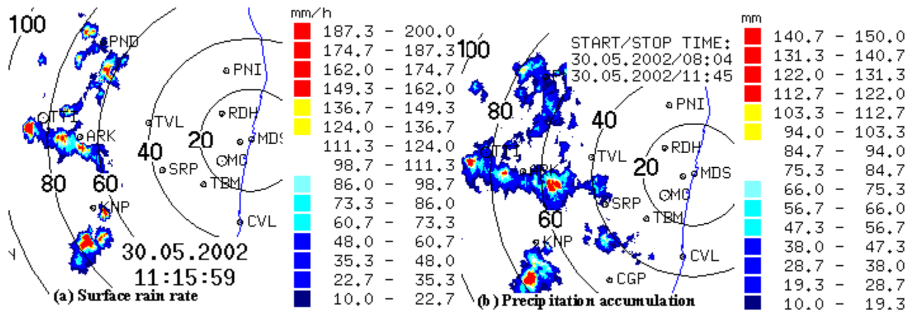
Fig. 6. CAPPI display of radial velocity at 18 km altitude at 1115 UTC on 30 May 2002. The maximum positive radial velocity is 33 mps (south of KNP) and negative velocity is –13 mps (just south of ARK)

5.2. *Maximum reflectivity*

Fig. 5(b) displays maximum reflectivity measured by the DWR at all elevations (from 0.2° to 19.8° elevations) of the scan strategy adopted on 30 May, 2002 at 1046 UTC. It has been displayed as top projection type of display in the centre. The top display is height of the reflectivity as one sees through the cloud from south to north and the display on the right hand side is the height of the reflectivity when viewed from west to east. The height of the echo top (corresponding to arbitrarily chosen reflectivity of 15/20 dBZ) was beyond 18 km indicating that the thunderstorm had a very high vertical extent. Intense clouds between 0946 and 1046 UTC were seen almost in the same place (a few km west of Arakonam) and the thunder cells got intensified to have a great vertical height and with high intensity, presumably because of the moisture feed and convergence due to shear. The height of highest reflectivity [*i.e.*, more than 55 dBZ to distinguish between hail and severe rain spell according to Baeck and Smith (1998); Fulton *et al.* (1998); Rinehart (1999)] extended from about 8.8 km at 0946 UTC to about 12 km at 1115 UTC when the storm was close to Arakonam. The middle level reflectivity exceeding 50 dBZ was also extending from 10 km height a.g.l. at 0946 UTC to more than 15 km at 1016 UTC and thereafter meandering between 12 and 14 km between 1046 and 1115 UTC. This confirms the hail warning conditions used by Smart and Alberty (1985) and Kessinger *et al.* (1995), *viz.*, threshold limit of cloud extending beyond 8 km and the presence of reflectivity core of more than 50 dBZ somewhere between 5 and 8 km. The minimum reflectivity of 50 dBZ at 3 km (Atlas, 1990) has been simply satisfied by and over a larger value of dBZ. Vertical cut of volume data of *Z* of the storm close to Arakonam as well as about 30 km south of Arakonam (about 5 km south of Kancheepuram, marked 'KNP' in figures) was made [Fig. 5(c)] and observed that maximum *Z* was 64 dBZ at 8 km altitude 45 dBZ extended upto 14 km height.

5.3. *Height of 45 dBZ reflectivity above freezing level*

The height of 45 dBZ at 0916 UTC was 12 km and it stretched to 18 km at 1115 UTC when the storm was close to Arakonam. Freezing level based on upper air RS/RW data from Meenambakkam observatory, Chennai at 1200 UTC on May 30 was 4886 gpm. Though Arakonam is about 60 km away from Meenambakkam, the freezing level at Arakonam is considered more or less the same as that of Chennai as no upper air sounding observation other than that is obtained at Chennai is available nearby to Arakonam. Table 2 lists the freezing level recorded by Chennai observatory at 0000 and 1200 UTC from 28 May to 2 June 2002. Since the Arakonam storm was about 60 km away from Chennai, there is no indication in the 1200 UTC upper air data of Chennai about the middle level warming and thereby higher freezing level as experienced on 29 May Villivakkam hail storm. But on the contrary compared to 1200 UTC of 29 May, the 30 May freezing level was close to normal. Climatologically (IMD, 1999) freezing level during May at 0000 UTC is 4730 m and at 1200 UTC is 4870 m. As



Figs. 7(a&b). Radar estimated (a) rain rate at 1115 UTC and (b) precipitation accumulation from 0804 to 1145 UTC on 30 May 2002

such the 1200 UTC freezing level (4886 m) on 30 May appears to be very much reliable. Hence, presuming that the freezing level over Arakonam might have gone upto the same level it went on 29 May due to intense convective activity over that area, the 45 dBZ echo top was higher than the freezing level by 6000 to 12000 m, atleast. This value according to Witt *et al*. (1998a) certifies a 100% chance of hail storm. This has been confirmed by the meteorological observation made at Arakonam observatory. The other conditions that atleast 50 dBZ at 3 km height (Atlas, 1990) has been very well satisfied in the Arakonam hail storm case.

5.4. *Upper level divergence*

NSSL used the diverging radial velocities at the upper level of storm, near the top of the storm, in the mid 1970s (Burgess, 1974; Burgess and Devore, 1979). Witt and Nelson (1991) extended this idea and prepared a plot to estimate the size of the hail stone from the difference in radial velocities of opposite sign (ΔV, where V is the radial velocity) near the storm top based on a study of 49 hail storms. In the present case, the ΔV was found to be more than 40 mps in 40 km stretch at 18 km height over the storm area between 1016 and 1115 UTC. The maximum positive velocity was 33 mps and the negative velocity was –13 mps at 18 km height and hence the ΔV was 46 mps in a span of 40 km when the storm was about 10 km south of Kancheepuram. The radial velocity at 18km CAPPI at 1115 UTC has been shown in Fig. 6. This value of the ΔV exceeding 46 mps, according to Witt and Nelson (1991), may be conducive for producing hail stone of size >1.9 cm with a probability of 0.80. Hence the observed fact confirms the method devised by them. Vertical cut of volume data of radial velocity at 1115 UTC has been displayed in Fig. 5(c). The maximum positive velocity was +39 mps and the negative velocity was –9 mps in a span of about 18 km at 18 km altitude. Thus ΔV was 48 mps in 18 km stretch. As such there could have been hail storm over Kancheepuram as well, albeit there was no report about the hail storm report in the print media.

5.5. *VIL and VIL density*

Since 0.2° elevation beam over Arakonam is at a height of about 0.6 km and the cloud top is around 16 km based on 15 dBZ threshold value for the echo top, VIL has been computed for the height 0.6 to 16.0 km height a.g.l. VIL was more than 50 kg/m^2 during 1014-1103 UTC between 0.6 and 16 km height over the regions where hail was observed at surface based on Douglas (1964) and Greene and Clark (1972) methods. Maximum VIL was 64.7 kg/m^2 at 1034 UTC and over 55 kg/ m^2 at 1103 UTC (figures not shown). VIL density was 3.81 kg/m^3. According to Greene and Clark (1972), hail may also produce fictitious value of liquid water due to enhanced return (Z > 55 dBZ) and that may be considered as an indicator of the severity of a storm. Thus, the very high VIL at 1034 UTC indirectly indicates that hail was present in view of higher reflectivity (exceeding 55 dBZ) prevailing at that time (Witt, 1990; Edwards and Thomson, 1998). The computed VIL and VIL density are well above the threshold limits set by Amburn and Wolf (1997) for identification of hail storms and issue of hail warning.

5.6. *Surface rainfall intensity and precipitation accumulation*

Surface rainfall intensity(R) was worked out based on Marshall and Palmer z – R exponential relationship as applicable to Chennai from the linear radar reflectivity factor (z). The z – R relationship used was $z = 267\ R^{1.345}$. Fig. 7 displays surface rain rate intensity at 1115 UTC and precipitation accumulation from 0804 to 1145 UTC on 30th. The rain rate was more than 100 mm/hr between 1034 and 1046 UTC and during rest of the period rain rate was less by an order of magnitude. This high value of rain rate is due to the enhanced value of Z (> 58 dBZ) during this period. This sort of fictitious rain rates have been well documented in hail analyses and the hail threshold has been fixed as 55 dBZ (Fulton *et al*., 1998; Baeck and Smith, 1998). The accumulation of precipitation from 1030 to 1115 UTC was around 21.0 mm which tallies with the ground truth (21.2 mm) recorded by the Meteorological Office at Arakonam. However there are spot values exceeding 80 mm (10 km east of Arakonam) during the hail storm period which could not be verified for want of rain gauges over these locations.

5.7. *Estimation of size of the hails*

The SHI at 1046 UTC over the storm area was in the range of 54 to 78 with MEHS 22 mm and POSH 30%. At 1115 UTC, the SHI was in the range of 61 to 89 with MEHS 24 mm and POSH 33%. This estimation confirms our earlier estimation based on the velocity divergence *viz*., more than 19 mm with 80% probability. The POSH, however, appears to give over forecasting perception of the severe hail detection algorithm over United States and it is being redefined for summer season storms with melting level above 4.0 km as POSH = 29 ln [SHI / (57.5 H_o – 121)] + 30 (Witt, Personal communication). Though it appears that the latest NEXRAD algorithm is applicable to this tropical region as well, we may have to wait for a number of hailstorms to certify its worthiness and/or to fine tune some of the adaptable parameters.

6. Discussion

6.1. *Unusual surface inversion at 1200 UTC*

At 1200 UTC on 29 May 2002 (*i.e*., 3 hours after the hail storm), Meenambakkam RS/RW recorded strong surface inversion (2.5° C rise in a layer of 289 m thickness). Climatologically surface inversion at 1200 UTC is very rare and during May it is practically nil. The surface inversion perhaps could be attributed to cooling at the surface by rain and subsidence warming aloft [*i.e*., cumulus induced subsidence, Pielke (1984)] after the passage of the storm which had caused strong divergence at 0915 and 0946 UTC in 0.4 to 1.2 km layer and/or subsequent release of latent heat during precipitation process. Raghavan (1962) has documented super refraction/anomalous propagation (AP) after the pass over of severe thunderstorms over Chennai during monsoon months and opined that one of the contributory cause for AP could be the surface inversion that sets up in the wake of a thunderstorm and the other being the prevalence of steep humidity gradient. Since clutter filters of notch width (± 1mps) were applied to volume scans during the period under study, we could not get any signal on super refraction / AP conditions. However, no surface inversion was observed at 1200 UTC on 30th since the storm was away from RS/RW observatory by more than 60 km. The rare surface inversion, according to the literature survey done by the authors, observed during pre-monsoon season at 1200 UTC needs to be analysed in-depth with more data sample, if it recurs.

6.2. *Applicability of Hail warning algorithm in tropics*

Though the hail detection algorithms that are in vogue in extra-topics use a threshold limit (50 to 55 dBZ) to distinguish between hail and heavy precipitation (see section 3.2 for references), the threshold, if any, applicable over Indian regions, is yet to be established. A number of hail storm occurrences from thunderstorms and tornadoes over north and northeast India have been reported in the past based on analogue radar data (Rakshit, 1962; Shravan Kumar and Sen Sharma, 1970; Mukherjee and Bhattacharya, 1972; Gupta and Ghosh, 1980). The above studies indicate the shape, structure and vertical extension of thunderclouds producing hail stones. The latest NEXRAD hail detection algorithm (build 9) also emphasizes the necessity of vertical extension of thundercloud well atop melting level. However, the applicability of this algorithm is to be tried for Indian weather conditions in the ensuing years using DWR data from Chennai, Kolkata, Sriharikota and contemplated DWRs at Machilipatnam and Visakhapatnam with a view to fine tune the parameters.

6.3. *Necessity of getting feedback about hail from public*

In United States, for the purpose of validating the storm detection algorithms, 'Storm data' had been generated and published on a monthly basis by the National Climatic Data Center (NCDC). The data consists of reports collected by National Weather Service besides input from public, volunteers, non-governmental agencies/ emergency management groups and print and electronic media. Even with the involvement of so many agencies in building-up a storm data for validating and fine-tuning the NEXRAD algorithms, it has been observed by Witt *et al*., (1998a&b) and Lenning *et al*., (1998) that these data are either inadequate or lack timeliness or precision especially in information pertaining to hail size / time of occurrence of hail storm. Nevertheless, these 'storm data' are not only the source for the algorithm developers but also used for validation purposes. In the present study, we had some difficulty in getting factual or accurate information about these two hail storms in the absence of information similar to 'storm data'. Based on the reported Villivakkam storm (which had data only upto 3.5 km above the earth surface due to narrow range from radar), we could extrapolate and identify hails over NW of Ponneri (PNI) about 40 minutes prior to the time of hail over Villivakkam as the radar was having data over this place upto 17 km. In Arakaonam hail storm case, there could have been occurrence of hailfall over 10 km south of Kancheepuram (KNP) in view of very high reflectivity, VIL, upper level divergence etc. But in both the cases, there is no report available from the public/print media. When a local survey was made and public were contacted after the incidences, information were not encouraging due to 'memory fading syndrome'. As such, it is highly desirable that an awareness has to be created among the service agencies/volunteers/public about passing the timely/factual meteorological information to develop a data base. These information, even if it lacks some precision, is expected to help to devise or fine tune some of the storm detection algorithms and to augment the nowcasting capabilities.

7. Conclusions

Two hail storms in and around Chennai, a coastal peninsular tropical station, have been studied based on the radar reflectivity factor and wind data measured from a single Doppler Weather Radar at Chennai. This study confirms the nowcasting capability of hail storms over Chennai based on the hail detection algorithms devised and operationally used elsewhere in the world. This study also confirms that hail is possible in the tropical coastal station like Chennai wherein climatological frequency of the hail storm has been reported in literature as nil. The hail warning conditions / thresholds on echo top of 45 dBZ exceeding freezing level by more than 1.4 km, vertically integrated liquid (VIL) of 43 kg/m^2 or more, VIL density of 3.5 g/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 though such studies were carried out in extra-tropics. Since there had been only two hail incidences so far after the installation of DWR, these conditions may have to be fine tuned for tropical atmosphere based on future hail storms, if any, over Chennai and its neighbourhood and hail storm observations made with other DWRs at Kolkata and Sriharikota. Nonetheless, the above thresholds may be used as tools to alert aviation community with a prophylactic value. The false alarms, if any, can be reduced based on the de-briefing received from that community. The latest enhanced hail detection algorithm of NEXRAD (build 9) has detected the possibility of hail around Chennai with a good probability. However, this algorithm is to be tried with a large data base of hail storms in the ensuing years and fine tuning, if any, has to be made. The study highlights the need to get accurate and timely public report about the hail occurrences to analyse the hailstorm more effectively.

Acknowledgements

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